Leveraging additive manufacturing for lightweight, multifunctional maritime components: A case study analysis

Massimo Piccioni
Design Department
Politecnico di Milano
Milan, Italy
massimo.piccioni@polimi.it

Francesco Belvisi
Nugae
Lomazzo, Italy
francesco@nugae.tech

Andrea Ratti
Design Department
Politecnico di Milano
Milan, Italy
andrea.ratti@polimi.it

***Abstract*—The maritime industry is witnessing groundbreaking innovation through the gradual introduction of additive manufacturing (AM) technologies. These advanced techniques can be employed to manufacture boats and components with enhanced design and performance. By leveraging the seamless integration of 3D printed hollow ribs with an internal reinforcement of pre-impregnated carbon fibre sleeves, it is possible to achieve significant advancements in lightweight construction and stiffness. This paper presents a detailed examination of this technological approach, focusing on a case study of a multifunctional seating unit of a motor yacht, serving as both a sofa and a kitchen cabinet. Throughout a comparative analysis with the conventional composite manufacturing technique, the efficacy and potential applications of the proposed AM methodology in yacht construction are explored, providing valuable insights into its advantages, limitations and future perspectives.**

Keywords—maritime industry, yacht design, additive manufacturing, 3D printing

I. Introduction

The advent of additive manufacturing (AM), commonly referred to as 3D printing, has marked a transformative technological era spanning various industries. A notable surge in its adoption stems from a substantial reduction in the expenses related to such technologies witnessed in recent times.

At its core, AM technologies rely on a digital blueprint that is sliced into thin layers. These layers are then built upon one another sequentially, resulting in the creation of a three-dimensional physical object. This layer-by-layer approach offers distinct advantages over traditional methods. First, it allows for the production of intricate geometric shapes without the need for complex tooling [1,2]. This translates to greater design freedom in the production process. Therefore, the creation of custom components tailored to the specific needs and preferences of each end-user is highly facilitated [3]. Moreover, this flexibility opens doors for the development of lighter and more structurally efficient components, ultimately enhancing the overall performance of parts [4]. AM's ability to minimise waste by precisely depositing materials contributes to lessening its environmental impact, making it a more sustainable manufacturing option [4]. Reference [5] emphasise the versatility that 3D printing offers to manufacturing, as its application can range from design evaluation to full-scale production of end-use parts.

The maritime industry, heavily reliant on composite materials for building hulls, appendages, and various internal components, faces several challenges with conventional manufacturing methods. These methods typically involve the use of moulds, which present limitations in terms of flexibility, environmental impact, and cost [6,7]. Moulds, for instance, are not well-suited for intricate designs and require significant modifications or complete replacements for even minor design alterations. This inflexibility hinders the exploration of innovative design solutions and impedes the industry's progress. Furthermore, the production of moulds often raises environmental concerns due to the use of non-reusable materials and the energy consumption associated with their fabrication. Additionally, traditional manufacturing can be a cost-intensive endeavour, particularly for low-volume production runs.

As the yacht market is witnessing a growing trend towards customisation [8], the integration of AM into this sector presents a compelling opportunity to address these longstanding challenges by eliminating the dependency on moulds. Although the adoption of 3D printing in the maritime industry is not as widespread as in other sectors [9], it is steadily growing in significance, mainly in these following applications: boat prototypes, moulds, spare parts, and custom components [10].

Prototype MAMBO (Motor Additive Manufacturing BOat) was the first 3D printed motorboat [6,11,12]. MAMBO was created through a hybrid process that combined AM and standard FRP manufacturing. The hull was produced as an assembly of separate printed parts, resulting in a total weight of approximately 800 kg.

In 2018, Oak Ridge National Laboratory and Alliance MG collaborated to 3D print a 10.36m catamaran hull mould using Big Area Additive Manufacturing (BAAM) [13,14]. The mould was printed in 12 sections assembled without external support, and coated for fibreglass hull production.

In 2017, throughout a collaboration with Bureau Veritas, RAMLAB produced the first class approved 3D printed propeller. [15,16]. The part, measuring 1.3 m in diameter, was created with Wire Arc Additive Manufacturing (WAAM) technology using a bronze alloy.

Superfici's steering wheel showcases unique design features, leveraging generative design integration in its creation process [17]. The intricate shapes could be achievable solely through AM technologies.

At the forefront of innovation within the maritime industry lies an Italian project known as Nugae, which uses AM techniques to fabricate boats and components boasting superior design and performance. Nugae prints hollow ribs seamlessly integrated into the structure, internally reinforced with pre-impregnated carbon fibre sleeves, resulting in substantial improvements in lightweight construction and stiffness. This paper aims to present the proposed technological approach, focusing on an experimental yacht component case study. With this focus, the research carries out a comparative analysis between the traditional manufacturing techniques and the 3D printing approach.

The paper is divided into five sections. Section 2 illustrates the methodology followed for this research and describes the proposed AM process. The selected component is described in section 2. Results of the two approaches are presented in Section 4, whereas discussion and conclusions regarding prototype evaluation are outlined in Section 5.

II. Methodology & Tools

A. *Analysis Strategy*

This research followed an experimental approach based on a comparative analysis to assess the potential of AM for yacht component fabrication. A selected case study was examined through two fabrication techniques: hand lay-up [18] and proposed 3D printing processes. This comprehensive approach allowed for a more nuanced understanding of the advantages and limitations of additive technologies for this specific application.

The analysis encompassed pre-production preparation and production phases, considering parameters such as times, final weight component, and related costs.

By recording timelines for both traditional and 3D printed fabrication methods, the research provided insights into production efficiency. The investigation delved into final weight examination of the components and the material properties employed by each technique. This holistic perspective on material usage and weight optimisation offered a clearer picture of the trade-offs inherent in each approach. By comparing the costs associated with each method, the analysis assessed the economic viability of 3D printing for yacht component fabrication.

A description regarding the specifics of the employed AM process is provided in the following paragraph.

B. *Overview of the Proposed 3D Printing Process*

The system employs an advanced 3D printing approach using a Fanuc M8001a robot arm integrated with a micro-extruder. The extruder utilizes a liquid cooling system and other features to ensure a continuous and precise material flow during printing. Downstream processes such as material drying and temperature control also contribute to print quality.

A patented technique is used to create structures with shell-like reinforcement through the generation of self-intersecting tubular cavities along printed surfaces (Fig. 1). This hollow ribs method aims to provide balance between rigidity and lightweight construction. The software plays a crucial role by rapidly generating boxed reinforcement structures to optimise production speed while maintaining component strength and durability.

A Grasshopper script allows geometric processing to select surfaces and generate hollow sinusoidal ribs through adjustable parameters for amplitude, length, and cross-sectional shape. The experience of the operator is important to achieve sufficiently rigid geometry and stress consistency. The main advantage of the software is its ability to automatically generate tapering ribs at start and end points to create self-supporting structures without risk of collapse.

The slicing software further discretises the geometries into layers as thin as 0.4mm with control points spaced at 3mm intervals. It can detect and join any unclosed curves occurring on the same plane to produce continuous printing paths. In applications, the software controls export of robotic commands to print self-intersecting tubular cavities for structural reinforcement.

Some components are reinforced internally using pre-impregnated composite sleeves inserted into the printed cavities and inflated for compaction. This allows significant stiffening without affecting the outer surface. In other cases, such as for this prototype, reinforcement is provided exclusively on outer surfaces, demonstrating the adaptability of the technique. The material selected for the illustrated application is Polycarbonate with a 20% carbon fibre reinforcement.

Fig. 1. 3D printing of the component.

III. The Case Study

The component selected for this comparative analysis is an L-shaped built-in structure (Fig. 2 and 3) belonging to a multifunctional unit located in the aft section of the 21.5 m yacht wallywhy100 built by the Italian shipyard Wally.

Specifically, the unit serves dual purposes as both a seating area and a kitchen cabinet for the yacht's interior layout. It connects the outdoor and indoor areas in the aft of the vessel. A notable detail is the raised countertop, which is a thin, flat surface that is elevated above the main structure of the component.

The dimensions of just the L-shaped section studied are: length of 3 m, width of 1.5 m, and a height of 1 m. The complex geometries and the multi-purpose functionality of the piece make it well suited for examining the advantages that AM techniques may provide over traditional moulding approaches.

The findings of this experimental case study aim to demonstrate the potential of 3D printing for yacht deck components with complex integrated designs.

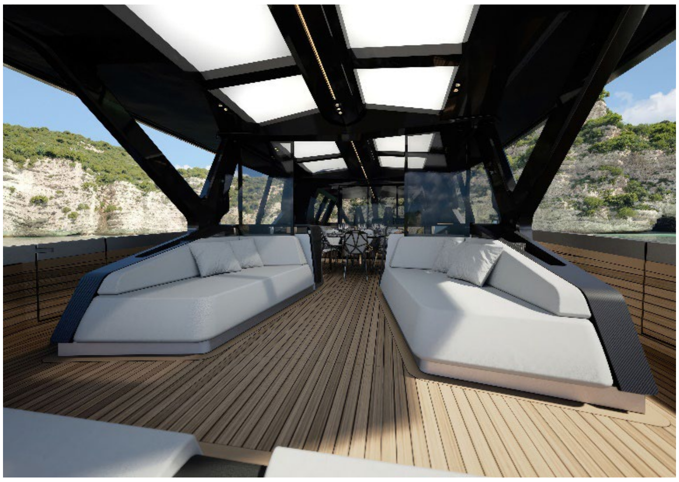

Fig. 2. Render of the component.

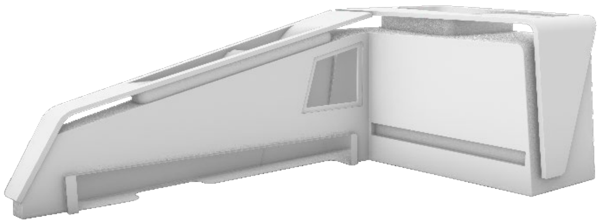

Fig. 3. Arctic view of the component from Rhino.

IV. RESULTS

A. Traditional Approach

Define As specified, the piece was made by hand lay-up technique, with manual placement of the gelcoat layer and the first two mat layers. The main material that was used to make it is fibreglass consisting of vinyl ester resin as a matrix and 35% glass fibre. Some parts have a PVC core.

With this production technique, the component is an assembly of three macro-parts: two parts that make up the countertop and one the main cabinet. In turn, these parts are made up of other parts.

With regard to the timing (considering 8 hours of work per day) and the number of manpower employed, indicative data are provided below:

Pre-production

- Production and mould preparation - five working days and two operators involved.

Production

- Gelcoat laying and manual lamination process - three working days and two operators involved;
- Bonding of parts and surface finishing: two working days and one operator involved.

In total, therefore, the time required amounts to 11 working days to obtain the finished component.

The final weight of the object is 84.9 kg, consisting of approximately 25 kg for the countertop and 59.9 kg for the main structure.

The costs incurred for the moulds are 3300€. The production of the component cost 1650€. The total therefore amounts to 4950€.

B. Proposed 3D Printing Approach

Through the AM process, it was possible to print the component in three different pieces: two for the countertop and one 3D moulding operation for the main part. The prototype is shown in Fig. 4.

The pre-production phase with this technique consisted in engineering the digital model to fit the 3D printing operation. This phase followed these steps: geometric adaptation, design of hollow ribs for reinforcement, design of supports for the printing process, and slicing. In total, the completion of these procedures took 15 hours. The 3D printing process of the component lasted 47 hours. As this is a prototype made for research dissemination purposes, surface finishing was only done on a small portion of the part, purely for demonstration purposes.

The prototype was manufactured with a thickness of 2 mm. with a resulting overall weight of 51.5 kg, with 39 kg attributed to the main cabinet and 12.5 kg to the countertop.

The comprehensive expenses associated with this approach totalled around 1500€, encompassing electricity costs for robot operation, material expenses, expenditures for robot maintenance, and personnel costs.

Fig. 4. 3D printed prototype displayed at JEC World 2024.

V. DISCUSSION & CONCLUSIONS

The primary objective of this research was to investigate the potential of AM techniques for the fabrication of lightweight and multifunctional maritime components. Through a comparative case study analysis, the proposed 3D printing approach was evaluated against the traditional hand lay-up method. The results obtained provide valuable insights into the advantages and limitations of leveraging AM for yacht component production.

The analysed case study aligns with the pioneering efforts witnessed within the maritime industry in projects like MAMBO and the BAAM-printed catamaran hull mould. These initiatives demonstrate the growing interest of this sector in adopting AM technologies.

One of the notable advantages of the proposed 3D printing process lies in the streamlined pre-production phase. By leveraging specialised software for geometric processing and model adaptation, the preparation time was significantly reduced. This eliminated the manual labour required for mould creation, resulting in substantial cost savings. However, it is important to note that while moulds incur upfront costs, they can be reused for mass production of components without design variations, amortising the associated expenses over time.

During the production phase, the 3D printed prototype required 47 consecutive hours of robot work, against three days of shifts for the traditional approach. This resulted in considerably less time for this phase and a notable reduction in the number of operators involved. With an experienced operator overseeing the process, the machine could run autonomously, without dependence on human presence or adherence to work shifts. In the case study, the prototype was left with a rough finish without undergoing surface treatments, which would typically require an additional 6 hours of work.

The creation of moulds for traditional component manufacturing represented a significant waste of materials and energy for the company, and at the end of their utility, disposal issues must be considered. In contrast, through 3D printing, material was precisely deposited only where necessary, thereby promoting sustainability by reducing the environmental impact associated with traditional mould-making processes.

With a weight of 51.5 kg compared to the original 84.9 kg component, the 3D printed prototype exhibited a substantial reduction in weight. From the perspective of utilising this technology for various boat components, the resulting vessel would be significantly lighter, leading to improved performance and reduced fuel consumption. However, it is crucial to consider that for a final version of the 3D printed component installed on board, an additional 30% of material usage may be necessary to ensure optimal structural performance.

While the research did not conduct finite element analysis (FEA) on the prototype, future studies will focus on this aspect, comparing stiffness and durability with the product obtained through traditional techniques. In this regard, the research will progress by examining the insertion of carbon fibre sleeves into the hollow ribs as an additional structural reinforcement measure. The development of the research could also focus on automating model engineering processes in the AM approach, further reducing time. In this context, it is worth considering that currently components such as the analysed case study are designed for traditional manufacturing methods. In a scenario where an additive approach is adopted, designers would work with a different design methodology oriented towards 3D printing from the outset. This shift in mindset could essentially eliminate the time required for model engineering, as it would be integrated in the design phase itself. By integrating design for additive manufacturing (DfAM) principles early in the process, components would be optimised for 3D printing, potentially leading to further improvements in performance and efficiency.

In conclusion, the findings of this case study highlight the promising potential of additive manufacturing in the maritime industry, particularly the approach adopted by Nugae. By leveraging 3D printing, yacht components can be produced with enhanced design freedom, reduced lead times, and significant weight savings. The ability to precisely deposit material and eliminate the need for moulds not only contributes to cost reductions but also aligns with sustainable manufacturing practices, minimising waste and environmental impact.

As the maritime sector continues to embrace customisation and innovative design solutions, the integration of AM technologies presents a compelling opportunity to overcome the limitations of traditional manufacturing methods. The seamless integration of hollow ribs with internal reinforcement could pave the way for lightweight and multifunctional components that can elevate the performance and efficiency of vessels.

While further research is warranted, particularly in the realm of structural analysis, optimisation, and automation, the case study serves as a testament to the transformative potential of 3D printing in the maritime industry, offering a glimpse into a future where design innovation and sustainable practices converge to redefine the boundaries of yacht construction.

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