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RESILIENCE AND SUSTAINABILITY

Towards a Life Cycle Design Framework in Floating Spaces

Exploring Challenges and Opportunities for Sustainable Yacht Design

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Abstract
The nautical sector has experienced significant growth, driven by technological advancements, evolving customer expectations, and increasing demand for luxury experiences. However, this expansion raises concerns about its environmental impact, particularly in the design of yachts as temporary and mobile living spaces. Their impermanent nature calls for design approaches that minimize environmental impact while ensuring long-term efficiency and resource optimization. In this context, Life Cycle Design (LCD) enables to integrate sustainability throughout all stages of a product's life cycle, contributing to the advancement of current practices within the sector.
This article presents the initial outcomes of an Industrial PhD research project focused on the integration of LCD principles into yacht design. The study explores the applicability of existing LCD methods and tools, analysing their effectiveness in fostering sustainability within the development of complex products. Results suggest that while current LCD approaches show considerable potential for the nautical sector, they require significant adaptation to meet its specific structural and functional characteristics.
By identifying key gaps and challenges, this study lays the foundation for refining LCD strategies tailored to yacht design. It contributes to the development of more sustainable approaches to designing mobile living spaces at sea and advances the discourse on sustainability in complex products.

1. Introduction

The nautical sector is inherently characterized by mobility and temporariness, qualities that shape its unique identity but also pose substantial challenges in terms of environmental sustainability.

In recent years, the industry has experienced considerable growth (Deloitte, 2024a; Montigneaux et al., 2025), driven by technological progress and shifting consumer expectations. However, this expansion has also raised critical concerns regarding its environmental impact, particularly in relation to the resource-intensive nature of yacht production, operation, and end-of-life management (Jacquet et al., 2024; Sanlorenzo, 2024).

Despite some advancements, current sustainability efforts in the sector remain fragmented and predominantly focused on incremental improvements at the component level, rather than addressing the entire yacht life cycle. While these efforts represent important progress, they often fall short of fully addressing the underlying complexity of yacht design and production systems (Ceschin & Gaziulusoy, 2022). As a result, many interventions remain insufficient when measured against the scale of necessary environmental mitigation, particularly given the sector's inherent challenges related to design, manufacturing, and operational processes.

In response to these gaps, this research seeks to investigate how Life Cycle Design (LCD) principles can be more effectively integrated into yacht design.

Also referred to as Eco-Design, LCD represents a significant advancement by holistically embedding environmental considerations throughout all phases of a product's life – from initial concept through production and operational use, to ultimate disposal or recycling (Vezzoli, 2018).

It offers the potential for more strategic, system-wide interventions, enabling the industry to achieve substantial improvements in environmental performance and significantly reduce its overall ecological footprint.

To achieve this objective, the research adopts a Design-Based Research (DBR) methodology, structured around iterative cycles of design, implementation, and evaluation (Wang & Hannafin, 2005; Ceschin, 2012). Through this approach, the research aims both to advance the theoretical foundations of LCD and to develop actionable, specialized strategies that the yacht industry can implement to transition toward a more sustainable future.

The results presented in this article are related to the first phase of an Industrial PhD research project conducted in collaboration with Sanlorenzo S.p.A., a leading company in the production of luxury yachts, renowned for its commitment to innovation and craftsmanship. This phase focused on mapping the environmental impact profile of yachts across their life cycle and evaluating the applicability of existing LCD methods and tools, laying the foundation for a conceptual framework to support sustainability integration from the early design stages.

2. Sustainability in the Yachting Sector

The global yachting industry has experienced remarkable expansion in recent years. In 2022, the new-build yacht market reached an estimated value of approximately €32.4 billion, which corresponds to 11% year-on-year growth (Deloitte, 2024a; Montigneaux et al., 2025).

This expansion is accompanied by growing environmental sustainability scrutiny, mainly driven by regulatory pressures and evolving consumer expectations.

At the regulatory level, international and European policies are imposing more stringent environmental regulations. The Paris Agreement (United Nations, 2015) and the European Green Deal (2020b) set ambitious emission reduction targets, while the GHG strategy by the International Maritime Organization (IMO) and MARPOL set stricter environmental regulations for the yachting industry.
Collectively, these regulations are rapidly raising the bar for what is considered acceptable environmental performance, forcing yacht manufacturers, shipyards, and operators to innovate and adapt.

Beyond regulatory pressures, evolving consumer expectations toward sustainability are reshaping the industry. According to the Deloitte Global Gen Z and Millennial Survey (2024b), 64% of Gen Zs and 63% of millennials are willing to pay a premium for environmentally sustainable products. This reflects a broader trend in the luxury market, where sustainability is increasingly recognised as a strategic asset, enhancing brand

reputation and influencing industry standards (Ansaloni et al., 2024; Kunz et al., 2020; Li & Leonas, 2019).
As awareness grows concerning planetary boundaries and the urgency of climate change, pressure mounts on yacht builders to provide tangible evidence of environmental responsibility and stewardship.

However, despite these sustainability drivers, the industry still faces critical challenges, particularly regarding materials, emissions, and energy consumption (Deloitte, 2024a). The sector remains heavily reliant on composite materials, which pose significant end-of-life disposal challenges and contribute to a high environmental footprint (Ravasio, 2022). Similarly, fossil fuels dominate yacht propulsion solutions, as alternative technologies remain limited, with only a few fully electric yachts ordered for 2025 (Montigneaux et al., 2025). While technological advancements and regulatory frameworks are pushing the industry towards greater environmental responsibility, these measures alone are insufficient to drive a comprehensive transformation.

Achieving significant impact reductions requires a fundamental rethinking of design processes, where sustainability must be embedded as a guiding principle rather than an afterthought (Yang & Vezzoli, 2024). Indeed, the design stage is critical in determining a product's environmental impact, with over 80% of its footprint established at this phase. Once a product enters the market, opportunities to mitigate its environmental effects diminish considerably (European Commission, 2020a; Stark, 2024; Hauschild et al., 2018).

3. From Green Design to Life Cycle Design in Yachting

Design for Sustainability (DfS) has emerged as a key discipline to address this challenge, offering a structured framework that integrates environmental and social considerations at multiple levels (Ceschin & Gaziulusoy, 2022). Early efforts within DfS, such as Green Design, aimed to reduce environmental impact through targeted modifications in materials and energy use, such as minimizing resource consumption, incorporating recyclable or bio-based materials, and improving energy efficiency (Yang & Vezzoli, 2024). While Green Design represented an important step toward sustainability, it remained limited by its narrow scope, limiting the effective environmental impact reduction.

A more comprehensive approach emerged with LCD, also known as Ecodesign, Circular Design, or Design for the Environment (DfE). Unlike Green Design, LCD expanded the design scope to encompass the entire product life cycle, integrating environmental considerations from raw material extraction through production, distribution, use, and end-of-life management. By adopting a life cycle perspective, this evolution marked a shift to a more holistic design strategy (Ceschin & Gaziulusoy, 2021; Vezzoli, 2018).

Although sustainability has gained increasing attention in the nautical industry, current yacht design efforts still predominantly align with Green Design. These initiatives focus on targeted innovations, such as the selection of low-impact materials, alternative propulsion and fuels, the use of certified resources, and improvements in waste management (San-

lorenzo, 2024; Ferretti Group, 2024; Azimut Benetti Group, 2024; The Italian Sea Group, 2024).

Although these strategies may contribute to lowering environmental impact, they remain narrowly focused on the risk of creating a gap between communicated environmental benefits and actual systemic impact. This discrepancy, often referred to as greenwashing, emerges when sustainability claims focus on specific attributes while overlooking the broader environmental footprint of a product (de Freitas Netto et al., 2020).

Without considering the entire life cycle – from raw material extraction to manufacturing, use, and disposal – such interventions risk burden shifting (Hauschild et al., 2018). For instance, bio-based composites and recycled thermoplastics, though seen as sustainable alternatives, often require chemical additives to meet performance and durability standards, complicating end-of-life disposal and recyclability.
While Green Design remains a fundamental starting point, its limitations have led to the evolution of LCD. However, in the context of yacht design, the integration of LCD principles remains sporadic and largely unexplored in academic research.

This research aims to fill this gap by developing a conceptual framework that effectively integrates LCD into yacht design. By building on existing DfS and LCD principles, this study seeks to establish a systemic approach to sustainable yacht design that moves beyond incremental improvements toward a more holistic and strategic application of sustainability into the product development process.

The outcomes will support designers, manufacturers, and policymakers in adopting more effective sustainability strategies, fostering a transition toward an environmentally responsible yachting industry. To address this objective an overarching research question has been articulated: How can Life Cycle Design (LCD) principles be effectively integrated into yacht design?

This question is further elaborated through four sub-questions:

- Sub-RQ1: What is the life cycle profile of yachts and their associated environmental impacts?
- Sub-RQ2: What are the strengths, limitations, and gaps of existing Life Cycle Design methods and tools for the implementation in yacht design?
- Sub-RQ3: What design criteria are essential to guide the industry in reducing the environmental impact of yachts throughout their life cycle?
- Sub-RQ4: What methods and tools need to be developed or adapted to effectively support stakeholders in designing sustainable yachts?

4. Methodology

To address the research questions, a Design-Based Research (DBR) methodology has been adopted. DBR is structured to improve both theoretical understanding and practical application through iterative cycles of design, implementation, and evaluation (Wang & Hannafin, 2005; Ceschin, 2012). This methodology ensures that interventions are developed in

close collaboration with stakeholders, enabling continuous refinement based on empirical feedback and contextual factors. The research follows a three-stage structure:

4.1. Stage 1: Explore and Define

The initial stage of the research aims to establish a robust foundation for the subsequent phases while addressing the first two Research Sub-Questions (Sub-RQ1 and Sub-RQ2).

As an initial step, literature reviews are carried out in two key areas: (i) the Yacht Life Cycle Profile (YLCP), describing yacht characteristics in terms of development, life cycle phases, and environmental impact; and (ii) evaluation of existing LCD methods and tools for the applicability in the nautical sector. Building on these insights, a conceptual framework is developed to guide the adaptation and integration of LCD principles into yacht design.

This phase is further strengthened through empirical validation, Life Cycle Assessment (LCA) data from industry sources is analysed to validate findings from the literature, while expert interviews and a workshop contribute to a critical assessment of existing LCD methods' relevance and limitations within yacht design contexts.

4.2. Stage 2: Prototyping and Assessment

The second stage of the research, Prototyping & Assessment, builds upon the results of the previous phase for developing actionable design guidelines (Sub-RQ3) along with methodologies and tools for sustainable yacht design (Sub-RQ4). Existing LCD

guidelines, methodologies, and tools are critically prioritized and adapted to the specific characteristics of the yacht design process. Where necessary, new tools are developed to bridge identified gaps.

Two key outputs are generated: (i) the Yacht Life Cycle Design (YLCD) Guidelines, offering structured sustainability-driven design criteria tailored to the yachting sector; and (ii) the Methodology for Yacht Design Sustainability (MYDS), providing practical instruments to guide designers through the integration of LCD principles.
These outputs undergo iterative evaluation through a multi-step assessment process: expert reviews, empirical implementation within a design project, and a final evaluation by practitioners and academic experts. This ensures the theoretical soundness and practical viability of the developed frameworks.

4.3. Stage 3: Reflection

The final stage involves a critical reflection on the research findings and the methodology itself. It evaluates the effectiveness, limitations, and potential generalizability of the developed guidelines and tools. This phase consolidates the study's contributions to both theory and practice, providing a foundation for further research and broader applications of LCD principles in complex product systems beyond the yachting sector.

By structuring the research across these iterative stages, the study ensures a dynamic interplay between theory and practice, fostering the development of context-specific, actionable strategies for embedding sustainability within yacht design.

5. Structuring Life Cycle Design (LCD) in Yachting: Impacts, Methods, and Tools

The results presented in the following section stem from the first stage of the research (Explore and Define), which aimed to establish a conceptual foundation for the subsequent development and testing of sustainability-oriented guidelines, methods, and tools. This exploratory phase focused on two core tasks: analysing the Yacht Life Cycle Profile (YLCP) and evaluating the applicability of existing Life Cycle Design (LCD) methods and tools within the nautical context.

5.1. Yacht Life Cycle Profile (YLCP)

A preliminary Yacht Life Cycle Profile (YLCP) was developed to address Sub-RQ1, outlining yacht characteristics across the development process, life cycle stages, and associated environmental impacts.

- Based on existing frameworks (Sullivan et al., 2022; Vezzoli, 2018; Tumidei & Ferrari, 2009), the research distinguished two main phases related to a yacht:
  The development process, covers product plan validation, concept design, detailed design and production design (Bionda, 2020).
- The yacht life cycle, encompasses pre-production, production, use, maintenance, and disposal (Sullivan et al., 2022).

(Fig. 1) integrates yacht development and life-cycle stages, providing a reference framework for correlating environmental impacts with each phase and aligning LCD methodology and tools with yacht development.

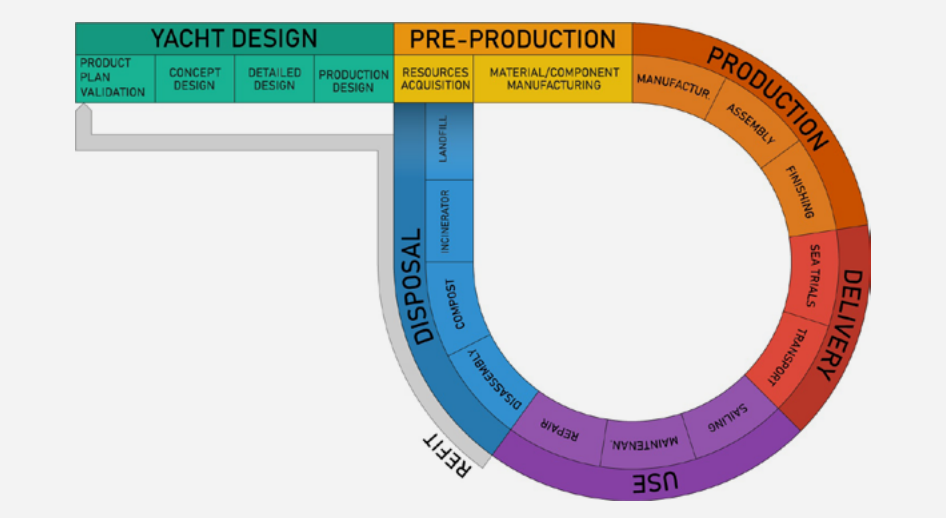

Figure 1. Integration of yacht development and life-cycle stages (Credits: Ludovico Ruggiero).

After mapping these stages environmental hotspots across the yacht's life cycle were identified, integrating insights from existing Life Cycle Assessment (LCA) studies (Favi et al., 2018; Favi et al., 2017).

In particular, the use phase accounts for over 85% of total CO2-equivalent emissions (GWP100), primarily due to fuel consumption, which correlates with engine power, operational hours, and navigation intensity, making energy efficiency and alternative propulsion key research areas (Favi et al., 2018; Favi et al., 2017). The production phase also showed significant impacts, particularly from the use of composite materials, aluminium, and steel, each associated with different environmental burdens (Favi et al., 2018). Maintenance activities and disposal further contribute to the yacht's environmental footprint, especially due to the use of antifouling paints, lubricants and the challenges linked to recycling composite materials.

5.2. Methods for LCD and Gap Analysis

Research in LCD has matured into a well-established field, offering numerous methods that support the integration of sustainability principles into the Product Development Process (PDP) (Schöggl et al., 2024). To address Sub-RQ2, a literature review was conducted to identify the most adaptable methods, validated in both academic research and design practice. Among the reviewed approaches, four emerged as particularly relevant and were compared using four criteria to assess their alignment with the research objectives, as summarized in Table 1.

METHOD	DESCRIPTION	YACHT INDUSTRIAL RELEVANCE	INTEGRATION INTO YACHT DESIGN PDP	INTEGRATION WITH LCD TOOLS	APPLICABILITY TO COMPLEX PRODUCTS
Vezzoli (2018) Method for Product Design for Sustainability (MPDS)	A structured and modular method integrating LCD into PDP. It provides strategic analysis, concept design, and engineering, while incorporating specific LCD tools	MODERATE Applied in various industries but not tested in complex product sectors	HIGH Provides structured and modular integration but needs adaptation for yacht life-cycle complexity.	HIGH Incorporates qualitative and quantitative tools for each phase of the PDP.	MODERATE Modular structure but requires adaptation for multi-stakeholder and long-life-cycle process.
Fernandes et al. (2016) Method for Integrated Product Development Oriented to Sustainability	A Three-step method supporting sustainability in early PDP stages by identifying impacted life cycle phases and providing design recommendations.	MODERATE Applied in various industries but not tested in complex product sectors	LOW Guides sustainability considerations in early PDP but lacks a structured integration process	LOW DfX tools are mentioned, but no structured integration with specific LCD tools like LCA	LOW Focuses on consumer goods; lacks explicit consideration for multi-subsystem, long-life-cycle products
Sanyé-Mengual et al. (2014) LCD method	A four-step method incorporating ecobriefing, strategy selection, and validation through prototyping	MODERATE Applied in various industries but not tested in complex product sectors	MODERATE Provides a structured LCD integration process, but lacks in detail for specific PDP phase alignment	HIGH Includes various quantitative and qualitative tools (QALCC, LCA, PCF) across PDP,	LOW Focuses on consumer goods; lacks explicit consideration for multi-subsystem, long-life-cycle products
Lewandowska & Kurczewski (2010) ISO 14062-Based LCD Process	A method derived from ISO 14062. It includes environmental planning, impact assessment, detailed design, and sustainability performance monitoring.	MODERATE Applied in various industries but not tested in complex product sectors	MODERATE Follows a structured PDP framework, but requires substantial adaptation for yacht life-cycle complexity	MODERATE Lacks a comprehensive set of tools for all PDP stages	LOW Focuses on consumer goods; lacks explicit consideration for multi-subsystem, long-life-cycle products

Table 1. Comparison of selected LCD methods for yacht design integration.

Among the methods analysed, MPDS emerged as the most aligned with the needs of yacht design due to its structured, modular framework and its integration of both qualitative and quantitative tools.

Developed by LeNS Lab at Politecnico di Milano, MPDS has been refined through European research projects and practical applications, ensuring robustness for sustainability-driven design processes. Moreover, MPDS aligns with international standards such as UNI ISO/TR 14062:2007, which provides guidelines for integrating environmental aspects into PDP. However, certain limitations remain for its implementation in yacht design. While MPDS has been applied across various industries, it has not yet been tested in Complex Product and Systems (CoPS) contexts (Hobday, 1998), raising questions about its adaptability to extended development cycles and multi-stakeholder dynamics. This structured integration into the PDP requires refinement to address specific yacht development complexities.

To explore these gaps, a dedicated six-day intensive workshop was conducted with 24 young professional yacht designers to evaluate MPDS's practical application in yacht design. Participants, divided into six groups, developed concept designs for a 50-foot charter yacht while applying the six LCD strategies described in the MPDS. The goal was to evaluate MPDS's effectiveness in integrating sustainability into the yacht concept design phase.
Results indicated that MPDS facilitated sustainability integration as a core parameter, helping designers incorporate

environmental considerations from the early stages without requiring prior expertise. Strategies, such as the use of extension and material consumption reduction, were the most implementable.

However, several limitations emerge. Since MPDS is a generic method, it requires adaptations to better align with the specific characteristics of yacht design. The high level of detail in MPDS guidelines made the simultaneous management of multiple sustainability strategies challenging, particularly in the concept design phase. Additionally, strategies related to materials and toxicity reduction demanded technical expertise beyond the typical knowledge of yacht designers, posing implementation difficulties.

5.3. Tools for Life Cycle Design

Integrating sustainability into yacht design requires structured tools to assess environmental impact and develop sustainable solutions. With the evolution of LCD, numerous tools have emerged to support sustainability in product development (Luu et al., 2022). However, the growing number of available tools often creates uncertainty among practitioners, who may struggle to select and apply the most suitable ones (Rossi et al., 2016). To address Sub-RQ2, a preliminary analysis was carried out to catalogue existing LCD tools, evaluate their applicability to yacht design, and identify key limitations.

As shown in Fig. 2, tools are classified into environmental impact evaluation tools and orientation tools for sustainable design, clarifying their role in the design process.

The analysis has currently focused on Environmental Impact Evaluation Tools, which are presented in Table 2, Table 3 and Table 4, with further work planned to cover other categories. Findings reveal key challenges for their implementation in yacht design: many quantitative tools are costly or limited in demo versions, restricting access for designers and small-scale shipbuilders. Additionally, qualitative tools tailored for yacht design remain scarce, limiting early-stage environmental assessments. Expanding such tools could enhance sustainability-driven decision-making.

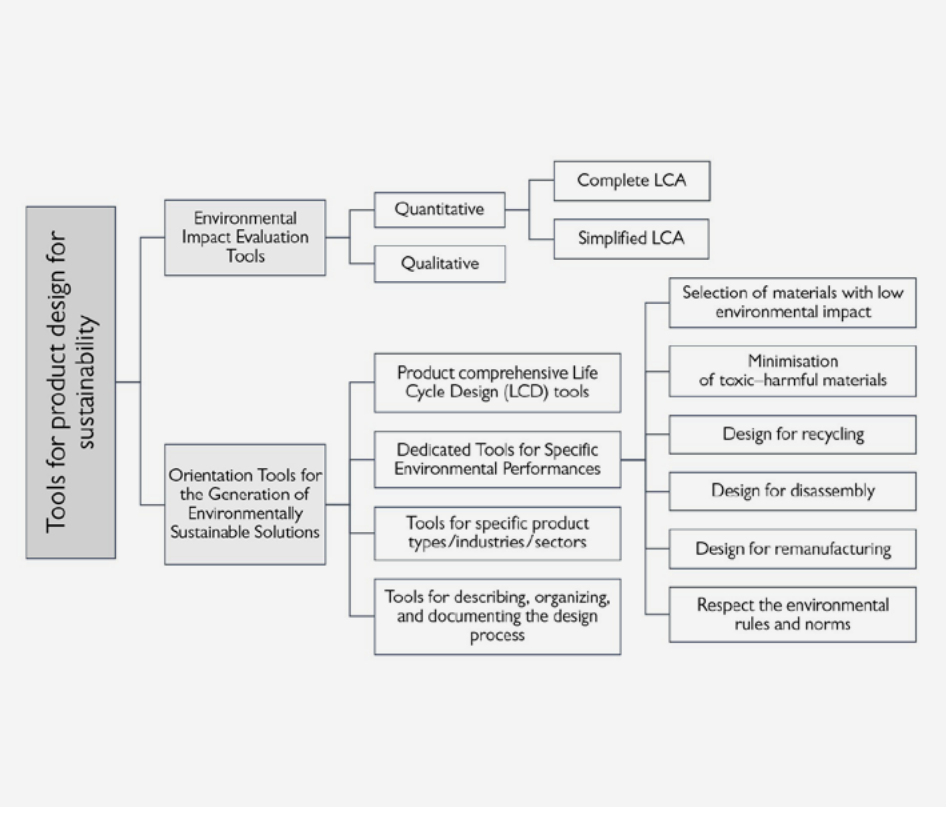

Figure 2. Map of existing LCD tools, adapted from Vezzoli (2018).

NAME	DEVELOPER	SOURCE	NOTES
EcoChain Mobius	Ecochain Technologies	ecochain.com	LCA software for business users, allowing measurement of product environmental footprints and comparison with industry standards.
GaBi	Sphera	sphera.com	Advanced LCA tool for detailed environmental assessments.
OpenLCA	GreenDelta	openlca.org	Open-source LCA software, compatible with various databases.
Umberto	iPoint-systems	ifu.com	Software for modelling material and energy flows.
Brightway2	Brightway	brightway.dev	Python library

Table 2. Environmental Impact Evaluation Tools - Quantitative - Complete LCA.

NAME	DEVELOPER	SOURCE	INDUSTRY	NOTES
OneClickLCA	One Click LCA Ltd.	oneclicklca.com	Construction	Simplified LCA tool for the construction sector
aPriori	aPriori Technologies	apriori.com	Manufacturing	Platform that helps manufacturers in the product development process.
Air.e LCA	Eco-innovazione	air-e.it	Generic	Software for creating complex life cycle models in a simple and transparent way.
Ansys Granta	Ansys Inc.	ansys.com	Generic	Software for assessing environmental impact and risks in products and design.
MarineShift360	Anthesis Group	–	Maritime	LCA platform designed to evaluate the environmental impact of recreational boats
Yacht Assessment Tool	Water Revolution Foundation	–	Nautical	Tool for life cycle analysis of superyachts.

Table 3. Environmental Impact Evaluation Tools - Quantitative - Simplified LCA.

NAME	DEVELOPER	SOURCE	NOTES
ECOFAIRE tool-kit	Ben Moussa et al.	(Ben Moussa et al., 2019)	Spreadsheet/checklist
Eco-design checklist (8 checklists)	Fraunhofer IZM, Berlin	sustainabilityguide.eu	Checklist
Checklist for LCD strategies pursuit evaluation (ICS_toolkit)	LeNS Lab Polimi	lenslab.polimi.it	Checklist
Checklist for LCD strategies pursuit evaluation (ICSxfurniture)	LeNS Lab Polimi	lenslab.polimi.it	Checklist
Checklist for LCD strategies pursuit evaluation (ICSxclothing)	LeNS Lab Polimi	lenslab.polimi.it	Checklist

Table 4. Environmental Impact Evaluation Tools - Qualitative.

6. Conclusion and Future Developments

This study addresses the pressing need for systemic sustainability integration within yacht design by proposing the foundations for a Life Cycle Design (LCD) framework specifically tailored to the nautical sector. The initial research phase has revealed the significant environmental impacts associated with yacht production, use, and disposal, underscoring the urgency of moving beyond fragmented, incremental improvements toward more comprehensive, life cycle-oriented approaches.

The preliminary framework developed through the Explore and Define stage provides a structured foundation for this transition. By critically analysing existing Life Cycle Design methods and tools, and by empirically testing their applicability within the context of yacht design, the research highlights both the potential and the current limitations of sustainability practices in the industry. The findings emphasize the importance of embedding environmental considerations from the earliest stages of design, while also recognizing the necessity of developing sector-specific tools that are accessible to designers and adaptable to the complexity of yacht projects.

The next phase of the research will focus on refining the proposed framework into operational guidelines and practical tools that can effectively support sustainable yacht development. This will involve iterative prototyping and assessment, engaging industry stakeholders and academic experts to ensure both theoretical robustness and practical viability. Furthermore, future work will explore methods to facilitate the broader adoption of LCD principles across the yachting

sector, promoting a shift in design culture that embraces environmental responsibility as a core value rather than a secondary consideration.

By advancing a structured, lifecycle-based approach to sustainable yacht design, this research contributes to bridging the existing gap between sustainability theory and practice. It aims to provide tangible instruments for designers, manufacturers, and policymakers committed to transforming the yachting industry into a sector capable of meeting the environmental challenges of the twenty-first century.

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IV

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PhD in Architecture and Design (Naval and Nautical Design curriculum) from the University of Genoa, with a research thesis entitled Interior Yacht Design, 100 years for 100 interiors. In 2016, she was a courtesy instructor at Florida International University of Miami (USA) and, in 2020, a visiting professor at Beijing University of Chemical Technology (China). She is currently an adjunct professor at the University of Genoa, where she teaches Interiors 1.2 for the Master's Degree in Design Navale e Nautico and Interior Design for the Master's Degree in Yacht Design.
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Architect (2001), with a Master in Intervention Methodologies in Architectural Heritage (2006) and PhD in Minimum Housing (2013) from Faculty of Architecture of the University of Porto (FAUP). Master in Product Designer (2017) and in Visual Arts (2021) by the School of Fine Arts and Design (ESAD.CR) of the Polytechnic of Leiria. Researcher on the "Forest-4future" project at the Polytechnic Institute of Leiria - Design and Arts Research Laboratory (2021-2023). Invited Adjunct Professor, at ESAD.CR of the Polytechnic Institute of Leiria (since 2021).
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She has coordinated numerous national and international research projects focused on product and service innovation, as well as emergency design. She is the author of several publications and academic papers exploring design culture, with particular attention to the communicative aspects of product, fashion, and living design. She also serves as the artistic director of the Lab Museum of Design, where she curates educational exhibitions on various design-related topics.
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Since 2016, she has been involved in several European and national research projects (Horizon 2020, Interreg, Fondazione Cariplo) and collaborated with companies in the furniture, home appliances, telecommunications, and non-profit

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Her research and teaching activities also include Design for Kids within the Master's program in Design for Kids and Toys at the Politecnico of Milan, and Jewelry Design in the Master's program in History, Design, and Marketing of Jewelry at the University of Siena. She is the author of numerous publications, including articles, book chapters, and conference proceedings at both national and international levels.
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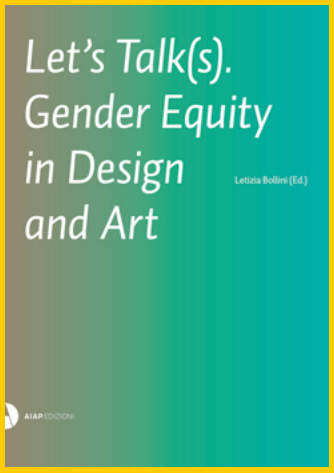

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