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Emerging approaches in yacht design and manufacturing: State of the art and future perspectives of generative design and additive manufacturing

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Abstract. The yacht industry is facing increasing demands for customisation and sustainability that challenge traditional composite manufacturing methods. Through a systematic literature review, this paper explores how the emerging technologies of generative design and additive manufacturing (AM) are transforming yacht design and production processes. A systematic search of recent publications uncovered various applications of these novel technologies that demonstrate their potential to address current industry challenges. Generative design enables the creation of innovative, optimised hull forms but have seen limited adoption in yacht design thus far. AM technologies are being applied more widely, from boat prototypes, hull moulds, spare parts, and custom components. Across the case studies examined, AM consistently provides unprecedented geometric flexibility and empower manufacturers to meet customisation demands without waste penalties. While research on integrating generative design and AM remains limited, the findings suggest these technologies could revolutionise yacht composites design and manufacturing. Their application fosters design innovation, flexible customisation, and more sustainable production practices. As the adoption of these emerging technologies progresses, their impact warrants further studies. This research provides insights for navigating their implementation and maximising their potential to shape the future of the yacht industry.

Keywords: Yacht design; maritime industry; additive manufacturing; 3D printing; generative design

1. Introduction

The mid-20th century was a turning point for boat manufacturing, as significant advancements reshaped the landscape of the industry (Musio-Sale et al., 2020; Peterson, 2022). One pivotal development that emerged during this era was the introduction of fibre reinforced plastic (FRP) as a primary construction material for boats. FRPs, which mainly have fibreglass as a reinforcement in the nautical sector, allowed the creation of cost-effective techniques for the serial production of boats through the employment of moulds. Composite moulding processes became therefore the most predominant solution among boats measuring 40 m or less. Above that length, mainly due to material properties and market demand, other boat manufacturing techniques and materials are more adopted.

Despite its widespread use, new trends in the yacht industry are compromising the efficiency of this technique, exposing its challenges regarding environmental drawbacks and flexibility limits. The growing demand for customisation of yachts' components made in limited series produces significant diseconomies and environmental impact factors related to the use of moulds in manufacturing composite components. These tools aren't suitable for the production of complex forms as the extraction from the mould is possible only using the correct draft angles (Musio-Sale et al., 2020). Because of this, parts require either adaptations, simplifying the original design, or expensive hand-craft processes. The low flexibility of composite material production tools results in a high material and energy waste for manufacturing, since each design modification precludes the reuse of the same mould. When moulds cannot be amortised over enough elements, they constitute one of the most relevant problems from an environmental point of view in terms of process Life Cycle Assessment (LCA).

To overcome the gap, new design approaches are required to shape spaces and products that foster a greater circularity of the resources employed. In this perspective, the Department of Design of Politecnico di Milano University, in collaboration with PNRR Made in Italy Circolare e Sostenibile (MICS) initiated the NEMO project with the aim of defining eco-design and manufacturing strategies for yacht flexible customisation. As a result, freeing from the traditional technologies of form transfer using models and moulds could mean adopting generative design models capable of exploiting additive manufacturing (AM) technologies for integrating customisation at the design and production stage. The increasing competitiveness in the market brings manufacturers to evaluate these innovative strategies to stay relevant and sustainable in the industry.

This paper represents the starting point of the above-mentioned research, intended to analyse the adoption of these novel methods and technologies by conducting a wide-ranging literature analysis that focuses on the nautical sector but also expands to encompass the entire maritime industry. The research therefore sets out to answer the following questions:

- How are generative design and AM applied in the maritime industry?
- How do they tackle the challenges of freeing flexibility in composite manufacturing?

2. Method

The search for documentation relating to the implementation of these two approaches in the maritime industry was mainly conducted using the Scopus database. Five clusters, each containing different keywords, were combined for the search: maritime industry, additive manufacturing, customisation, sustainability and generative design. In total, through this method, the database provided 130 documents.

Initially, an initial selection of documents was made based on reading the titles and abstracts, excluding those that were not relevant. Subsequently, they were further skimmed through in-depth reading, thus reducing the number to 17, as the only pertinent to the yachting industry. To broaden the research, additional documents were found through several steps of manual searching on the Google and Google Scholar platforms. Finally, the research phase concluded with cross-referencing, bringing the total to 24 relevant studies and articles.

The analysed documents were subjected to a cataloguing and organisation process through the assignment of summary keywords. The use of keywords made it possible to effectively summarise the topics covered in each article, thus speeding up comparison activities. Thematic connections between the various works have been identified, allowing grouping by conceptual and thematic affinities. Finding complementary information on the same topic was therefore facilitated.

The literature review highlighted that tools such as generative design and AM can provide solutions to the aforementioned challenges arising from conventional methods of manufacturing composite materials. Initially, an analysis of the characteristics of the documents examined was carried out, in order to provide an adequate context on the topic. Secondly, an overview of the two tools was introduced. Then, generative design and AM were described in relation to the application scope, examining their implications and benefits in the maritime industry. In light of the results presented in the review, it was possible to draw conclusions regarding the current level of implementation of these new tools and the benefits in composite manufacturing deriving from them.

3. Results

Among the 24 documents retrieved, 19 of them tackle the application of AM technologies in the yacht and maritime industry, 4 examine the use of generative design and only one covers both topics. The studies reveal that this is an emerging research topic, since they were all released after 2017 and the majority of them (18 out of 24) was released from 2020.

3.1. Generative design and AM overview

Many industries are adapting to the innovations brought by Industry 4.0 by implementing in their processes intelligent digital systems capable of creating cutting-edge design alternatives through artificial intelligence models (Khan et al., 2022). One prominent example of this technological advancement is generative design, an approach that uses algorithms to automatically generate and optimise multiple design options, facilitating the work of designers by presenting them with candidate solutions that best satisfy the input requirements (Krish, 2011). Generative design, therefore, aims for a quicker design process. By developing complex optimised forms, it has been shown to potentially reduce materials usage by 20% to 40% compared to traditional design methods (Turney, 2023) The adoption of generative design can radically change the design process, fostering innovation and creativity. In addition to that, Industries will have a much lower environmental impact thanks to reduced energy consumption (Pollák and Török, 2022).

Because of the complex geometries that characterise products developed with generative design, conventional manufacturing methods can't be employed. AM technologies, on the other hand, are the only capable of producing generatively designed forms (Turney, 2023) from a digital model. The term additive manufacturing does not just identify a technology, but encompasses all those additive processes in which the deposition of different layers of material upon each other forms a product (Attaran, 2017). From rapid prototyping, the applications of AM are expanding to the fabrication of end-use components. AM adoption can reduce or eliminate the need for using specific production tools.

Thanks to its layer-upon-layer technique, AM has unique capabilities that differentiate it from traditional manufacturing practices: shape complexity, hierarchical complexity, functional complexity and material complexity (Gibson et al., 2015). This characteristic also provides greater flexibility by allowing the use of a wider variety of materials (Bionda and Ratti, 2017).

Attaran (2017) highlights several significant advantages of AM. First, it advances customisation, enabling products to be tailored to specific customer requirements. Additionally, it substantially reduces production lead times, allowing for quicker response to market demands. Furthermore, it enables on-site and on-demand manufacturing, eliminating the need for extensive inventory and reducing storage costs. Finally, it boasts a small environmental footprint, as it minimises waste by utilising only the necessary amount of material, contributing to sustainable manufacturing practices.

Thanks to the integration of both tools, it's consequently possible to achieve substantial material and cost savings. The complete design freedom allows intricate organic shapes to be produced for lightweight and optimised products (Coulthard and Wang, 2022).

3.2. Generative design applications

Within the maritime industry, implementing generative design has lagged compared to other fields. The typical design process for naval architects and designers is to work on existing hull forms, making slight modifications in order to achieve the desired characteristics (Khan et al., 2022). For this reason, the main research activity about the implementation of generative design in this sector concerns its application for hull design.

Karczewski and Kozak (2023) proposed a generative design method used for a 12 m sailing yacht case study. The software used was Rhinoceros with Grasshopper as the generative design tool. Design criteria relating to mass, resistance, stability, and internal space were formulated parametrically and used as objectives for optimisation. Constraints on geometry, topology, and performance were defined. An evolutionary multi-objective algorithm drove the optimisation to search for Pareto optimal solutions meeting the criteria. The optimisation tool used was Octopus, a Grasshopper plugin.

Khan et al. (2022) presented a new CAD tool called ModiYacht, which comprises a generative design module and an attribute-based design module. N-subpopulation-based teaching learning-based optimisation (N-TLBO) algorithm was used in order to obtain optimisation. The algorithm produces various design alternatives within the design space. In order to have a uniform distribution of alternatives across the design space, the generative approach uses a space-filling and non-collapsing optimisation strategy After making initial selections, the design space can be further optimised through the application of a space-shrinking technique (SST). This method reduces the design space and generates fresh design possibilities within the narrowed scope for subsequent iterations. This interactive process continues until the user achieves a hull design that aligns with their desired characteristics.

In another paper, Khan et al. (2023) explored different modes for effectively exploring generative design spaces (GDSs) resulting from generative AI models like GANs for complex design problems, like ship hull design. Three exploration modes were developed: random (REM), semi-automated (SAEM), and automated (AEM), with varying levels of user involvement. REM allows users to manually explore the GDSs randomly based on intuition. SAEM involves collaboration between the user and an optimiser to guide exploration towards optimised and user-preferred regions. AEM uses an optimiser to automatically search for the global optimum based on performance. A custom GAN called ShipHullGAN was trained on ship hull datasets, bypassing therefore the use of a single parent hull. ShipHullGAN was used to create a 20-dimensional GDS for ship hull design. The study revealed that SAEM is most effective overall, allowing users to guide exploration towards preferred regions while the optimiser focuses on performance. This highlights the need for hybrid exploration methods for complex GDSs.

Apart from research regarding hull design, the interiors of Bolide VM80 by Victory Design are an example that shows the adoption of generative design tools for lightweight structural yacht elements made of carbon fibre (Dallorso and Morello, 2023).

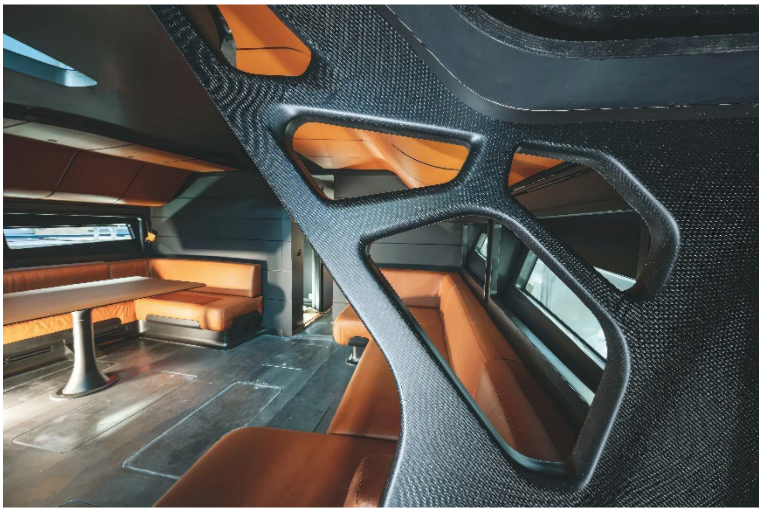

Fig. 1. Bolide VM80
Source: Dallorso and Morello, 2023

3.3. AM applications

Significant progresses in AM technologies have ushered in a transformative era for industrial design, with some of these breakthroughs gradually permeating the maritime industry. Initially, these technologies were primarily employed as a means to create scale models of yachts for purposes such as design evaluation and marketing (Peterson, 2021).

Upon the retrieved documents, four primary areas of recent additive manufacturing applications have emerged within this sector: boat prototypes, hull moulds, spare parts, and one-off/custom components.

3.3.1. Boat prototypes

The use of these technologies for boat manufacturing has been tackled by 7 documents across the examined literature (Amelia, 2023; de la Peña Zarzuelo et al., 2020; Musio-Sale et al., 2020; Peterson, 2021; Peterson, 2022; Rutheford, 2022; Taş and Şener, 2019; Ziółkowski and Dyl, 2020).

The first case reported dates back to 2012, when a group of students from the University of Washington 3D printed a small hull for a local regatta (Peterson, 2022). The peculiarity of this first example is that the material adopted was obtained from reclaimed milk jugs. Since then, many other prototypes have been proposed and produced, mainly focusing on small watercrafts.

Dutch company Tanaruz produces 3D printed highly customisable runabouts that range from 4.5 m to 7.5 m in length, leveraging the dimensional scalability potential enabled by AM. (Amelia, 2023; Rutheford, 2022). This year, the design studio founded by Jozeph Forakis presented megayacht concept Pegasus 88 m, which showcases a 3D printed framework for both hull and superstructure (Amelia, 2023).

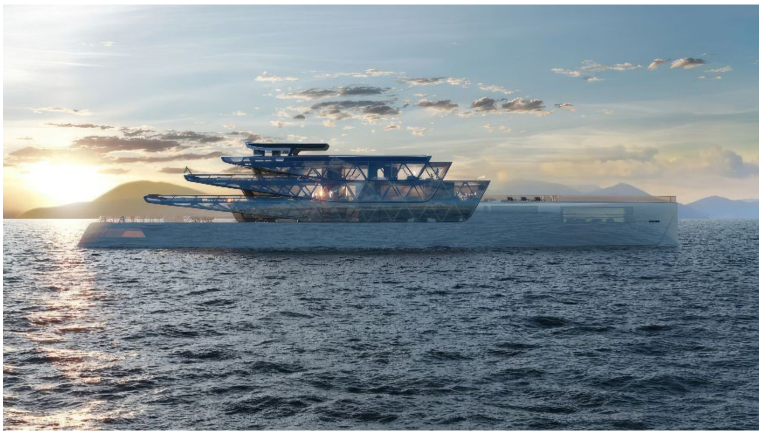

Fig. 2. Pegasus 88 m Concept by Jozeph Forakis
Source: Amelia, 2023

Although Peterson (2021) claims that additive manufactured boats are not yet ready for mass production, among the case studies collected there are some promising examples worth examining in more detail.

Livrea Yacht, in collaboration with startup OCORE, launched Mini 650 sailing yacht in 2018 to compete in a race from France to South America (Musio-Sale et al., 2020; Taş and Şener, 2019). Sophisticated computer modelling and control software allowed the robot to precisely deposit carbon fibre strands within the hull form, creating an optimised weaved structure. The thickness and reinforcement were controlled to balance weight, stiffness, and performance. Furthermore, Livrea patented a fractal-inspired printing algorithm. This ambitious project represents an important benchmark for the nautical industry, as it resulted in the first 3D printed racing boat, stronger and yet lighter than similar sailing yachts thanks to AM.

In 2019, the University of Maine's Advanced Composites Center successfully produced the first fully 3D printed patrol boat in a single operation (Peterson, 2022). The 3Dirigo boat, with a length of 7.62 m was also recognised as the world's largest 3D printed object. For this project, the researchers worked with a custom-built machine, capable of printing objects up to 30.5m long, 6.7 m wide, and 3.05 m high using sustainable composite materials.

In 2020, Italian start-up MOI Composites unveiled MAMBO, the first 3D printed fibreglass motorboat. Designed in collaboration with Autodesk, Catmarine, Micad and Owens Corning, MAMBO utilised a hybrid manufacturing process combining AM and standard FRP boatbuilding techniques (Musio-Sale et al., 2020; Amelia, 2023). The hull was produced as 50 separate parts extruded by two robotic arms working together. This allowed fibres to be oriented in multiple axes, substantially increasing stiffness without significant weight gain. At 800 kg, MAMBO was over 30% lighter than a production FRP hull of similar size. The printed parts were bonded to a PVC core and laminated with fibreglass fabric before integration. Finally, the exterior was sanded, faired and painted. While not entirely manufactured through additive techniques, this case study demonstrates their potential to directly produce customised FRP hull designs with an outstanding design freedom compared to traditional FRP boatbuilding.

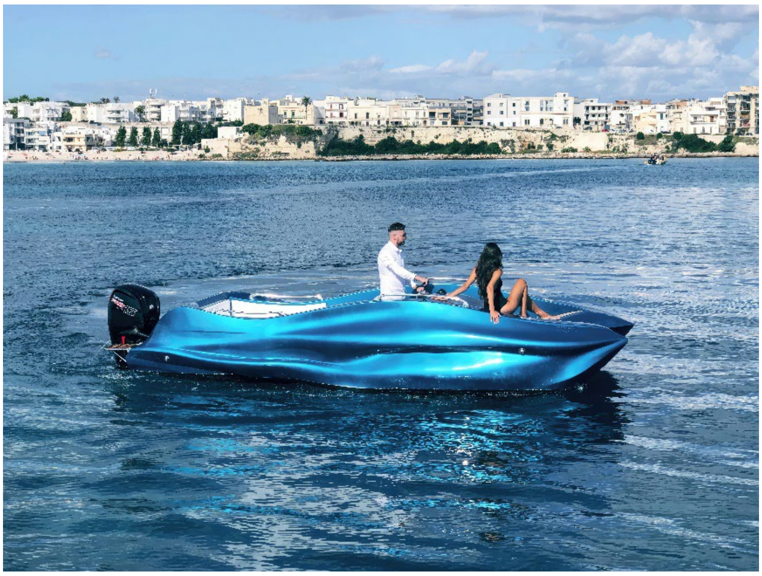

Fig. 3. MAMBO by MOI Composites
Source: Amelia, 2023

3.3.2. Hull moulds

The adoption of additive technologies in the nautical sector has also addressed the field of hull mould manufacturing, as mentioned in 6 papers (de la Peña Zarzuelo et al., 2020; Musio-Sale et al., 2020; Paquet et al., 2021; Peterson, 2021; Peterson, 2022; Post et al., 2019). As Peterson (2021) stated, moulds represent a substantial financial outlay for manufacturers of FRP yachts, and the utilisation of 3D printing technology significantly reduces both the time and costs associated with crafting moulds for intricate manifold surfaces in this context.

One of the first additive manufactured hull moulds was produced in 2017 by Thermwood (Musio-Sale et al., 2020). The firm used its proprietary Large Scale Additive Manufacturing (LSAM) technology to print a positive mould for a production series skiff. Paquet et al. (2021) discussed the potential of Foam Additive Manufacturing (FAM) for producing hull moulds. This novel methodology consists in the use of a two-component material, able to expand in volume up to 40 times and cure in a matter of seconds.

One of the most interesting examples in this field is the 10.36 m catamaran hull mould produced in 2018 by researchers at the Oak Ridge National Laboratory in collaboration with Alliance MG (Post et al., 2019; Peterson, 2022). The team used Big Area Additive Manufacturing (BAAM) to 3D print the mould in 12 sections using with 20% chopped carbon fibre reinforced acrylonitrile butadiene styrene (CFABS), reducing the coefficient of thermal expansion and minimising distortion and warping in the final part. The BAAM system printed the 12 mould sections at a travel speed of 27.51 cm/s at a flow rate of about 35.38 kg/h. The parts were printed vertically in order to eliminate the need for supports while optimising surface finish and accuracy. The sections were then CNC machined and assembled using a post-tensioning system that allowed the large mould to be self-supporting without an external framework. The finished mould was coated with a thin vinyl ester layer and successfully used to produce a fibreglass hull via vacuum assisted resin transfer moulding. This project demonstrated the potential for BAAM technology to rapidly manufacture large-scale moulds at lower costs by eliminating the traditional mould plug construction process. Although some post-processing was still required, BAAM's ability to directly fabricate a boat hull mould with minimal support structures illustrates the value proposition for marine applications.

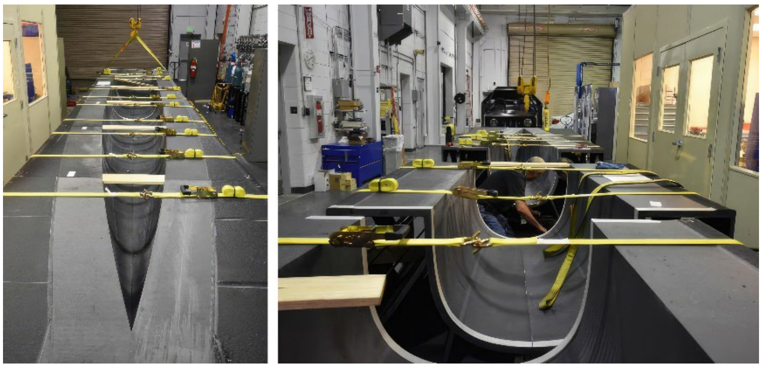

Fig. 4. Catamaran hull mould by Oak Ridge National Laboratory
Source: Post et al., 2019

3.3.3. Spare parts

The adoption of Although spare parts manufacturing is not discussed for the nautical sector, this field of application of AM is the most common in the whole maritime industry, with 9 documents that tackle this topic (Alexandrea, 2022; Gonzaga et al., 2023; Kostidi and Nikitatos, 2017; Kostidi et al., 2021; Lamvik, 2021; Profumo, 2017; Ramesh Babus et al., 2021; Taş and Şener, 2019; Ziółkowski and Dyl, 2020).

Profumo (2017) identifies 3 models of application for spare parts production through AM technologies:

- Maintenance effectiveness: 3D scanning + 3D printing
- Warehouse management: digital CAD + 3D printing
- New service model: digital library/remote engineering + 3D printing

Kostidi and Nikitakos (2017) argue that the utilization of AM for spare parts is being assessed due to its potential to expedite the delivery of spare parts and components to remote areas by eliminating superfluous intermediaries and reducing lead time.

In another paper, the same authors observed that the main advantages derived from 3D printing spare parts are: economic efficiency, reduced inventory, and improved service, followed by environmental benefits and asset availability (Kostidi et al., 2021).

Despite the major help provided by additive technologies, Lamvik (2021) reports that the most relevant barriers to their full implementation are the absence of expertise and comprehension regarding these processes. For these reasons, it is important to achieve full understanding of the technologies and make regulations for AM produced parts, especially for those important for the safety of the ship, in order to assess their quality (Junghans et al., 2021). Current standards for traditional components are not sufficient, but could be useful for establishing the basis.

3.3.4. One-off/custom components

This field appears to be the least discussed in the literature surveyed, with only 3 documents reporting it (Loibner, 2020; Musio-Sale et al., 2020; Peterson, 2022).

However, the nautical sector is worldwide renowned for its high quality and high personalisation degree. In this context, AM provides major benefits, allowing the production of customised objects without an increase in costs, since they depend only on the quantity of material used (Bionda and Ratti, 2017). Moreover, Brun and Karaosman (2019) report a positive correlation between the extent of customisation and the perceived value of products within the yacht industry. Their paper emphasises that companies offering more exclusive products tend to encourage greater levels of customisation and customer engagement.

Superfici, an Italian design laboratory based in La Spezia, stands out as one of the most prolific manufacturers of one-off and custom components using 3D printing.

Starting from small-scale commissions, such as ABS customised speaker housings for Tankoa Shipyard (Musio-Sale et al., 2020), the company gradually began to manufacture larger custom components.

One prime example is the console for the Sacs Marine 700 Series (Peterson, 2022). Because of its complex forms, the product couldn't be realised using traditional FRP manufacturing techniques. Thanks to the efficiency of Fused Filament Fabrication (FFF), the object was designed, manufactured in various parts and later assembled within a month, using a standard 3D printing machine. This achievement stands as an important benchmark for the production of larger direct-to-market AM products. Additionally, the console boasts the advantage of being easily and rapidly updated with new electronic components, requiring no intricate or time-consuming operations.

One of the most innovative products manufactured by Superfici is a yacht steering wheel, called Smart-Wheel (Loibner, 2020). The product features a Raymarine multifunctional display at the centre. For both the design and production processes, generative design and AM have been integrated. The software used for the generative design process was Autodesk Fusion 360, which adopts an algorithm based on a mono-cellular organism for creating unique, organic, lightweight, and optimised forms. The product was 3D printed using an ABS Pro filament, a stronger version of standard ABS. The deposition rate was set at 60mm/s, accompanied by a 15% infill and five perimeters. The overhang angle function of the software proved to be highly beneficial in optimizing the model for 3D printing, reducing both time and material usage.

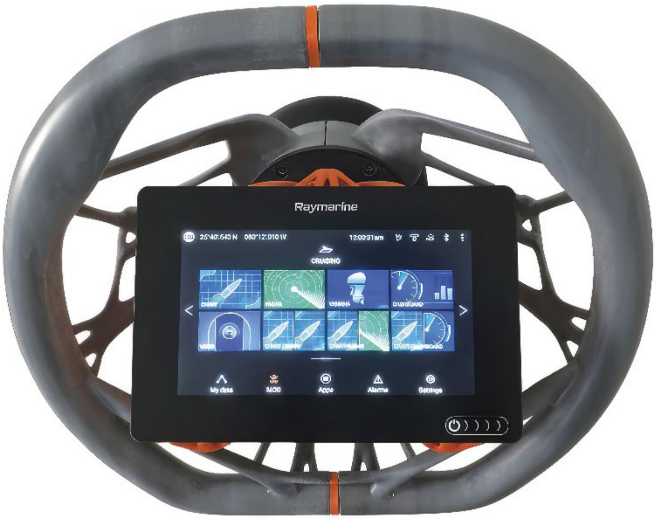

Fig. 6. Smart Wheel prototype by Superfici
Source: Loibner, 2020

4. Discussion and conclusions

This literature review examined emerging applications of generative design and additive manufacturing in the maritime industry, evaluating their current application and assessing how they can effectively address the challenges associated with traditional composite manufacturing methods. A total of 24 documents were retrieved regarding the two approaches and all of them were published recently within the last 5 years, demonstrating these are emerging areas of research.

Methodologically, the majority of literature employed case studies to demonstrate specific AM and generative design projects. While helpful for showcasing applications, case studies have limitations such as small sample sizes that might not perfectly depict a framework of the situation. Future experimental and survey research methodologies could provide more robust and generalisable insights. On the other hand, the strengths of this review are its wide scope that encompasses the whole maritime industry and its systematic approach to the collection and screening of the documents.

Most of the documents on generative design highlight its capacity to offer substantial support during the preliminary design phase. Generative design facilitates the generation of innovative and unbiased solutions while enhancing performance, ultimately surpassing conventional design methods. However, the literature revealed that generative design uptake has lagged in the maritime industry compared to other industries and is mainly studied for hull design.

The majority of the collected documents explored the use of AM. Four main fields of application were identified in the literature: boat prototypes, hull moulds, spare parts, and one-off and custom components. Throughout the analysis of these fields, the main benefits of AM could be validated. A common finding among boat prototypes and components was that 3D printing enables bespoke geometric complexity that conventional FRP manufacturing techniques cannot achieve, leading to optimised lightweight finished products. Additionally, the studies about hull moulds and spare parts manufacturing exposed the economic efficiency and, particularly highlighted by the latter field of application, the advantages of digital inventories enabled by AM.

Additionally, the steering wheel prototype created by Superfici is a pioneering example for the yacht industry as both generative design and 3D printing tools have been employed for its creation.

While sparsely addressed in the literature concerning the maritime industry, an important finding from the overview on generative design and AM, is the minimal environmental footprint that these tools afford, ensuring a significant reduction of energy and material waste.

There were a few notable gaps in the literature. First, there were relatively few studies that examined generative design applications compared to the number that explored additive manufacturing. This indicates generative design is an under-researched area in need of more empirical study, particularly for applications beyond basic hull design. Moreover, most of those studies have been conceptual demonstrations rather than full-scale implementations. Another gap is that only one example was found in the literature that integrated both generative design and AM techniques. As the benefits of combining these tools were frequently discussed, more studies that seamlessly integrate generative design and AM across various yacht components and applications are needed, providing valuable insights on design and manufacturing process optimisation.

To further encourage customisation in the maritime industry, additional areas for future research are recommended. With the aim of fostering the transition to these tools, it is advised to conduct comparative LCAs and cost analyses to quantify sustainability and economic benefits against conventional manufacturing. As the adoption of generative design and AM grows, the development of design guidelines and workflows is necessary in order to fully leverage customisation benefits derived from their integration. Furthermore, the range of dimensional constraints that are acceptable within the domain of AM technologies and their related equipment will need to be defined, encompassing both large and small scales.

In conclusion, the present research sees its future in addressing current gaps and limitations adopting an integrated approach in flexible yacht design and manufacturing. AM and generative design show strong promise to revolutionise composites design and production processes in the nautical sector and, on a broader scale, in the maritime industry. Literature shows that the combined use of these tools is bringing major benefits across other industries, such as automotive (Vasco, 2021; Junk & Rothe, 2022), aerospace (Pilagatti et al., 2023), and product design (Dean and Loy, 2020). Their powerful combination of optimised design freedom and performance enhancement positions these tools at the forefront of a customisation-centred innovation that could drive both competitiveness and increased customer satisfaction with highly tailored products.

5. Acknowledgements

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