diid

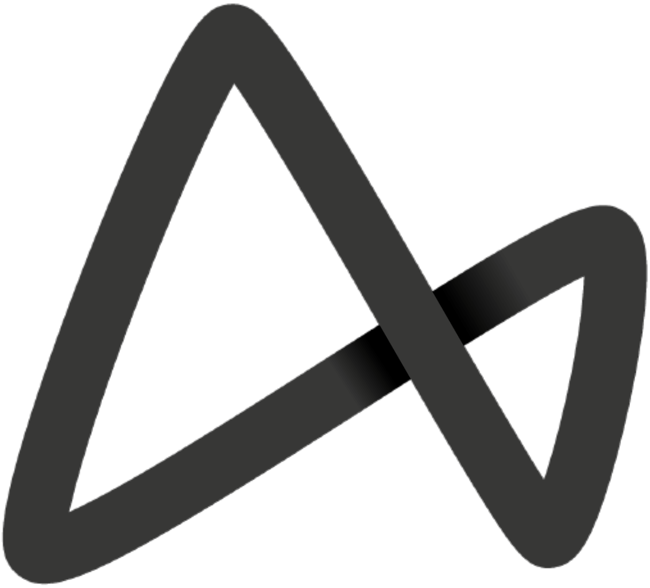
disegno industriale
industrial design

theorìa
pòiesis
praxis

diid.it

DIGITAL
SPECIAL
ISSUE
3

Design and Innovation for Made in Italy



Editors
(Eds)
Michele Zannoni
Giuseppe Lotti

Colophon

diid
disegno industriale
industrial design
Digital Special Issue 3

Year
XXIII

diid is an open access
peer-reviewed scientific
design journal

diid is published
three times a year

Registration at Tribunale
di Roma 86/2002
(March 6, 2002)

www.diid.it

Publisher
Fondazione
Bologna University Press
Via Saragozza 10
40123 Bologna
Tel. (+39) 051 232 882
Fax (+39) 051 221 019
www.buponline.com
info@buponline.com

ISSN
1594-8528

ISSN Online
2785-2245

DOI
10.30682/diidmics25

Reviewers

The Design and Innovation for Made in Italy diid Digital Special Issue have undergone a rigorous peer-review process to ensure the scholarly quality of the contributions contained herein.
The Editors extend their sincere appreciation to the following Scholars who served as Reviewers for this Digital Special Issue.

Roberta Angari
Francesco Armato
Laura Badalucco
Alessandra Bosco
Alessia Brischetto
Carmen Bruno
Luca Casarotto
Rosa Chiesa
Pietro Costa
Davide Crippa
Eleonora D’Ascenzi
Veronica Dal Buono
Giorgio Dall’Osso
Raffaella Fagnoni
Cinzia Ferrara
Juri Filieri
Carlo Franzato
Silvia Gasparotto
Gabriele Goretti
Roberto Iñiguez
Carla Langella
Sabrina Lucibello
Marco Mancini
Patrizia Marti
Jacopo Mascitti
Roberto Montanari
Francesco Monterosso
Gabriele Monti
Giovanna Nichilò
Davide Paciotti
Lucia Pietroni
Alessandro Pollini
Riccardo Pulselli
Emilio Rossi
Carmen Rotondi
Romina Santi
Chiara Scarpitti
Dario Scodeller
Benedetta Terenzi
Eleonora Trivelin
Davide Turrini
Anna Paola Vacanti
Margherita Vacca
Elena Vai
Riccardo Varini

This study was carried out within the MICS (Made in Italy – Circular and Sustainable) Extended Partnership and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.3 – D.D. 1551.11-10-2022, PE00000004). This manuscript reflects only the authors’ views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

Contents

Introduction

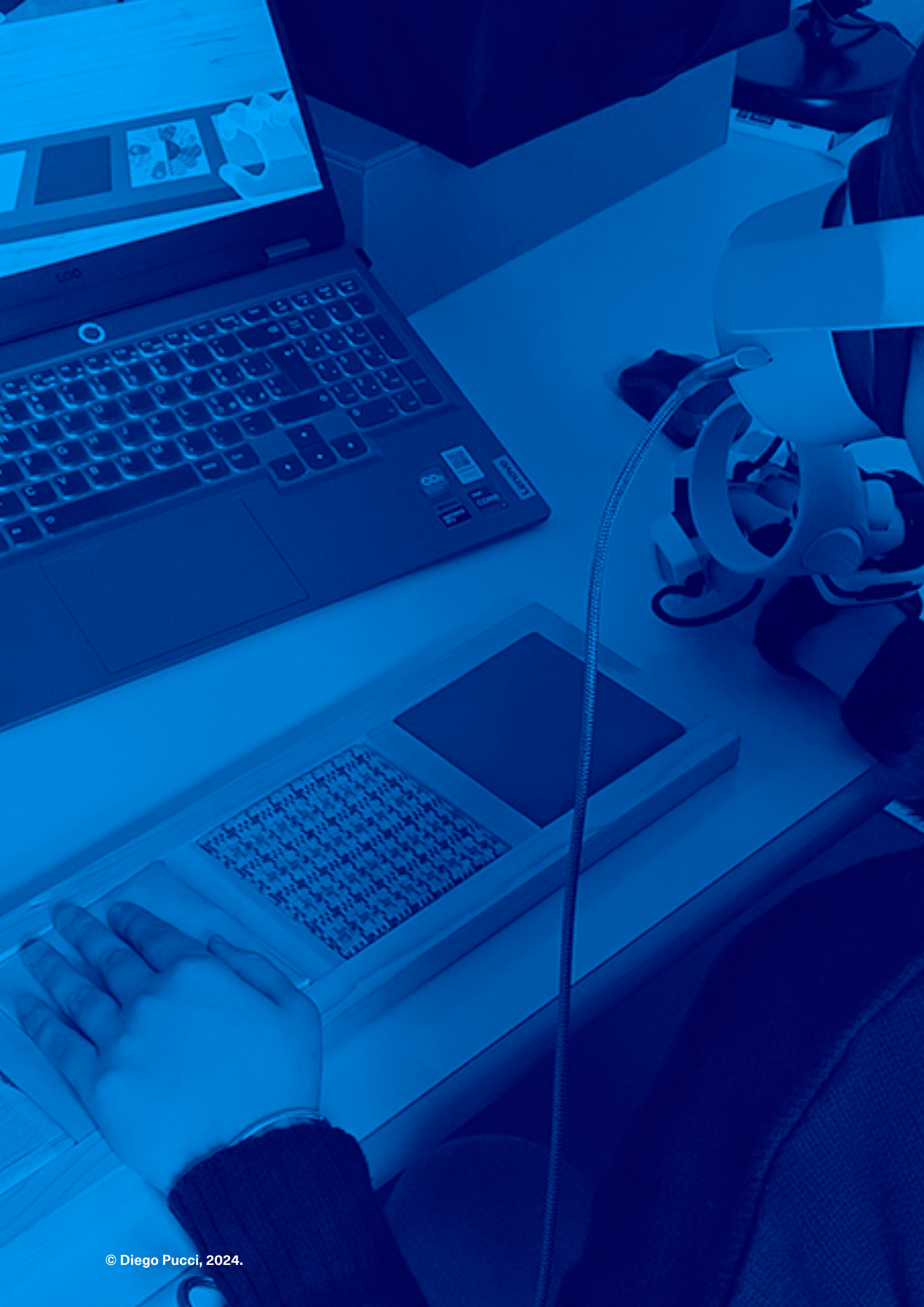
Systemic and Strategic Design for Industrial Transitions

Material Circularity and Regenerative Approaches

Digital Transition, Advanced Design and Hybridization

Design, Culture, Territorial Memory for Sustainable Regeneration

Digital Transition, Advanced Design and Hybridization



Flexible Customization of Large-Scale Yacht Components through a Design-Driven Approach

Andrea Ratti
Politecnico di Milano
andrea.ratti@polimi.it
ORCID: 0000-0003-4115-2732

Massimo Piccioni
Politecnico di Milano
massimo.piccioni@polimi.it
ORCID: 0009-0007-2789-2642

Arianna Bionda
Politecnico di Milano
arianna.bionda@polimi.it
ORCID: 0000-0002-7817-3070

Abstract

The yacht industry's reliance on traditional mold-based composite manufacturing presents significant challenges in terms of design flexibility, cost, and environmental sustainability, particularly for customized or limited-series components. This paper presents the results of the NEMO and CYClaDEs research projects, which explore a zero-tools flexible approach that integrates large-scale composite-reinforced additive manufacturing (AM) with computational design.
A comparative case study of an integrated yacht component was conducted, benchmarking the proposed method against the conventional processes.
The findings reveal significant improvements across key manufacturing metrics, prompting a critical discussion on the broader implications, including the redefinition of the designer's role in a digital workflow, the enhancement of product value through deep customization, and a clear pathway towards more circular and scalable production models.
This research demonstrates a viable, design-driven pathway for the Made in Italy nautical sector to achieve greater flexibility and circularity, aligning the demand for high-level customization with sustainable and digital innovation.

Keywords
Yacht design
Additive manufacturing
Computational design
Flexible customization

diid DSI No.3 – 2025
10.30682/diidmics25r

INTRODUCTION

Prior to the mid-20th century, yacht construction was fundamentally a craft-based practice, dominated by the use of wood and metal materials. Each vessel was a testament to artisanal skill, resulting in unique but costly and time-intensive creations available only to a niche market. The introduction of fiber-reinforced plastic (FRP) composites marked a profound paradigm shift for the nautical industry, particularly for boats under 40 m (Musio-Sale et al., 2020; Peterson, 2022). This material innovation, based on the use of molds, enabled cost-effective serial production, standardizing construction processes and drastically reducing build times. This industrialization had a significant socio-economic impact, effectively democratizing the sector by making yachting accessible to a much broader audience and fueling its post-war expansion. However, while this mold-based model catalyzed the growth of the modern recreational marine industry, it also consolidated a rigid production approach that, today, shows clear and pressing limitations.

Indeed, the established mold-based paradigm now confronts two interconnected challenges: environmental sustainability and design flexibility. This crisis is particularly acute for the high-end segment of the market, where Italian industry holds established global leadership (La Nautica in Cifre, 2024). This segment thrives on a culture of personalization and differentiation, creating a central tension for manufacturers. On one hand, the market's growing demand for bespoke solutions (Brun & Karaosman, 2019) is a core tenet of the "Made in Italy" brand and its celebrated artisanal know-how. On the other hand, the economic and technical realities of mold-based production push towards standardization. The need for draft angles limits morphological freedom, forcing designers into compromises or requiring a return to complex, fully manual craftsmanship to achieve unique forms (Musio-Sale et al., 2020). Furthermore, the environmental toll is substantial. Molds are typically fabricated from composite materials that are difficult to recycle, becoming large-scale industrial waste destined for landfills after a limited production run. When costs cannot be amortized over a sufficient number of units, the mold itself becomes a critical factor of waste in terms of resources, materials, and energy.

To overcome these critical issues, a profound reconsideration of the role of the design discipline in driving innovation—not only of the product, but of the entire production process—is necessary. Addressing these challenges requires a strategic shift towards zero-tools, data-driven manufacturing paradigms capable of uniting industrial efficiency with craft-level flexibility.

The NEMO (Design 4 Yacht Flexible Customization) and CYClaDEs (Circular Yacht Customization through Design and new business models Experimentations) research projects, initiated by the Design Department of the Politecnico di Milano within the PNRR MICS (Made in Italy Circolare e Sostenibile) partnership, fit squarely into this scenario. The projects explore how the integration of additive manufacturing (AM) and computational design can enable radical flexible customization possibilities in the yacht sector. The viability of this approach is demonstrated through an experimental case study analyzing a yacht component and benchmarking the results against traditional composite manufacturing methods.

Starting from the restitution of the activities carried out in the two projects, the article delves into a critical reflection on how a design-driven approach supported by digital technologies can drive process innovation towards

greater personalization and sustainability, strengthening the competitiveness and specificity of Made in Italy in the nautical sector.
To this end, the paper will first review the state of the art in the application of AM and computational design in the nautical sector. It will then detail the methodology and tools developed, present the comparative results of the experimental case study, and conclude with a discussion on the broader implications of these findings.

AN OUTLINE OF ADDITIVE MANUFACTURING AND COMPUTATIONAL DESIGN

ADDITIVE MANUFACTURING

Commonly referred to as 3D printing, AM represents a fundamental shift from traditional subtractive or formative manufacturing paradigms. The process constructs three-dimensional objects directly from a digital model by depositing material layer-by-layer (Gibson et al., 2015). This method dismantles many of the geometric constraints imposed by conventional techniques like molding and subtractive practices, offering an unprecedented degree of design freedom, enabling the creation of intricate and organic forms that would otherwise require the implementation of complex and costly solutions (Khajavi et al., 2014). This inherent flexibility is pivotal for mass customization, as it facilitates the efficient production of components tailored to specific functional requirements or individual user preferences without incurring prohibitive tooling costs, such as molds (Ford & Dean, 2013). From a sustainability perspective, AM significantly minimises waste by precisely depositing material only where it is structurally necessary, reducing the overall environmental footprint (Hao et al., 2010). This same principle allows for the creation of structurally optimised, lightweight parts, enhancing material efficiency and performance.
The field encompasses a diverse range of technologies (Attaran, 2017), with recent experimentatal applications also for large-scale components. Ultimately, the strategic value of AM is most evident in contexts defined by a high demand for tailored products, geometric complexity, and production agility (Weller et al., 2015; Jarža et al., 2023), making it a key enabling technology for the challenges of flexible and sustainable manufacturing.

COMPUTATIONAL DESIGN

Computational design represents a significant paradigm shift in creative and technical fields, moving beyond direct manipulation to the design of processes that generate form (Caetano & Leitão, 2020). It is a methodology where shape is dictated by mathematical and programmatic rules, utilizing algorithms and parameters via textual or visual programming to solve design problems (Manavis et al., 2023). This approach transforms design into a dynamic, repeatable process, enhancing productivity and enabling the creation of more robust and varied solutions compared to traditional manual drafting (Ramage, 2022). The core idea is to translate design steps into a coded language that computers can process, allowing for flexibility and simplicity in creating and modifying complex forms, shapes, and geometries. These aspects, as highlighted by Li et al. (2020), enable computational design to drive performance-driven outcomes across various industries, where it is being applied with several distinct approaches, prominently including parametric design and generative design (Caetano et al., 2020; Ramage, 2022).

Within this framework, parametric design is defined as the exploration of relationships between project dimensions through a design based on parameters (Moretti, 1971; Jabi 2013). Changes to independent parameters automatically update dependent ones (Turrin et al., 2011), enabling the investigation of numerous design options through real-time adjustments.

On the other hand, generative design leverages computational power to automatically create and evaluate a multitude of design alternatives starting from a defined problem and set of constraints (Gradišar et al., 2022).

APPLICATION IN THE YACHT INDUSTRY

The synergistic combination of AM and computational design yields considerable advantages, particularly in enhancing design freedom, production flexibility, and overall sustainability. The transformative impact of this synergy is well-documented in pioneering sectors such as automotive, aerospace, and construction, where its application has led to significant advancements (Vasco, 2021; Chatterjee et al., 2022; Anton et al., 2021). In these domains, AM and computational design are mature technologies, specifically valued for enabling the design and production of structurally efficient parts with complex geometries.

In contrast to these leading industries, the yacht sector has demonstrated a more measured pace in the comprehensive integration of these technologies. To date, most applications tend to showcase individual technological deployments rather than deeply synergistic workflows that combine AM with computational design tools. This pattern of discrete, rather than fully integrated, implementation becomes clearer upon reviewing how AM and, subsequently, computational design are specifically being adopted in nautical contexts.

The adoption of AM is particularly crucial for yacht design because it offers the most viable pathway to overcome the twin challenges inherent in the segment: the unsustainable waste generated by traditional composite molds and the technical rigidity that limits the high-level customization demanded by the market.

Within the yacht industry, it has seen a growing number of experimental and early-stage commercial applications, ranging from the production of molds and individual components to the fabrication of entire boats.

As highlighted previously, molds have always represented a costly and time-consuming aspect of boat building. Illustrating this, Thermwood employed its Large Scale Additive Manufacturing (LSAM) technology in 2017 to print a positive mold for a skiff intended for series production (Musio-Sale et al., 2020). Similarly, a collaborative project in 2018 between researchers at the Oak Ridge National Laboratory and Alliance MG led to the successful creation of a 10.36-meter catamaran hull mold using Big Area Additive Manufacturing (BAAM) (Post et al., 2019; Peterson, 2022).

Perhaps one of the most emblematic examples the direct fabrication of vessels is MAMBO (Motor Additive Manufacturing Boat), recognized as the first 3D printed motorboat (Amelia, 2023; Musio-Sale et al., 2020; Rutheford, 2022). The prototype effectively highlighted AM’s capability to realize complex surface morphologies, including features that are typically difficult or impossible to achieve with conventional mold-based composite lamination. Another notable application is the water taxi jointly produced by Al Seer Marine and Abu Dhabi Maritime, which holds the title for the largest single-operation 3D-printed object, spanning 11.38 m in length (Madeleine, 2023). Previously, this record belonged to the 7.62-meter-long 3Dirigo patrol boat, which was built by the University of Maine's Advanced Composites Center using a specialized 3D printing system (Peterson, 2022).

In terms of product commercialization, Dutch companies Tanaruz and IMPACD Boats are among the early adopters producing limited series of AM boats (Amelia, 2023; CEAD Group, 2024). Their focus is on manufacturing runabouts, with lengths varying from 4.5 to 7 meters, emphasizing a sustainable production approach. The 6 m monolithic catamaran for open waters developed by V2 Group and Caracol AM represents another significant case, with plans for industrialization currently underway (Nehls, 2025).

The main applications of computational design in the nautical sector concern the creation of hull forms. The first parametric approaches date back to the late 1990s and early 2000s (Harries & Abt, 1999; Hochkirch et al., 2002). Mancuso et al. (2021) proposed a parametric approach for the generation of sailing boat hulls based on quadratic and cubic rational Bézier curves. This method relies on the definition of parameters such as length and beam at the waterline, along with other dimensionless coefficients.

Another parametric approach to hull design is represented by Swordfish, developed in 2021 and available as a plugin for Rhinoceros Grasshopper. While primarily developed for BIM architecture, the Rhinoceros plugin VisualARQ also offers parametric functionalities applicable to nautical purposes, such as the development of hull structures (Salla, 2020).

Khan et al. (2023) presented a generative approach to naval hull design based on a GAN model (ShipHullGAN), trained on a large dataset of validated hull geometries. This method enables the creation of a 20-dimensional generative design space (GDS) that allows for the exploration and generation of both traditional and unconventional hull forms. Three different approaches to exploring the GDS—random, semi-automated, and fully automated—were proposed to assess designers' ability to generate new and high-performance designs.

Beyond hull design applications, the interior design of the Bolide VM80 by Victory Design provides a case in which generative design was employed to produce lightweight yacht structures from carbon fiber (Dallorso & Morello, 2023).

In the nautical sector, the only documented example of integration between AM and computational design is the Smart Wheel prototype by Superfici (Loibner, 2020), whose complex and organic design was created using the generative tool Autodesk Fusion 360 and subsequently 3D printed with an ABS Pro filament.

METHODOLOGY AND TOOLS

CASE STUDY AND ANALYSIS STRATEGY

The yacht component under study, shown in **Fig. 1**, is an integrated element of a multifunctional unit positioned in the aft area of the 21.5 m yacht wallywhy100, built by the Italian shipyard Wally. This unit serves a dual purpose as both a seating area and a bar cabinet, bridging the interior and exterior spaces at the aft of the vessel. The component consists of three separate sections: an L-shaped main cabinet, a seating base, and a countertop. It measures 3 m in length, spans 1.5 m in width, and reaches a height of 1 m.

Fig. 1
Render of the wallywhy100 component (Source: Wally, 2024).

For this research, an experimental approach was adopted, with a focus on a comparative evaluation of various fabrication techniques to assess the feasibility of our developed flexible approach for yacht components. The proposed method was benchmarked against the conventional hand lay-up process employed by the Wally shipyard. The corresponding data for this established technique, which is described in principle by Andresen (2001), were provided directly by the shipyard for the analysis. In parallel, the research team fabricated the component using the proposed process, which will be described in the following section.

The comparative analysis was based on a set of defined parameters, chosen to provide a comprehensive assessment of both manufacturing approaches. These indicators include:

- Time required
- Final weight of component
- Costs

To ensure the reliability and comprehensiveness of the data collected for these parameters, the analysis encompassed the entire production cycle of the component, including preparatory pre-production stages, the actual manufacturing phase, and subsequent surface finishing operations.

OVERVIEW OF THE PROPOSED APPROACH

The research led to the development of a system based on the 3D printing of hollow ribs on the surface of the component, which are subsequently reinforced internally. The aim is to increase the mechanical properties without significantly altering the weight of the component and with a lower use of material resources. The reinforcement is achieved by inserting pre-impregnated composite sleeves into these cavities, which are compacted using inflated tubular bags to ensure adhesion and structural integrity. The entire design-to-fabrication workflow is underpinned by a set of custom computational tools and hardware, thoroughly described by Belvisi et al. (2024). The design of the hollow rib structure, in **Fig. 2**, is governed by a patented parametric process (Patent No. 102020000023260), which optimizes the shape and distribution of the ribs.

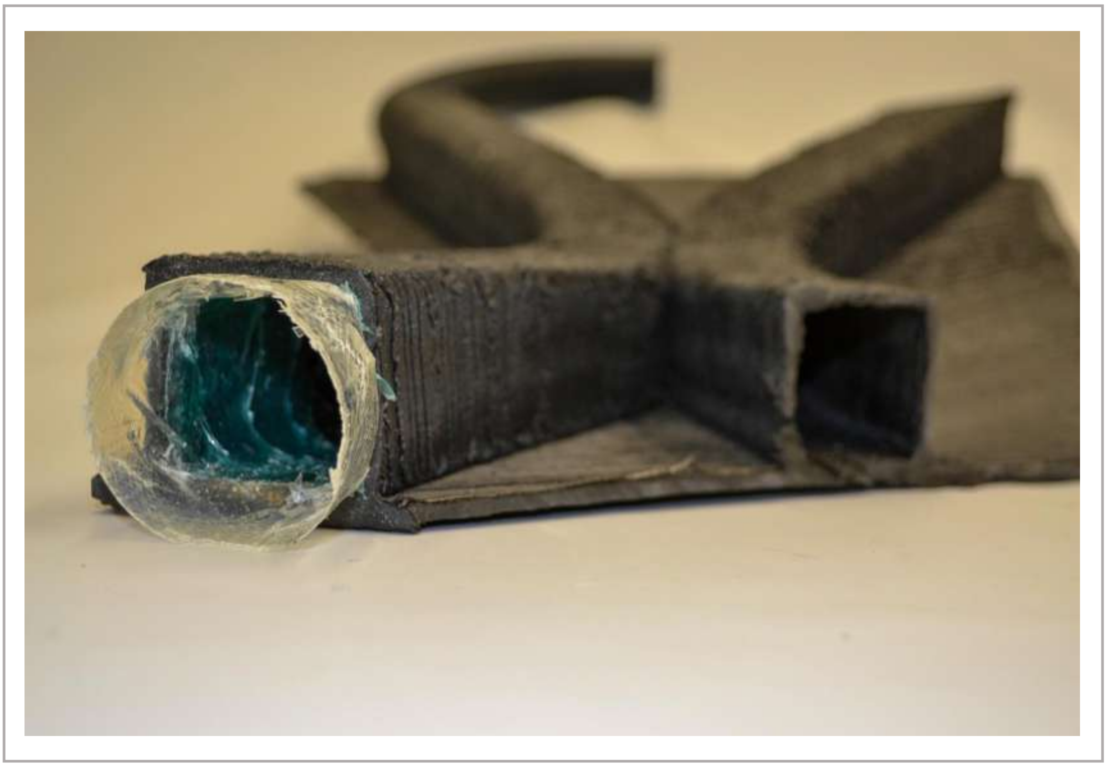


Fig. 2
Details of hollow ribbed panels reinforced with composite material (Credits: The Authors, 2024).

This process is implemented through custom Python scripts (Version Nugae.002) running within the Rhino Grasshopper environment, allowing designers to specify parameters such as the amplitude and length of the curves and the rib cross-section, typically circular or rectangular. The software also allows to automatically generate ribs with tapered ends, creating self-supporting geometries that prevent structural collapse at the start and end points of a path. To translate the digital model into machine instructions, a bespoke slicing software, also developed as a Grasshopper diagram, is employed. This tool processes the geometry by dividing it into layers and includes a feature that automatically detects and joins any unclosed curves on the same plane to produce continuous printing paths. It provides granular control over the process, allowing the operator to balance manufacturing speed against geometric precision by adjusting the density of control points along the print path. The software also contains a data file-writing section that encodes the necessary robot commands and manages file directories. The fabrication is carried out using a robotic AM setup. This system comprises a Fanuc M8001a industrial robot arm integrated with a micro-extruder that utilizes nozzles ranging from 0.9 to 1.2 mm in diameter. To ensure a continuous and precise material flow, the extruder is equipped with a liquid cooling system, and its reliability is further enhanced by a granule blockage prevention system that uses a vibrator and a Venturi suction unit. During fabrication, a constant print speed of 250–300 mm/s and a layer thickness of 0.4 mm are typically maintained. The system is equipped with an integrated tool-changing mechanism, enabling the 3D printing head to be replaced by a milling unit. This configuration permits in-situ subtractive post-processing, such as surface finishing, without requiring the removal of the component from the platform.

EXPERIMENTATIONS

TRADITIONAL APPROACH

The reference component, as fabricated by the Wally shipyard, was produced using a consistent hand lay-up process for all its main parts. The material composition, however, varied across the different sections. For the main cabinet and its base, an FRP composite with a vinyl ester resin matrix and 35% fiberglass content was used, with a PVC core integrated into certain areas. In contrast, the two-part countertop was laminated with carbon fiber to ensure a high-quality finish. The production timeline and labor requirements, based on an eight-hour workday, were significant. The workflow began with a pre-production phase focused on molds preparation and fabrication, a task which required four operators over a period of five working days. Following this, the component entered the production and finishing stages. The initial gelcoat application and the manual lamination process involved three operators for three working days. The final stage consisted of bonding the various parts together and completing the surface finishing, which included sanding and painting. This was completed by a single operator over two working days. In aggregate, the entire traditional manufacturing process to obtain the finished component amounted to 10 working days. The final weight of the complete assembly was 209 kg, broken down into approximately 25 kg for the countertop, 69 kg for the base, and 115 kg for the main cabinet. The total cost incurred for producing the component using this conventional approach was reported to be € 8270.

PROPOSED FLEXIBLE APPROACH

For the proposed approach, all parts of the integrated seating unit were fabricated using the Additive Manufacturing process detailed in the methodology. The selected material for this application was a polycarbonate filament reinforced with 20% carbon fiber (PC-CF20). The workflow began with a digital pre-production phase focused on engineering the model for additive fabrication. This involved several steps: adapting the component's geometry, designing the sinusoidal hollow ribs for structural reinforcement, generating the necessary support structures for the printing process, and slicing the final model into machine-readable code. The completion of these digital procedures required a total of 15 hours. The subsequent 3D printing phase for all component parts, shown in **Fig. 3**, had a duration of 72 hours. The raw prototype, manufactured with a layer thickness of 2 mm, had a total weight of 62.5 kg. This was distributed as follows: 30 kg for the main cabinet, 20 kg for the base, and 12.5 kg for the countertop. Following the printing process, the prototype underwent a surface finishing stage, which required 55 hours to complete. For the base and main cabinet, this involved filling, coating with resin, and applying a final gelcoat finish, while the countertop was covered in Ohoskin bio material, a sustainable leather-alternative derived from orange and cactus by-products. These finishing processes increased the final weight of the complete component to 114 kg. The finished prototype is shown in **Fig. 4**. Summing the durations of the pre-production, printing, and finishing phases, the total time required for the flexible approach amounted to 142 hours. The comprehensive cost for this method was approximately € 6000, a figure that includes expenditures for electricity to power the robotic system, raw material expenses, robot maintenance, personnel costs, and the materials and labor for all surface finishing operations. Tab. I provides a summary of the comparative analysis results.

Fig. 3
3D printing of the component (Credits: The Authors, 2024).

Fig. 4
3D printed prototype displayed at Made in Italy Innovation Forum (Credits: The Authors, 2025).

DISCUSSION

The experimental results presented in this paper offer a multifaceted view of the potential held by the proposed flexible manufacturing approach when compared to traditional composite fabrication methods in the yacht industry. A comprehensive discussion, however, requires moving beyond a surface-level reading of the data to interpret the broader implications for performance, process, product value, and the industry as a whole.

PERFORMANCE ANALYSIS

A direct comparison of the quantitative results reveals a complex but promising picture. The most striking outcome is the significant weight reduction of approximately 45%, from 209 kg to 114 kg. The geometric freedom afforded by AM allowed for the creation of a hollow rib stiffened structure, which strikes a balance between structural integrity and material efficiency. This lightweighting reflects implications for the nautical sector. It directly translates to improved vessel performance and enhanced fuel efficiency, thereby reducing the environmental impact of the vessel during its operational life.

The analysis also highlights a cost reduction of approximately 27%, from €8,270 to €6,000. This advantage is primarily attributable to the complete elimination of molds—a core problem identified in the introduction. By circumventing the need for designing, fabricating, and amortizing costly and resource-intensive tooling, the proposed approach becomes economically competitive, especially for the one-off or limited-series components typical of the semi-custom yacht market.

The parameter of time, however, requires a more nuanced interpretation. While the traditional method took 10 working days (approximately 80 hours of labour), the proposed approach required a total of 142 hours. Although seemingly a disadvantage, this figure must be deconstructed. The 72 hour printing phase, which constitutes the largest portion of this time, was almost entirely autonomous, requiring only occasional supervision. The robotic system can operate continuously, 24/7, without being constrained by standard work shifts. Therefore, the total lead time in days could be significantly shorter, and more importantly, the active man-hours are drastically reduced. This shifts the paradigm from measuring efficiency in total hours to evaluating it based on automation.

A NEW PARADIGM FOR DESIGN AND PRODUCTION

The true potential of this technology transcends the mere replacement of one manufacturing technique with another, but demands a fundamental shift in the design-to-production paradigm. The case study component was originally conceived for traditional manufacturing and subsequently re-engineered for 3D printing. In a scenario where a Design for Additive Manufacturing (DfAM) mindset is adopted from the outset, this re-engineering phase would be absorbed into the primary design process. Designers would no longer be constrained by the design limitations of molds, such as draft angles, but would instead leverage the new geometric freedoms to optimize performance—for example, through the developed customized inner structures—and explore new aesthethic languages facilitated by the AM process.

This paradigm shift inevitably redefines the role of the designer to a more computational-oriented thinking, defining the parameters and rules that govern the creation of an object, rather than just creating its final shape. Such evolution would elevate the design discipline to a central, strategic role in driving process innovation.

Furthermore, this new production model holds the potential to bring significant benefits for workers health and safety since traditional composite lamination exposes operators to Volatile Organic Compounds (VOCs), posing considerable risks. The proposed automated approach removes workers from direct contact with potentially harmful materials and repetitive manual processes, fostering a safer and more sustainable work environment.

REDEFINING PRODUCT VALUE AND USER EXPERIENCE

The implementation of the AM-based workflow detailed in Section 4 demonstrates the capacity to overcome the rigidities of traditional manufacturing, thereby achieving the increased flexibility necessary to meet the high demand for bespoke solutions in the yacht sector. This capability for radical customization presents new opportunities for product customization, enabling the satisfaction of diverse consumer requirements. According to Brun & Karaosman (2019), this level of personalization in the yacht market translates into a greater perceived product value, which in turn establishes a significant emotional bond between the end user and the product. Such a bond is often manifested in a prolonged product life, as the end-user exhibits a reduced propensity for replacement. In this light, customization ceases to be a mere luxury and can become a powerful strategy for sustainability.

SYSTEMIC IMPACT AND VISION

On a systemic level, the primary environmental advantage of this approach is the elimination of composite molds, directly addressing one of the most critical waste streams in the nautical industry. This immediately reduces the consumption of materials and energy associated with tooling. This adoption of a zero-tools, digitally-enabled paradigm for large-scale production fundamentally aligns this research with the Sustainable Development Goal 9 (SDG 9) (United Nations, 2015): Industry, Innovation, and Infrastructure. Specifically, it provides a clear pathway for sustainable industrialization (Target 9.2) and fosters technological innovation (Target 9.5) by redefining the traditional manufacturing value chain. The choice of a thermoplastic material (PC-CF20) for the AM process allows for its reprocessing, supporting the transition to a “cradle-to-cradle” lifecycle for components and aligning the sector with the principles of the circular economy.

The results obtained in this research also suggest a high degree of scalability in industries where flexibility and optimization of spaces is critical. For this reasons, project’s innovations can find potential application in related fields, such as recreational vehicles (RVs), hospitality, and the whole furniture industry. Knowledge transfer and visibility of these technologies can foster a ripple effect, driving advancements and enhancing the global competitiveness of Made in Italy.

LIMITATIONS AND FUTURE RESEARCH

While the results of this research are promising, it is important to acknowledge its limitations, which in turn define clear pathways for future investigation. The current study is based on a single pilot case development. Future work should therefore focus on applying and validating the methodology across a wider range of functional nautical components with different geometric complexities and structural requirements.

Furthermore, while this research has not yet included a Finite Element Analysis (FEA) to simulate and validate the structural performance of the specific prototype, it should be noted that such analyses have been conducted on other components developed in parallel with this research. A crucial following step, therefore, will be to concentrate on simulations and physical load testing to quantitatively compare the stiffness and durability of the additively manufactured case study against its traditional counterpart.

The research could be expanded by evolving the computational tools from a parametric to a generative design approach. By defining performance criteria and constraints, generative algorithms could be used to explore a vast array of structurally optimized, organic geometries for the reinforcing rib structure, potentially yielding solutions that are even lighter and more performant than those achievable with the current parametric method.

In line with the projects' sustainability principles, there is significant potential in exploring the use of raw materials with a lower ecological footprint for the AM process. This could involve investigating polymers derived from recycled industrial feedstocks or new natural fibers, thereby moving the entire methodology closer to a truly circular model.

Finally, primary future developments of the projects are oriented to explore how the design freedom offered by AM can innovate assembly and finishing processes. Research will focus on developing integrated features such as mechanical snap-fits and designing methodologies for reversible surface finish and assembly. This would further enhance the flexibility of the approach and align it with Design for Disassembly (DfD) principles, facilitating easier repairs, upgrades, and end-of-life recycling.

CONCLUSION

This paper has explored the transformative potential of integrating composite-reinforced AM and patented computational design workflows within the context of the semi-custom yacht industry. Through a comparative analysis between traditional composite techniques and the flexible approach proposed by the NEMO and CYClaDEs projects, the research has demonstrated tangible advantages in terms of weight reduction, production cost, and environmental impact. This new paradigm enables a more agile design-driven model capable of addressing current sustainability challenges and the evolving demands for customization in the high-end nautical sector.

By reframing the production process through the lens of digital manufacturing, the role of the designer is redefined, elevating the discipline from a downstream activity to a critical enabler of sustainable innovation.

Furthermore, the research points toward a potential reconfiguration of the value chain, fostering safer working conditions and more circular lifecycle strategies, all of which contribute to the long-term competitiveness of the Made in Italy model.
While the results presented are based on a single case study, they open a promising trajectory for future research and industrial application across various industries. Broader validation across varied use cases and reversible finishing design strategies will be critical to unlocking the full potential of this approach. As the nautical sector confronts rising pressures for ecological responsibility and market differentiation, design-led digitally enabled solutions such as those developed in the two projects offer a compelling vision for the future of sustainable yacht manufacturing.

	Preparation	*40h*	*Main body*	*115kg*	*Main body*	*2275 €*
	Production	*40h*	*Base*	*69kg*	*Base*	*2495 €*
			Countertop	*25kg*	*Countertop*	*3500 €*
Proposed Approach	***TOTAL***	***142h***	***TOTAL***	***114kg***	***TOTAL***	***6000 €***
	Preparation	*15h*	*Main body*	*60kg*	*Prep. + Prod.*	*2500 €*
	Production	*72h*	*Base*	*40kg*	*Surface finish*	*3500 €*
	Surface finish	*55h*	*Countertop*	*14kg*		

Tab. I
Summary of the comparative analysis between the two approaches.

References

Amelia, H. (2023, August 18). *Navigating the Best Examples of 3D Printed Boats. 3D Natives.* https://www.3dnatives.com/en/3d-printed-boats-300320214/

Andresen, R. (2001). Open molding: Hand lay-up and spray-up. In D. B. Miracle & S. L. Donaldson (Eds.), *ASM handbook* (Vol. 21, pp. 450–456). ASM International. https://doi.org/10.31399/asm.hb.v21.a0003406

Anton, A., Reiter, L., Wangler, T., Frangez, V., Flatt, R. J., & Dillenburger, B. (2021). A 3D concrete printing prefabrication platform for bespoke columns. *Automation in Construction*, 122, 103467. https://doi.org/10.1016/j.autcon.2020.103467

Attaran, M. (2017). The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing. *Business Horizons*, 60(5), 677-688. https://doi.org/10.1016/j.bushor.2017.05.011

Belvisi, F., Piccioni, M., & Ratti, A. (2024). Combining Lightness and Stiffness through Composite-Reinforced Additive Manufacturing in the Yacht Industry: Case Study Analysis and Application on Large Functional Components. *Journal of Marine Science and Engineering*, 12(6), 918. https://doi.org/10.3390/jmse12060918

Brun, A., & Karaosman, H. (2019). Customer influence on supply chain management strategies: An exploratory investigation in the yacht Industry. *Business Process Management Journa*l, 25, 288–306. https://doi.org/10.1108/BPMJ-05-2017-0133

Caetano, I., & Leitão, A. (2020). Architecture meets computation: an overview of the evolution of computational design approaches in architecture. *Architectural Science Review*, 63(2), 165-174.

Caetano, I., Santos, L., & Leitão, A. (2020). Computational design in architecture: Defining parametric, generative, and algorithmic design. *Frontiers of Architectural Research*, 9(2), 287-300. https://doi.org/10.1016/j.foar.2019.12.008

CEAD Group. (2024, March 11). *3D printing in boat manufacturing*. https://ceadgroup.com/3d-printing-in-boat-manufacturing/

Chatterjee, A., Mishra, A., Sharma, S., & Bhagchandani, R. K. (2022). Review on lightweight materials, additive manufacturing techniques and design optimization of an airplane. *Proceedings of AIP Conference*. https://doi.org/10.1063/5.0110507

Dallorso, E., & Morello, M. (2023, September 2). Y*acht: Nuovi orizzonti di design, infiniti come il mare. AD Italia*. https://www.ad-italia.it/gallery/yacht-nuovi-orizzonti-di-design-foto/

Ford, P., & Dean, L. (2013). Additive manufacturing in product design education: Out with the old in and in with the new? In *Proceedings of the E&PDE 2013 15th International Conference on Engineering and Product Design Education* (pp. 611-616). Dublin, Ireland, 5–6 September 2013.

Gibson, I., Rosen, D., & Stucker, B. (2015). *Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing*. Springer. https://doi.org/10.1007/978-1-4939-2113-3

Gradišar, L., Klinc, R., Turk, Ž., & Dolenc, M. (2022). Generative Design Methodology and Framework Exploiting Designer-Algorithm Synergies. *Buildings*, 12(12), 2194. https://doi.org/10.3390/buildings12122194

Hao, L., Raymond, D., Strano, G., & Dadbakhsh, S. (2010). Enhancing the sustainability of additive manufacturing. *Proceedings of ICRM 2010: 5th International Conference on Responsive Manufacturing* (pp. 390-395). IET. https://doi.org/10.1049/cp.2010.0462

Harries, S., & Abt., C. (1999). Parametric Design and Optimization of Sailing Yachts. *In Proceedings of SNAME 14th Chesapeake Sailing Yacht Symposium*, Annapolis, Maryland, USA, January 1999.

https://doi.org/10.5957/CSYS-1999-009

Hochkirch, K., Röder, K., Abt, C., & Harries, S. (2002). Advanced Parametric Yacht Design. *In Proceedings of HPYD 2002, High Performance Yacht Design Conference*, Auckland, New Zealand, December 4-6, 2002. https://doi.org/10.3940/rina.ya.2002.14

Jabi, W. (2013). *Parametric design for architecture*. Laurence King Publishing.

Jarža, L., Čavlović, A. O., Pervan, S., Španić, N., Klarić, M., & Prekrat, S. (2023). Additive technologies and their applications in furniture design and manufacturing. *Drvna Industrija*, 74(1), 115-128. https://doi.org/10.5552/drvind.2023.0012

Khajavi, S.H., Partanen, J., & Holmström, J. (2014). Additive manufacturing in the spare parts supply chain. *Computers in Industry*, 65(1), 50–63. https://doi.org/10.1016/j.compind.2013.07.008

Khan, S., Kaklis, P., & Goucher-Lambert, K. (2023). How does agency impact human-AI collaborative design space exploration? A case study on ship design with deep generative models. *In Proceedings of the ASME Design Engineering Technical Conference*, Boston, USA, 20-23 August 2023. https://doi.org/10.48550/arXiv.2305.10451

La Nautica in Cifre (2024). *LOG. Analisi del mercato per l'anno 2024*. https://lanauticaincifre.it/

Li, S., Liu, L., & Peng, C. (2020). A Review of Performance-Oriented Architectural Design and Optimization in the Context of Sustainability: Dividends and Challenges. *Sustainability*, 12(4), 1427. https://doi.org/10.3390/su12041427

Loibner, D. (2020, September 28). Superfici prints Smart Wheel. *Professional Boatbuilder Magazine*. https://www.proboat.com/2020/09/superfici-prints-smart-wheel/

Madeleine, P. (2023, November 20). *World's First 3D Printed Water Taxi Is Also Largest 3D Printed Boat. 3D Natives*. https://www.3dnatives.com/en/3d-printed-water-taxi-is-worlds-largest-3d-printed-boat-201120234/

Manavis, A., Kakoulis, K., & Kyratsis, P. (2023). A Brief Review of Computational Product Design: A Brand Identity Approach. *Machines*, 11(2), 232. https://doi.org/10.3390/machines11020232

Mancuso, A., Saporito, A., & Tumino, D. (2021). Parametric hull design with rational Bézier curves. In L. Roucoules, M. Paredes, B. Eynard, P. Morer Camo, & C. Rizzi (Eds.), *Advances on mechanics, design engineering and manufacturing III* (Lecture Notes in Mechanical Engineering, pp. 221–227). Springer. https://doi.org/10.1007/978-3-030-70566-4_36

Moretti, L. (1971). Ricerca Matematica in Architettura e Urbanistica. *Moebius IV* (1), 30e53.

Musio-Sale, M., Nazzaro, P. L., & Peterson, E. (2020). Visions, concepts, and applications in additive manufacturing for yacht design. *Advances in Intelligent Systems and Computing*, 975, 401-410. https://doi.org/10.1007/978-3-030-20216-3_37

Nehls, G. (2025, February 26). *V2 Group, Caracol achieve large-format 3D printed monolithic boat. CompositesWorld*. https://www.compositesworld.com/news/v2-group-caracol-achieve-large-format-3d-printed-monolithic-boat

Peterson, E. (2022). Recent innovations in additive manufacturing for marine vessels. *Maritime Technology and Research*, 4(4), Article 257491. https://doi.org/10.33175/mtr.2022.257491

Post, B. K., Chesser, P. C., Lind, R. F., Roschli, A., Love, L. J., Gaul, K. T., Sallas, M., Blue, F., & Wu, S. (2019). Using big area additive manufacturing to directly manufacture a boat hull mould. *Virtual and Physical Prototyping*, 14(2), pp. 123-129. https://doi.org/10.1080/17452759.2018.1532798

Ramage, M. (2022, April 21) *What Is Computational Design?. Trimble Construction.* https://constructible.trimble.com/construction-industry/what-is-computational-design

Rutheford, T. (2022, October 21). *Can 3D printing transform the way boats are designed and built?. BOAT International.* https://www.boatinternational.com/yachts/yacht-design/is-3d-printing-the-future-of-yacht-design

Salla, F. (2020, July). *VisualARQ per progettazione navale [VisualARQ for naval design]. VisualARQ.* http://visualarq.com/it/visualarq-per-progettazione-navale/

Turrin, M., von Buelow, P., & Stouffs, R. (2011). Design explorations of performance driven geometry in architectural design using parametric modeling and genetic algorithms. *Advanced Engineering Informatics*, 25(4), 656-675. https://doi.org/10.1016/j.aei.2011.07.009

United Nations (2015). *Transforming our world: the 2030 Agenda for Sustainable Development (A/RES/70/1).* https://sdgs.un.org/2030agenda

Vasco, J. C. (2021). Additive manufacturing for the automotive industry. In J. Pou, A. Riveiro, & J. P. Davim (Eds.), *Additive manufacturing* (pp. 505–530). Elsevier. https://doi.org/10.1016/B978-0-12-818411-0.00010-0

Weller, C., Kleer, R., & Piller, F. T. (2015). Economic implications of 3D Printing: Market structure models in light of additive manufacturing revisited. *International Journal of Production Economics*, 164, 43–56. https://doi.org/10.1016/j.ijpe.2015.02.020

Acknolwedgments
This book brings together the results of research carried out within the NEMO and CYClaDEs projects, funded by the Italian National Recovery and Resilience Plan (PNRR) under the Made in Italy Circular and Sustainable (MICS) programme, Spoke 2, grant number PE_00000004.

Andrea Ratti
Architect, PhD, publicist, researcher, and Associate Professor of nautical design and architecture technology at Politecnico di Milano, Design Department. He is currently director of Master in Yacht Design, operational manager of the Laboratory for boating (SMaRT-lab), and vice president of the Italian Naval Technical Association (ATENA) Section Lombardy.

Massimo Piccioni
Researcher in the field of nautical design at Politecnico di Milano, Design Department. He has a Master's degree in Yacht & Cruising Vessel Design from University of Genoa, as well as a Bachelor's degree in Interior Design from Politecnico di Milano.

Arianna Bionda
PhD in Design, she is a researcher and Professor at the School of Design at the Politecnico di Milano. Her research activities are mainly focus on innovative technologies and materials role in a yacht design project. She is also vice-director of the Specialized Master in Yacht Design and Project Manager of the sports&design team 'Polimi Sailing Team'.

Published in January 2026 by Bologna University Press

DIGITAL SPECIAL ISSUE 3

This special issue of DIID brings together the broadest possible reflection on projects that, with a low Technology Readiness Level (TRL), have attempted to translate years of ongoing research within the sector towards unexplored directions, towards renewal processes framed by sustainability and circularity. All of this is pursued with the aim of enhancing the sustainable competitiveness of Made in Italy through concrete actions developed in collaboration with companies involved from the very beginning, as well as with other firms interested in the relevant themes.

The projects were developed within the following universities: Politecnico di Bari, Politecnico di Milano, Politecnico di Torino, Università degli Studi di Napoli Federico II, Università degli Studi di Palermo, Università di Bologna, Università di Firenze e Sapi-enza Università di Roma.

The overall picture that emerges from this overview of research activities is rich in in-sights and demonstrates how our scientific sector, when compared with fields that have a longer historical tradition in research, is nevertheless capable of making a significant contribution. It also shows that scientific research in the field of Design is able to generate incisive and relevant reflections and solutions for the driving sectors of Made in Italy.

Michele Zannoni
Giuseppe Lotti

DSI No. 3 — 2026
Year XXIII
ISSN 1594-8528
ISSN Online 2785-2245

Bologna
University Press