Designing yachts in the digital era

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DESIGN INTERNATIONAL

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Preface

Designing Yachts in the Digital Era results from ten years of research on the role of computational technologies and the new manufacturing models in transforming the yacht design sector. Furthermore, over the past three years, the research has evolved and deepened within the framework of the PNRR MICS (Made in Italy, through the NEMO and CYClaDES projects. The choice of focusing on this research topic does not derive from a recognised field of study but rather from an intuition about the need to foresight the role of the new digital technologies in the transformation of the sector to understand and guide the undergoing digital transformation.

The book emerges from the observation that yacht design, while a mature and multifaceted discipline with deep historical roots, remains detached from the wider digital transformation currently reshaping design, production, and industry at large. In the current design landscape, the spread of artificial intelligence, advanced robotics, connected products, immersive simulation, and data-driven design has already begun to reconfigure not only tools and processes, but also the very role of design within society. Industry has increasingly moved from the production of isolated artefacts to the delivery of services, experiences, and adaptive systems. Manufacturing has become entangled with people's lives, continuously drawing upon patterns of behaviour and data streams to redefine its own outputs. Within this context, the continued reliance of the yacht design sector on incremental, engineering-centred practices risks leaving it at the margins of a paradigmatic change that demands fresh theoretical frameworks, new practices, and different professional roles.

Responding to this critical gap, the research underpinning this volume draws upon the field of Advanced Design and is guided by a dual methodological orientation: both research for design, which seeks to support practice by providing knowledge and tools, and research through design, which treats design practice itself as a generator of knowledge. Central to the investigation is the use of Strategic Foresight, a framework well suited to fragmented and complex contexts. Over the course of a decade, this approach was operationalised through phases of framing, scanning, forecasting, visioning, planning, and acting, each of which is reflected in the organisation of the book. Historical analysis, empirical surveys, cluster mapping, field observations, and co-design workshops with key industry actors form the backbone of the inquiry, ensuring a balance between theoretical depth and practical engagement.

The study demonstrates that the integration of digital technologies into yacht design is still immature and not yet fully exploited. Real-time data, connected systems, and generative algorithms are rarely used to inform early design decisions, not employ them to close the gap between performance simulation and lived experience. At the same time, a younger generation of yacht users is reshaping expectations, favouring flexible layouts, immersive connections between interior and exterior spaces, sustainable materials, and digitally enhanced on-board environments. These shifts place pressure on shipyards, designers, and suppliers to move beyond traditional workflows and to embrace digital infrastructures capable of supporting customisation, responsiveness, and sustainability.

The findings of this book point towards a necessary reorientation of yacht design as a discipline. Rather than persisting in an iterative, trial-and-error approach to incremental innovation, yacht design must adopt a systemic and anticipatory stance. This entails recognising the yacht not simply as a static object but as a hybrid, adaptive, and intelligent system that interacts dynamically with its environment, its users, and its digital shadow. Such a repositioning requires designers to act as strategic mediators between technological possibilities, cultural practices, and environmental imperatives.

By presenting both the critical analysis and the prospective frameworks required to interpret this transformation, Designing Yachts in the Digital Era offers a comprehensive foundation for rethinking the discipline of yacht design in the digital era. It invites scholars, practitioners, and industry leaders to consider design not merely as the shaping of forms or the engineering of performance, but as a strategic intelligence able to anticipate futures, orchestrate complex systems, and guide the sector through its most profound transformation since its emergence as a modern discipline.

Introduction

The ongoing digital transformation has its roots in the industrial revolutions of the 18th century. These subsequent industrial revolutions have shaped the modern world, transforming not only the manufacturing landscape but also society, resource opportunities, and human relations with nature and artefacts.

At the end of the 18th century, the first industrial revolution began by introducing mechanical manufacturing based on water and steam. This marked a shift from agrarian economies to mechanised factory systems. The development of steam engines, mechanised looms, and early ironworks laid the foundation for urban industrialisation, marking one of the major turning points in world history as impacting all aspects of daily life worldwide, from economy to transportation, from health and medicine to urban assets (Lucas, 2009)

The second industrial revolution traced back to the start of the 20th century, was characterised by the introduction of new production organisations and four main technological advances. First, there was the use of a new energy source, i.e., electricity, and the implementation of the internal combustion engine. Then, the applied research on chemicals, including petroleum and natural gas, led to the plastic and pharmaceutical industry and, finally, the advancement in the information and communication industry with the telephone, radio, and cinema (Gordon, 2000). In these years, the concept of mass-assembly production was directly connected with modernity.

The third industrial revolution started at the beginning of the 70s with the introduction of Information and Communications Technology (ICT), which enabled a higher level of production automatisation. It is the era of computers and electronics driving automated processes and robotics in industry. The proliferation of computers, programmable logic controllers, and early robotics enabled higher automation and precision in manufacturing. Industries shifted from analogue to digital, laying the groundwork for globalised production networks and just-in-time manufacturing. All three Industrial Revolutions were associated with intense waves of productivity and the company's competitive advantages (Bergeaud *et al*., 2016), driving economic growth at the macro level vision.

The fourth one represents the present time of our industry. Since 2011, when it was first conceptualised, Industry 4.0 has been at the centre of increasing attention from organisations, governments, and the scientific community. The fourth industrial revolution is triggered by the Internet, which allows the convergence of cyber-physical systems, cloud computing, and big data within the manufacturing environment (Brettel *et al*., 2014). Industry 4.0, therefore, is not based on a single technology but a system in which interrelated innovations interact. These include robots, IoT, smart materials, additive manufacturing, artificial intelligence, and predictive analytics. It represents the real capability of breaking the boundaries between the digital and physical worlds both in manufacturing and in daily life. As described by Herman, Pentek, and Otto (2015), the early fascination for Industry 4.0 was twofold. First, for the first time, an industrial revolution was predicted a-priori, not observed ex-post, providing opportunities for researchers and companies to shape the future actively.

The same visioning approach for forecasting the Industry 4.0 journey is now implied for the next fifth industrial revolution. Only ten years after the introduction of the 4.0 concept, the expression Industry 5.0 has emerged in literature, blogs, institutional channels and innovation programs as a new vision that bridges digital technology with a human-centred and sustainable approach. Developing studies on I5.0 identify it not only as an industrial revolution but also as a techno-political phenomenon (Xu *et al*., 2021). However, literature reviews reveal that Industry 5.0 is associated with broader and different concepts (Ghobakhloo *et al*., 2023; Raja Santhi & Muthuswamy, 2023; Piccarozzi *et al*., 2024), highlighting a forecasting approach to the next steps of industrialisation and a need for a new sustainable approach to manufacturing, rather than describing a current industrial phenomenon.

While institutional programs are working on the roadmap for 5.0, speculative approaches to 6.0 and 7.0 have emerged. Even if few researches are present in the literature, the world digitalisation roadmap is settled. Potential evolving scenarios for 2050 and beyond include a paradigm shift in production and consumption models, characterised by a full-embedded digital ecosystem: adoption of clean energy sources and mechanisms, advanced autonomous production systems under robotics and Artificial Intelligence (AI), environmentally friendly products designed for easy recycling, and the implementation of cost-effective mass transportation systems (Ruiz Estrada, 2024).

In the field of design, artificial intelligence, digital technologies, the Internet of Things (IoT), and intelligent products are profoundly transforming not only the representation of a design project but also the formal references, the input data, the communication strategy, and the design process itself. In the contemporary panorama, a designer must face design requirements strongly influenced by an advanced technological system characterised by connected, computational, and open-sourced digital manufacturing (Giaccardi, 2015). Industry passes from being a producer of objects to a producer of services. Manufacturing mixes with people's lives quickly and continuously draws from them useful indications to redefine the production itself (Frison, 2016). However, the discussion on digital technologies impacting yacht design discipline is still immature: the discipline seems to be absent and, therefore, exempt from considering this transition as a paradigmatic change of one's role and purpose.

At the heart of the current transformation in design lies a shift in how products are conceived: not only as physical artefacts but as hybrid, data-driven, and service-oriented systems. In this domain, the design of traditional products into digitally embedded, adaptive systems represents a disruptive form of innovation (Lyytinen *et al.*, 2016; Raff *et al.*, 2020). This transformation echoes what Yoo *et al.* (2010) describe as digital artefacts exhibiting qualities such as component consubstantiality (intelligent artefact serving as a standalone product), product agnosticism (intelligent artefact conceived as a component), and contingently obligatory relations (artefacts with no predefined smart functions but contingent on the product-system combination). These characteristics allow artefacts to serve as standalone products and components in diverse configurations, like Google Maps integrated into a car or Amazon Alexa embedded across home appliances. In this context, yacht design stands at the edge of a critical redefinition, where the boundaries between object, system, and service begin to dissolve. Despite the presence of smart systems onboard, the yacht design process continues to rely on traditional workflows, limiting the integration of these digital capabilities.

The unexplored potential of IoT and real-time data in yacht design further highlights the gap between yachting and other industries. Connected sensors and devices offer an unprecedented possibility of making use of real-time data and user behaviour, environmental conditions, and system performance during the design phase. However, in practice, these data are rarely integrated into early-stage design. Even if America's Cup regatta campaigns demonstrate progresses in real-time data management for design insights, designers still based on traditional sources like market insights, expert knowledge, or simulated performance, without having full access to real data streams that could enable user-informed design decisions.

At the same time, shifts in user expectations are amplifying the importance of experiential and sensory qualities. Clients increasingly seek immersive environments that blur the boundaries between interior architecture and exterior seascape (Carmosino *et al.*, 2021). Advances in smart materials, transparent structures, and responsive systems offer new tools to achieve these aims.

To manage this increasing complexity, a systemic perspective is essential. The traditional linearity of yacht design no longer suffices. Nowadays, maritime design processes are still dominated by incremental engineering refinements with a trial-and-error approach: naval architects typically start with a parent hull form and apply incremental, experience-based adjustments until satisfactory performance is reached. While effective, this process is resource-intensive, iterative, and resistant to disruption. In contrast, as introduced by Oxman (2006), Digital Design Thinking is non-typological and non-deterministic digitally mediated design in supporting the discrete and differentiated process over the generic and the typological. In this context, generative design – the computational method that leverages algorithms to produce and evaluate design alternatives automatically – has shown promise in enabling designers to navigate expansive solution spaces quickly and efficiently (Krish, 2011). Despite its potential, the implementation in the yachting sector remains minimal, primarily confined to hull optimisation (Khan *et al*., 2023).

In response to the contemporary digital challenges, the design discipline is being called to reposition itself as a form of strategic intelligence: one that can mediate between people, artefacts, and digital infrastructures. Giaccardi *et al.* (2022) argue that the role of design today must expand beyond form and function to embrace the crafting of agency: how both humans and artificial agents engage meaningfully in co-constructing knowledge, experiences, and futures. This is particularly crucial in the context of complex systems, such as yachting, where designers draw on knowledge from engineering, architecture, and social science to respond to latent user needs.

In this light, the need for a new perspective on yacht design becomes evident. Digital technologies offer more than improved productivity: they open-up a new framework where data, systems thinking, and strategic foresight play central roles. The challenge, then, is not only to adopt these technologies but to embed them within a new design process: one that can interpret complexity, enabling adaptation, and anticipating change.

It is precisely within this context that this book positions itself. In this evolving panorama, it foresees the role of digital technologies and new manufacturing models in transforming the yacht design sector with a strategic thinking mindset, aiming to explore alternative futures.

Research methodology and structure of the book

Designing Yachts in the Digital Era presents the outcomes of a multi-year research project examining the transformative role of computational technologies and advanced manufacturing paradigms in the yachting sector. The choice of focusing on this research topic does not derive from a recognised field of study but rather from an intuition about the need to foresee the role of new digital technologies in the sector's transformation to understand and guide the undergoing digital transformation.

This research was situated within the disciplinary framework of Advanced Design and followed a dual methodological orientation, combining both Research for Design and Research through Design approaches, as conceptualised by Jonas (2007). A practice-centred orientation guided the study activities (Saikaly, 2003), in which the design process is not only an object of analysis but also a means of generating knowledge. This orientation allowed for a continuous interplay between theoretical insight and practical experimentation, with co-design practice serving as both a reflective and generative tool. To navigate the complexity and rapid evolution characterising the yacht design domain, the research employed the Strategic Foresight framework by Hines and Bishop (2006), a methodology particularly suited for disciplines dealing with volatile, uncertain, complex, and ambiguous contexts. Within this framework, the study adopted the six-phase structure of foresight activities: Framing, Scanning, Forecasting, Visioning, Planning, and Acting. Each phase was enacted with a specific mindset, aligning expert-driven approaches with participatory methods. The initial phases, Framing and Scanning, were conducted primarily through expert consultation and analysis; in contrast, the subsequent phases embraced participatory modes of engagement, involving stakeholders in envisioning alternative futures and co-developing strategic pathways.

These six phases were not confined to the research process alone but were also explicitly reflected in the organisation of this book, thus offering the reader a narrative arc that mirrored the progression of the inquiry.

Framing defined the scope of the research and mapped the system of actors, technologies, and policies influencing the digital transformation of yacht design. This phase resulted in a dynamic system map used throughout the study to refine inquiry boundaries. Book chapters 1, 2, and 3 contextualise the research within the evolution of industrial eras, examine the disciplinary characteristics of yacht design, and present the socio-economic and behavioural dynamics affecting the industry, respectively.

Scanning gathered empirical data on adopting Industry 4.0 and 5.0 principles within the yacht sector. This phase employed mixed methods, including a quantitative industrial survey, cluster analysis, unstructured field observations, key informant interviews, and case studies analysis. These activities generated the Yachting digital forecasting framework, which integrates 4.0 design principles, enabling technologies, and sector-specific challenges. Chapter 4 explores the principles of Industry 4.0 and 5.0, while Chapter 5 discusses their application in yacht design and production best practices.

Forecasting involved stakeholders from within and adjacent to the yacht design ecosystem in Future Technology Workshops. Participants included yacht designers, shipyard managers, association representatives, and digital innovation experts. The workshops facilitated the generation of multiple scenario models addressing the integration of digital tools in yacht design and production. This phase is fully described in Chapter 6, where a consolidation of all the insights from the industry is presented, highlighting the drivers of digitalisation in yacht design practices.

Visioning and Planning translated scenarios into specific context-of-use models and roadmaps. This phase critically assessed the readiness and challenges of implementing advanced technologies, identifying gaps between current practices and projected futures. Chapter 7 details the strategic roadmaps and computational approaches for digitally enabled yacht design. Each roadmap is here analysed across four design domains: data input, process, tools, and communication media.

Finally, Acting provides a critical synthesis of the findings, contextualising the research within broader academic activity now ongoing in Politecnico di Milano. Specifically, emerging approaches in designing for yacht sustainability and flexible customisation are introduced, and new roles and skills in the design process are discussed.

PART 1

Framing

1. The Yacht Design Discipline

1.1 Origins and development of yacht design as discipline

Architect Carlo Sciarrelli jokingly says that people who go to sea mainly fall into two categories: those who studied English in high school and those who studied French (Sciarrelli, 2001). Through this paradox, he points to tradition's importance, a cultural foundation that serves as a matrix for much of the nautical world. This underlying culture represents a shared body of knowledge that one must refer to when evaluating the complex interrelation between a yacht's technical, formal, and functional aspects (Felci, 1990). Therefore, yacht design development is inseparable from the evolution of the culture and maritime terminology, which reflects the cultural, functional, and technological underpinnings of seafaring traditions (Herreshoff, 1891). The term *vessel* originates from the Old French vessel, meaning a container, and has since become a general term for any floating structure used to carry people or goods. The word *boat*, derived from Old English bat, referred to a hollowed-out tree trunk – an early form of watercraft. Today, *boat* typically designates small waterborne vehicles for transit or leisure. By contrast, *ship*, from Old English scip, once synonymous with *boat*, now refers to larger, often commercial or military craft designed for oceanic travel. Most pertinent to this discussion is the word *yacht*, derived from the Dutch jacht, meaning *hunt* or *to chase*. Its original naval usage referred to a swift, maneuverable vessel employed to pursue enemies or pirates. Over time, *yacht* came to signify fast, elegant sailing craft used privately for pleasure, competition, or display, often reflecting luxury and innovation (Oxford English Dictionary, 2024).

While the origins of watercraft design can be traced back to antiquity, the formal discipline of yacht design emerged distinctly in the early modern period, shaped by shifting socio-economic contexts, technological advancements, and the evolving relationship between humans and the sea (de Winter & Burningham, 2001). In the 17th century, the Dutch Republic played a pivotal role in the genesis of recreational sailing. Wealthy merchants and naval officers began commissioning yachts as status symbols and diplomatic gifts, marking the earliest convergence of functionality and luxury in watercraft design (Killing & Hunter, 1998). England soon followed, particularly after King Charles II was presented with a Dutch yacht in 1660. This moment catalysed the adoption of yachting among the British aristocracy and planted the cultural seed for organised sailing as a pursuit.

By the mid-19th century, yacht design in Britain began to intersect more deliberately with performance. The cutter emerged as a dominant design typology characterised by a single mast set further aft, a long bowsprit, and a fore-and-aft sail plan optimised for windward ability. Cutters were admired for their speed, manoeuvrability, and seaworthiness, becoming the favoured choice for early regattas (Larsson *et al.*, 1994). The cultural fervour around competitive sailing culminated in the now-historic 1851 race around the Isle of Wight, in which the American yacht America defeated the British fleet to win what would become the first America's Cup: a milestone that formalised yachting as an international sport and catalysed a demand for technical innovation in design till today.

The transition from purely functional maritime vessels to recreational yachts marks the inception of yacht design as a specialised discipline. Even if till the late 19th century, yacht building remained largely artisanal, rooted in shipwright tradition, the pressures of competition and the prestige attached to performance spurred experimentation with hull forms, rigs, and materials.

Yachting reached new heights in the 20th century, driven by the common use of internal combustion engines, technological advancements, and the rise of industrial wealth. Two superyacht masterpieces mark the history: Morgan's *Corsair*, launched in 1930, and Onassis's *Christina O*, launched in 1943. Both set new benchmarks for luxury, including amenities like swimming pools, libraries, and cinemas.

The transition from traditional sailing yachts to motorized vessels revolutionized the industry, as yacht designers began integrating more and more powerful engines. The mid-20th century also marked a democratization of yachting culture. No longer the exclusive domain of the aristocracy, yachting attracted a broader cohort of wealth-being individuals.

By the mid 20th century, yacht design began to coalesce into a formalised, interdisciplinary field. Academic institutions introduced naval architecture curricula emphasising small craft and sailing performance. Simultaneously, new materials combined with emerging computational tools to expand the possibilities of yacht form and function (Larsson *et al*., 2022). As a result, yacht design today stands as a mature and multifaceted discipline situated at the intersection of naval architecture, design, ergonomics, and system engineering, where cultural tradition and formal shapes continually evolve to meet the changing demands of innovation, sustainability, and owner/brand identity.

1.2 The role of design, engineering and architecture

As far as the genesis of the project is concerned, however, it can be said that the greater complexity derives from the fact that the pleasure craft embodies both the internal symbolic and functional values of the house, of the refuge (stability, strength, safety, privacy), and the external ones of the vehicle (lightness, dynamicity,

> **maneuverability). […] the external shell takes upon itself the arduous task of carrying out the role of a boundary, limit, edge, real and symbolic, between an internal, finite, static, and domestic world, and the sense of infinity conveyed by the external marine context, which is variable, unstable, wild, and indomitable. […] Therefore, for the designer it is a matter of dealing with an articulated system of historically represented morphological and spatial relations, in which the multiplicity of human activities, the spatial areas, and the equipment present on the craft, which, if, on the one hand, continues even today to relate to a strong tradition of nautical practice, on the other hand, is called on to deal with the evolution of roles and tasks on board, which tend to follow morphological, functional, and technological modifications in positions and equipment. (Di Bucchianico & Vallicelli, 2011).**

Yacht design is a cross-disciplinary sector dealing with the panning of pleasure boats involving knowledge of the scientific fields of engineering, design, and architecture with their specialized disciplinary articulations. Each of these domains contributes specific methodologies and epistemologies, forming a complex and collaborative practice. At its core, the discipline is concerned with the conception and development of pleasure boats, a category that encompasses both sailing and motor yachts, and which requires the integration of performance criteria, spatial quality, structural integrity, and aesthetic coherence. This convergence of expertise demands fluency not only in technical disciplines such as mechanics, hydrostatics, hydrodynamics, and material science, but also in ergonomics, interior and exterior design, and the architectural articulation of space.

The interrelationship among architecture, design, and engineering within yacht design is far from hierarchical; rather, it is a dynamic and iterative exchange. Yacht design is, therefore, not reducible to a singular method or process. Instead, it operates as a systems-oriented design practice, where knowledge from multiple domains is synthesized and re-evaluated continuously. Similar to product design, there are no singularly optimal solutions in yacht design; rather, compromises are negotiated among competing demands of performance, comfort, cost, safety, aesthetics, and manufacturability. As such, the process requires continuous trial-and-error exploration, where intuition, precedent, and experiential knowledge complement quantitative modelling and simulation. As Larsson *et al.* (1994) observe, a yacht design project has to satisfy market or owner requirements and deal with a compromise between many factors with no explicit values. The ultimate results cannot be explained entirely rationally.

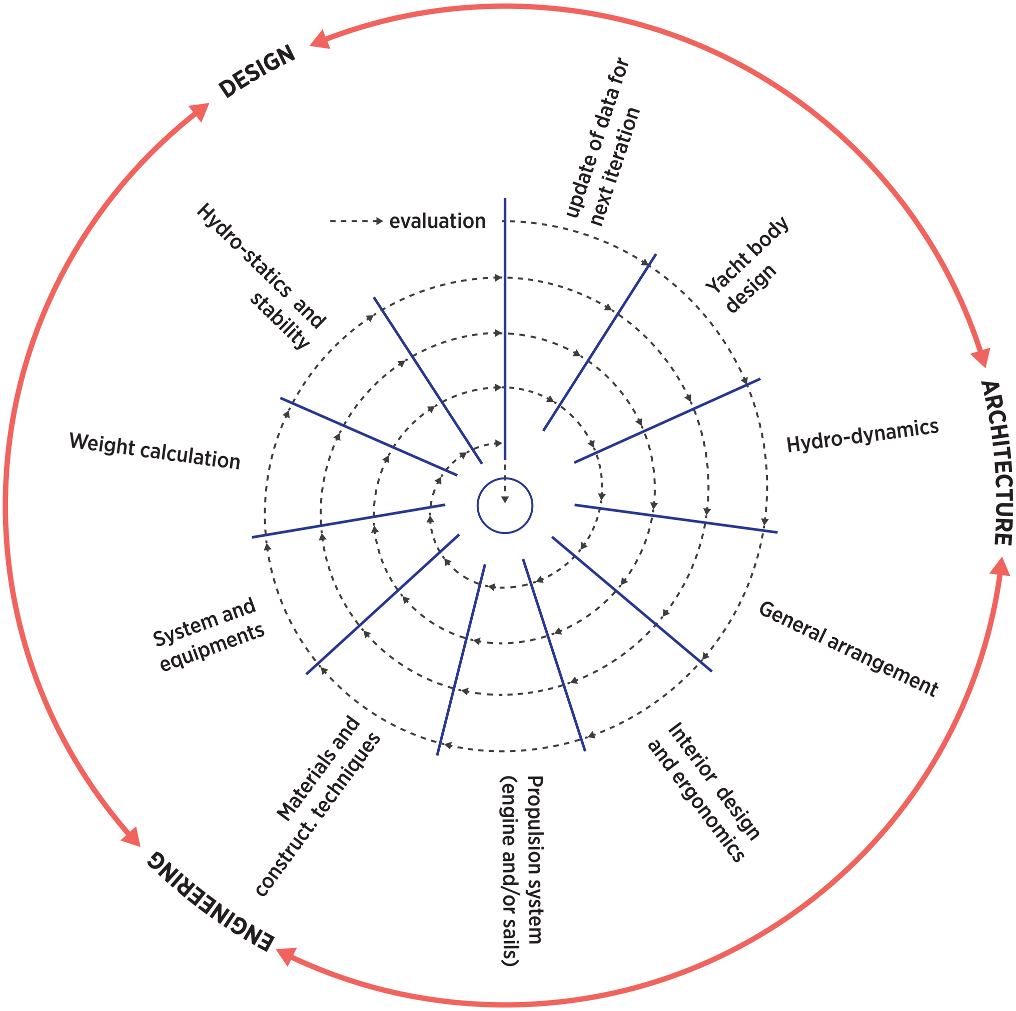
> **The knowledge and experience needed by a designer in the initial times of yacht design are often considered an art. […] A vessel must be light enough to be driven easily by a moderate breeze, stiff enough to stand up to her canvas in hard wind, shallow enough to be and to run with speed. She must have depth enough to hold her up to windward, breadth enough to give her stability; she should be long enough to reach well, and short enough to turn well, with plenty of freeboard to keep the sea off her decks. She must be broad, narrow, long, short, deep, shallow, tender, stiff.It is not strange that designers pass sleepless nights, and that anything like finally and perfection of type is impossible to conceive." (van Harpen, 1998).**

Despite the central role of the design discipline in a yacht design project, in the literature, this field of study is generally explored with an engineering approach. The large quantity of scientific articles is focused on naval architecture (the study of resistance to the movement of the hull), aerodynamics (efficiency of the appendages and sails), structural engineering, construction, and material technology.

The yacht design process is described overall as an iterative trial-and-error process aiming to satisfy predefined requirements. The sequence of operation is represented as a spiral involving incremental optimization from the yacht's requested capability to the final design evaluation. As described by Larsson *et al.* (2022), the input data in the design process are engineering knowledge, customer demand, and data from previous yacht projects. Then, the author depicted at least ten sectors of refinement: (1) yacht body design, (2) hydro-dynamics, (3) general arrangement, (4) interior design and ergonomics, (5) propulsion systems including engines and/or sails, (6) material and construction techniques, (7) system and equipment, (8) weight calculation, (9) hydrostatic and stability, (10) general design evaluation. Not all the operations need to be carried out in each turn, and the drawing, modelling, and calculation tools used in each step may vary from step to step.

The traditional yacht design process, schematised in figure 1, results in a slow process of incremental innovation from the design concept to design engineering. While computational tools and parametric modelling have introduced new degrees of freedom in recent years, the overall structure of the design process, rooted in iterative refinement and cross-disciplinary negotiation, remains intact.

Figure 1.
Yacht design spiral. interpretation of the yacht design spiral retrieved in Larsson *et al* (2022).



1.3 Performance, Technologies, and lightweight materials as historical drivers

The history of yacht design cannot be separated from the pursuit of performance. Since its first steps, the discipline has evolved through a continuous tension between tradition and innovation, in which speed, manoeuvrability, and structural efficiency have acted as principal motivators of technological change (Trivellin, 2017). In this context, the continuous improvement of lightweight structures has represented a challenge, not only for yachts but also for maritime vessels more broadly. While aesthetic and symbolic dimensions remain integral to yacht conception, performance parameters – especially in competitive sailing – have often driven form, materials, and technology breakthroughs.

The influence of performance as a historical driver becomes especially evident in the context of racing (Robin *et al.*, 2025). Since the 19th century, regattas have served as laboratories for innovation, where the desire to gain a competitive edge encouraged experimentation with hull geometry, appendages, and sail configurations. The America's Cup has long served as a technological frontier in yachting, while UIM motorboat racing has similarly driven advances in hull design, composites, foiling, and electric propulsion, reshaping contemporary design practices.This iterative feedback between competition and design has, over time, led to a systematic refinement of hydrodynamic and aerodynamic performance through computational tools, model testing, and full-scale sea trials.

One of the most transformative developments in yachting has been the introduction of lightweight composite materials. Yacht construction, once limited by traditional wooden craftsmanship, was revolutionized in the 20th century by the introduction of aluminium, fibre-reinforced plastics (FRP), and later advanced composites such as carbon fibre.The first large vessel built in FRP, and more specifically glass reinforced plastic (GRP) was the 46-metre minehunter launched in 1972. For more than a decade she was reputed to be the largest GRP ship in the world and its design and construction represented a milestone in the history of ship-building and the technology of composite materials (Baley *et al.*, 2024).

In the evolution of yachting, the extensive use of FRP is strictly connected with the advancement of production technologies not only in this industry but also in other compartments like terrestrial transportation, furniture design, and aerospace (Felci, 1990). From hand lay-up to vacuum infusion, pre-preg curing, and autoclave technologies, the advancement in production processes and tools enabled high-precision construction, reducing variabilities that previously limited performance predictability (Larsson *et al*., 2022). While originally developed for elite racing contexts and small boats, these material innovations have gradually diffused into the production of cruising and semi-custom large yachts, demonstrating a clear pathway from experimental application to broader market adoption.

Technological advances have extended beyond materials to reach design and engineering tools for performance simulation. Today, computational fluid dynamics (CFD), finite element analysis (FEA), and velocity prediction programs (VPP) are vastly adopted in the design process, allowing for high-fidelity modelling of forces acting on the hull and rig. These tools support performance optimization during the early design stages, enabling designers to simulate multiple scenarios and adjust forms with greater precision. Nowadays, the integration of data acquisition systems on racing yachts could also provide real-time feedback, creating a feedback loop that refines design parameters based on observed behaviour under real conditions.

Yet, the pursuit of performance is not without compromise. The widespread use of carbon composites raises issues of recyclability and lifecycle impact, prompting recent research into bio-based, recyclable, and hybrid materials that balance performance with sustainability.(Castegnaro *et al*., 2017).

A continuous balancing between speed and comfort, performance and safety, innovation and tradition thus shapes the historical trajectory of yacht design. Technologies and materials have served as enablers of new design possibilities, both formal and structural. In this context, innovation in performance is seen as an abstract value but as continuous research in the correlation between hull forms, deck ergonomics, appendage shapes, spatial configuration, production processes, and materials.

2. The contemporary Yachting industry

2.1 The Global yacht market

Yachting represents the pleasure sector of the maritime industry, evolving from its early roots of leisure sailing to a complex global market. Despite its longevity, comprehensive data on the sector remains relatively scarce, which presents challenges for academic study. Industry experts have estimated that approximately ten million yachting holidays are taken every year, and the industry has been exhibiting significant growth over the last two decades. However, the impact of this sector on the global tourism economies is often understated (Ajagunna & Casanova, 2022).

In recent decades, the yacht market has demonstrated considerable resilience and dynamism, particularly following the recovery from the economic downturn initiated by the 2010 financial crisis and, later, the pandemic. Since 2016, the market has experienced a robust evolution, driven by macroeconomic factors such as increased disposable income, the expansion of the global luxury market, and an intensifying consumer preference for ultimate leisure experiences (Deloitte, 2024).

In 2023, the global yacht market size was estimated at USD 9.39 billion and is projected to grow at a compound annual growth rate (CAGR) of 5.1% from 2024 to 2030 (Grand View Research, 2024).

North America and Europe continue to dominate, accounting for approximately 70% of the global yacht market while emerging regions such as Asia-Pacific and the Middle East are steadily gaining traction.

In the Western traditional markets, mature infrastructures, such as well-established marinas, shipyards, and support services, sustain a steady demand for both new builds and refit projects. The Mediterranean basin, particularly Italy and south France, remains a key hotspot, driven by historical prestige, favourable cruising grounds, and dense concentrations of service providers (Confindustria Nautica, 2025). Similarly, the United States, especially Florida and the Northeastern seaboard, maintains its leadership through a strong domestic client base and a thriving charter market (Grand View Research, 2024).

However, growth patterns in emerging markets suggest a gradual shift in the global balance of the industry. Asia-Pacific, led by countries such as China, Singapore, Thailand, and Australia, is experiencing rising demand fuelled by the expansion of high-net-worth populations and increasing familiarity with yachting as a lifestyle. Despite infrastructural limitations in some areas, investment in marinas, yacht clubs, and regional boat shows has accelerated, reflecting strategic efforts to position the region as a future hub for both leisure and commercial yachting (Deloitte, 2024).

The Middle East represents another crucial growth frontier. Nations such as the United Arab Emirates and Saudi Arabia invest heavily in maritime infrastructure and luxury coastal developments, aligning yachting with broader economic diversification strategies (Forbes, 2024). Major projects such as Dubai Harbour and the Red Sea Project exemplify how state-driven initiatives create new opportunities for yacht ownership, chartering, and brokerage within the region. At the same time, Latin America and Africa, though at earlier stages of market development, present niche opportunities, particularly in chartering and eco-tourism segments. Countries such as Mexico, Costa Rica, and South Africa are beginning to leverage their rich coastlines and biodiversity to attract a more adventurous and environmentally conscious yachting clientele (Ajagunna & Casanova, 2022).

Understanding the yacht market requires examining the broader yachting ecosystem, an intricate network of industries and services that support, enable, and sustain yacht ownership and operation. Beyond the vessels themselves, the ecosystem includes marinas and ports, specialized shipyards, crew recruitment and training institutions, maintenance and refit providers, luxury service providers, and technology firms offering navigation, security, and sustainability solutions. Marinas are not only essential docking facilities but also serve as key nodes for tourism, luxury hospitality, and high-end retail, fostering value chains that connect local economies to the wider movements of the global yacht market. Similarly, crew-related services – ranging from recruitment and professional training to crew welfare – play a critical role in maintaining the operational standards and onboard experiences expected by yacht owners and charter clients.

At the same time, sustainability has emerged as a significant focus, with practices like eco-friendly refits, the integration of renewable energy sources, and carbon footprint reduction initiatives gaining traction across the industry in response to growing environmental concerns among owners and shipyards. In this context, the role of technology providers has become increasingly important, driving advancements in hybrid and reduce energy demand propulsion systems, smart equipment integration, and personalized digital services.

Focusing on the yacht product, the segmentation of the industry is equally complex, mirroring the vessels' diverse nature and possible uses. Several criteria can categorise yachts, including purpose, propulsion type, typology, dimensions, number of hulls, usage patterns, and production methods. A primary distinction exists between pleasure craft for private use – boats employed for recreational or sporting purposes without commercial intent – and pleasure craft for commercial purposes, such as vessels used for charter, recreational navigation training, or diving support operations. Commercial pleasure craft also include larger vessels such as superyachts and megayachts (hull length exceeding 24 meters) when deployed exclusively for rental in international tourism (Ajagunna & Casanova, 2022).

Further differentiation emerges in production typologies, particularly between Series-produced, semi-custom, and custom yachts. Series-produced yachts are manufactured in medium-large volumes (a comparison with industrial production scale in no meaningful), typically based on standardized designs, allowing for economies of scale that render them more affordable and widely accessible. These vessels are generally small (under 20 meters) and characterized by shorter production times and limited opportunities for personalization, appealing predominantly to entry-level and mid-range buyers.

On the other hand, custom yachts represent the top of the line of personalization within the industry. Every aspect of a custom yacht is designed and built to the owner's specifications, from the hull shape and structural architecture to the interior design and décor and technological equipment integration. Custom projects typically involve intensive collaboration between owners, shipyards, naval architects, and interior designers, resulting in vessels that are unique in both aesthetics and technological advancement. The design and construction timelines for custom yachts are significantly longer, often extending over three years, with costs considerably higher, reflecting the bespoke nature of the product.

In between the two typologies, the Semi-custom yachts offer a compromise between efficiency and personalization, representing the most requested typology of vessel in the last 5 years (Boat International, 2024). Built on standardized hull platforms, these yachts permit substantial customization of interior layouts, aesthetics, and onboard technologies, allowing owners to tailor significant elements of the yacht to their preferences while maintaining cost and time efficiencies relative to full-custom builds. Thus, while the yacht market is unified by the pursuit of leisure and luxury experiences, it is simultaneously marked by diverse production models and usage patterns that mirror broader socioeconomic trends and consumer behaviours.

2.2 The superyacht and mega yacht sectors

The superyacht and mega yacht segments represent the top-of-the-line of luxury in the broader yachting industry, responding to a clientele whose design and service preferences reflect evolving notions of wealth, exclusivity, and status. These vessels, often customized to the most exacting specifications, symbolize not only private leisure but also a form of mobile, high-end real estate that integrates advanced technology, advanced design, and lifestyle services. In recent decades, the expansion of global wealth, particularly among high-net-worth individuals (HNWIs), has significantly reshaped this market (Merendino, 2013; Deloitte, 2024).

A superyacht is typically defined as a professionally crewed motor or sailing vessel measuring from 24 meters (approximately 79 feet) up to around 180 meters in length (Bees, 2016). Although originally private, nowadays, an increasing number of superyachts are also available for luxury charter, expanding their economic and cultural footprint within the tourism and hospitality industries. Mega yachts, a term often used for vessels exceeding 50 meters, represent a further evolution where size and technological innovation combine with increasingly sophisticated notions of luxury, such as personalization, wellness, and sustainability (Williams, 2023; Fortezza, 2008).

The market for superyachts and mega yachts has shown robust performance in recent years despite broader global economic fluctuations. According to Deloitte (2024), the Superyachts Global Order Book for vessels over 30 meters recorded 600 units delivered in 2022, representing a 21% year-on-year increase from 2021 and a cumulative market value of €25.3 billion. This growth is particularly remarkable given that the superyacht sector accounts for only about 1% of the overall luxury market, yet it has exhibited a CAGR of 5.4% between 2019 and 2022. Meanwhile, in Europe alone, the value of the luxury yacht industry was estimated at €4 billion, directly employing around 148,000 individuals across approximately 5,000 active vessels (Benevolo & Spinelli, 2021).

The drivers of this market expansion are closely tied to demographic and socioeconomic shifts. The number of HNWIs globally has grown steadily, and this clientele forms the exclusive consumer base for superyachts, whether for personal ownership or for luxury chartering (Von Wallpach *et al.*, 2020). Superyacht prices vary significantly: vessels under 120 feet generally start around $25 million, whereas those between 120 and 250 feet can range from $25 million to $100 million, and yachts over 250 feet often exceed $100 million in price (Mobility Foresights, 2022). Operating costs, estimated at roughly

10% of a yacht's value annually, add an additional layer of exclusivity to ownership (Adamczyk, 2015).

However, over time, the superyacht and mega yacht sectors have evolved beyond traditional notions of luxury defined merely by size and opulence. Contemporary owners and charter clients now seek enhanced onboard experiences, ranging from dedicated wellness spaces staffed with health professionals to immersive adventure itineraries. Wellness offerings, including spa treatments, yoga instruction, personal training, and bespoke nutrition services, have become standard onboard larger yachts (Williams, 2023).Technological innovation has become another defining feature of this market. Mega yachts increasingly integrate cutting-edge systems in hybrid propulsion, automation, and cybersecurity, responding to owner demands for both performance and environmental responsibility (Ansaloni *et al*., 2022; Cazzaniga Francesetti, 2008). Sustainability is no longer a peripheral consideration but has moved to the centre of yacht design and construction, with shipyards collaborating with environmental organizations to develop greener technologies and reduce ecological footprints. As a consequence, a shift in the meaning of luxury itself is evident. Where once the focus was on visible opulence, today's superyacht market reflects an *advanced luxury* paradigm: one that emphasizes experiential value, and ethical responsibility (Fortezza, 2008). This evolution aligns with broader consumer trends in the luxury market, where authenticity, personalization, and impact increasingly guide purchasing behaviour (Philip Connors, 2023).

Structurally, the superyacht industry operates within an environment of oligopolistic competition: a limited number of major shipyards dominate, competing on innovation, customization, and brand prestige rather than price leadership. Growth is often achieved through acquisitions of smaller shipyards, which allows leading brands to expand service offerings and technological capabilities (Merendino, 2013).Despite the challenges of an evolving global economy, the superyacht and mega yacht sectors have proven remarkably resilient. Their success demonstrates not only the enduring appeal of extreme luxury but also the industry's capacity to adapt to changing consumer values, technological advancements, and environmental imperatives.

2.3 Socioeconomic impacts: from the 2010 crisis to the pandemic boost

The yachting industry, like many luxury sectors, has historically demonstrated sensitivity to macroeconomic fluctuations, although it often proves more resilient than mass-market goods due to its reliance on HNWIs (Merendino, 2013). The period between the global financial crisis of 2008–2010 and the COVID-19 pandemic provides a clear example of how external economic shocks shape industry dynamics, from contraction to renewed growth and diversification.

The financial crisis of 2008-2010 triggered a significant downturn in the yacht and superyacht markets. Sharp declines in wealth, coupled with greater social scrutiny around conspicuous consumption, led to a reduction in new orders, a slowdown in deliveries, and a rise in the availability of pre-owned yachts at depressed prices (Benevolo & Spinelli, 2021; Merendino, 2013). The global order book for superyachts shrank considerably, and many shipyards either reduced production or shifted their business models toward refitting and maintenance to survive. Although the luxury sector overall retained a level of resilience, the capital-intensive nature of yacht construction made it particularly vulnerable to the liquidity shortages and investor caution characterizing this period (Bruni & Carcano, 2009).

In between 2012 and 2106, the yachting market entered a slow but steady phase of recovery, driven by the rebound of global financial markets and the increasing number of ultra HNWIs in emerging economies, particularly in Asia and the Middle East (Deloitte, 2024). In 2018, the gradual return of consumer confidence allowed builders to regain momentum, though with an important shift: buyers became more selective, favouring smaller, more efficient yachts with lower operational costs, and showing heightened interest in resale value and sustainability (Confindustria, 2023).

The COVID-19 pandemic, initially feared to cause another devastating blow to the sector, instead acted as a major accelerator of growth. Lockdowns, travel restrictions, and concerns over public health redirected the spending habits of affluent individuals toward private, controlled environments, including yachts (Williams, 2023). Ownership and chartering of yachts offered a means of maintaining luxury travel experiences while minimizing exposure to health risks. As a result, the global yacht market experienced an unexpected surge, with new builds, brokerage sales, and charter demand reaching record levels between 2020 and 2022 (Deloitte, 2024).

During the pandemic years, the Global Order Book reported unprecedented figures, with 600 new superyacht units delivered in 2022 alone; a 21% increase compared to the previous year (Deloitte, 2024). The increase in demand extended beyond traditional Western markets, with heightened activity observed in Southeast Asia, Oceania, and parts of Africa, reflecting the increasingly global nature of wealth distribution. Moreover, the pandemic reshaped consumer values, further influencing yacht design and usage patterns. Privacy, autonomy, and self-sufficiency became paramount, prompting new features such as enhanced medical facilities onboard, longer-range capabilities, and multipurpose spaces that could adapt to both leisure and business use. An increased emphasis on sustainability also emerged, with owners demanding hybrid propulsion, eco-friendly materials, and carbon footprint offsetting programs (Ansaloni *et al*., 2023).

Societally, the yachting boom during and post-pandemic also rekindled debates around wealth inequality and environmental impact, leading to greater public scrutiny. Owners and builders responded by framing yachts as not merely symbols of personal luxury but as platforms for philanthropy, scientific exploration, and conservation initiatives (Von Wallpach *et al*., 2020).The resilience and renewed dynamism of the yachting sector illustrate broader transformations in the global luxury economy. Affluent consumers increasingly seek investments that combine status with security, experience, wellness, and ethical responsibility (Connors, 2023).

2.4 Emerging user behaviours and experience-driven design trends

In a market where yacht owners and sailors value experiences more than goods, the yacht stands apart from the rest as the ultimate and most exclusive way to enjoy luxury. It's not simply a monetary reason. It's the multitude of experiences made possible by yachting, as well as its ability to transcend time itself through its lifecycle. Nowadays, the yachting sector is undergoing a profound transformations that reflect a shifts in global demographics and consumption patterns. A significant factor driving this change is the growing influence of Millennials generation, whose expectations and values differ from those of previous generations (26 North Yachts, 2022). Recent studies indicate that Millennials are projected to account for 60% of superyacht owners in the coming ten years, highlighting a pivotal demographic transition that will redefine the industry's future (Deloitte, 2024). Five main trends are emerging: experiencing vs owning, blurring exterior and interior design with versatile spaces, environmental consciousness including fuel efficiency, smart onboard technology and connection, and safety as a priority.

Since 2018, earlier yacht customer generations often associated ownership with status and permanence. On the contrary, contemporary owners are primarily looking for unique experiences, environmental stewardship, and technological innovation (Cain, 2023). For this reason, luxury yachting is increasingly measured not by possession but as access to exclusive, tailor-made experiences, often connected with emotional adventure. The concept of experiencing rather than owning has taken root, with new ownership models such as yacht-sharing programs, bespoke charters, and adventure-driven itineraries gaining traction (Deloitte, 2024).

Simultaneously and fostered by pandemic new needs, traditional and compartmentalized layouts are progressively giving way to fluid, versatile spaces that can easily shift between social, private, wellness, or work environments. The integration between exterior and interior spaces has become more seamless, with trasformable terraces, modular furnishings and transparent walls, allowing for unprecedented flexibility (Williams, 2023). Modern yachts must now serve as dynamic environments capable of hosting multiple activities in a single setting, reflecting the increasingly multifaceted lifestyles of their owners.

At the same time, environmental consciousness has emerged as a central value among new buyers. Driven by a heightened awareness of climate change and ocean health, today's owners demand yachts that embody sustainable innovation. This includes hybrid propulsion systems, energy-efficient hull designs, advanced waste management solutions, and the use of recyclable or responsibly sourced materials throughout the construction and interior outfitting processes (Ansaloni *et al.*, 2023; Deloitte, 2024). Many examples could be retrieved in the recent years on yacht design toward sustainability. Beside shipyard R&D activities on hybrid propulsion technologies and lightweight materials, initiatives of the Water Revolution Foundation demonstrate the industry's growing commitment to scientific, measurable sustainability practices throw-out the entire yacht lifecycle. On the other hand, collaboration with marine foundations, such as Parley for the Oceans, are supporting marine conservation projects worldwide.

In parallel with sustainability, technological innovation plays a decisive role in shaping the expectations of new yacht owners. For a generation raised in a digitally interconnected world, seamless technological integration is not an optional luxury but a baseline requirement. Modern superyachts are requested to be equipped with advanced navigation systems and hyper-connected entertainment systems capable of ensuring consistent performance even under extreme maritime conditions (Cain, 2023). In the technological context, a critical aspect of emerging user behaviour is represented by the prioritization of safety features. AI-assisted safety automations and operations, cybersecurity systems and alarms, and the availability of medical-grade facilities have become essential elements of the modern superyacht offering. Safety is no longer viewed merely as a regulatory compliance issue but as an integral component of the broader lifestyle and experiential package demanded by clients (Deloitte, 2024).

The new generation of owners is reshaping the market with values rooted in personalization, responsibility, and innovation, challenging shipyards, designers, and service providers to rethink every aspect of their offerings. As the sector continues to evolve, those who anticipate and adapt to these emerging user behaviours will be best positioned to thrive in a market where luxury is increasingly defined not by possession, but by meaningful, curated experiences at sea.

3. The Digital Transformation of Industry

3.1 The Industry 4.0 and 5.0 frameworks

The term *Industrie 4.0*, and consequently Industry 4.0, became publicly known in 2011, when the initiative «Industrie 4.0: an association of representatives from business, politics, and academia» was created to promote the concept of a next industrial revolution and to strengthening the competitiveness of the German manufacturing industry (Kagermann *et al.*, 2011). The German federal government supported the idea of integrating the vision in the initiative *High-Tech Strategy 2020 for Germany* and forming the *Industrie 4.0 Working Group*. The government purpose was to foster the national industry as a worldwide leader in advanced manufacturing. In 2013 the first recommendations for Industrie 4.0 scenario implementation were presented in the Final Report of the Industrie 4.0 Working Group (Kagermann *et al.*, 2013):

> **In the future, businesses will establish global networks that incorporate their machinery, warehousing systems and production facilities in the shape of Cyber- Physical Systems (CPS). In**

the manufacturing environment, these Cyber-Physical Systems comprise smart machines, storage systems and production facilities capable of autonomously exchanging information, triggering actions and controlling each other independently. This facilitates fundamental improvements to the industrial processes involved in manufacturing, engineering, material usage and supply chain and life cycle management. […] The embedded manufacturing systems are vertically networked with business processes within factories and enterprises and horizontally connected to dispersed value networks that can be managed in real time – from the moment an order is placed right through to outbound logistics. In addition, they both enable and require end-to-end engineering across the entire value chain.

Focused on the establishment of intelligent products and production processes, this industrial revolution has been placed succeeding the three other industrial revolutions in the history of humankind. According to experts from industry and research, the fourth industrial revolution was triggered by the Internet, which allows communication between humans as well as machines in CPS throughout large networks (Brettel *et al*., 2014). Furthermore, the origin of this process is attributable to the situation in which a high number of technologies, generally called *digital enabling technologies* (i.e. additive manufacturing, IoT, and virtual reality) have simultaneously become cost-effective and quantitatively widespread (Celaschi, 2017).

There is still no standard definition of Industry 4.0 in the scientific literature, and different names call the phenomenon. The terms Industry 4.0, fourth industrial revolutions, IIoT, Smart manufacturing, are often proposed without distinctions. In the present study, Industry 4.0 is defined according to Saldivar *et al.* (2015): «Industry 4.0 is the digital transformation of manufacturing with connected factories, smart decentralized manufacturing, self-optimizing systems and digital supply chain in an information-driven cyber-physical environment».

According to Zhou *et al.* (2015), the primary purpose is building a highly flexible production model of personalized and digital products and services, with real-time interactions between people, products and devices during the whole product life cycle.

As businesses started to embrace Industry 4.0, along came the fifth industrial revolution. Industry 5.0 is conceived to recognize the power of industry to achieve societal and sustainability goals beyond digitalization, by making production respect the boundaries of our planet (Xu *et al.*, 2021).

The introduction of the 5.0 concept is based on the observation that current digitalization advancement is focused on increasing efficiency and flexibility in production, while lacking on human-cantered approach. For this reason, whereas Industry 4.0 is considered to be technology-driven, Industry 5.0 is placed in a value-driven framework. The transition to 5.0 is, therefore, promising to face the Sustainability Trilemma, the current challenges that industries face in achieving all the three sustainability pillars such as economic, social, and environmental sustainability simultaneously (Raja Santhi & Muthuswamy, 2023). As results, while industries are starting to implement the digital technologies and integrative-system approach of Industry 4.0, global challenges and societal need are forcing the shift to a more sustainable and human-centric approach promoted by Industry 5.0, blurring the boundaries between the two concepts and highlighting their interconnections.

3.2 Core digital design principles

In the past decade, there has been a growing effort in trying to classify and define the main concepts that collectively represent the digital transformation. Most of those still don't have a consolidated definition and, in some cases, there are overlapping terms with no commonly agreed hierarchy.

As presented by Herman *et al.* (2015) and Qin *et al.* (2016), six core design principles support the strategic vision of industry 4.0 along the integration of digital technologies in the product-process-services value chain. The design principles are:

- Virtualization: Creating of a virtual (rather than actual) version of the physical world.
- Self-configuration: the arrangement of parts or elements in a particular form, figure, or combination independently.

- Real-time capability: to be able to collect real-time data, store or analyse it, and make decisions in real-time and according to new findings.
- Service orientation: the design paradigm for the virtual system in the term of abstract units of functionality called services.
- Decentralization: the dispersion or distribution of functions and powers.
- Flexibility: to be able to adapt to change requirements by replacing or expanding individual modules. This concept embeds the modularity principle at the core.

These core principles could be analysed and grouped according to the different dimensions of digital integration: while interoperability consists of virtualization, decentralization and flexibility, (interoperability is creating a collaborative and flexible environment in which many devices can talk to each other, and data from various sources can be leveraged), real-time capability, self-configuration, and service orientation comprise consciousness (these principles represent the cognition level engaging the artificial intelligence in the network, which is considered as future attributes of manufacturing).

Furthermore, these principles make possible the development of Industry 4.0 at two levels of integration: a horizontal level – peer-to-peer and over the business value networks – and a vertical level through the manufacturing system, value chain, and customer services. Horizontal integration refers to the integration of the systems for and across the various product, production, or business planning processes. In other words, horizontal integration is about digitization across the whole value chain, whereby data exchanges and connected information systems are centralized managed. Whereas horizontal integration is about systems and flows in the value chain and the various processes happening across it, vertical integration has a hierarchical level component.

These hierarchical level are respectively the field level (interfacing with the production process via sensors and actuators), the control level (regulation of both machines and systems), the process line-level (that needs to be monitored and controlled), the operations level (production planning, quality management and so forth) and the enterprise planning level (order management and processing, the overall production planning etc). In this integration, a digital execution platform plays a central role in transforming the manufacturing headquarter in a hub of information and connectivity.

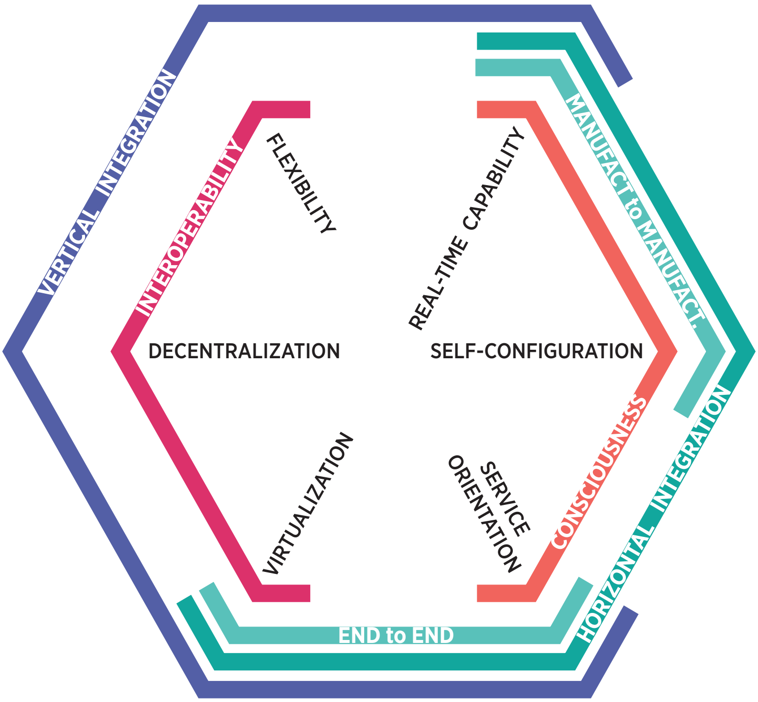


Figure 2.
Graphical interpretation of the design principles accoring to the different dimensions of digital integration.

3.3 Enabling technologies and the impact on companies and design systems

The Industrial Revolution can be described as the continuous transformation of traditional industrial practices into new techniques shaped by the technological advancements available at each historical stage. The first three industrial revolutions were respectively driven by mechanisation, electrification, and automation – each of which progressively reshaped an agrarian economy into one dominated by manufacturing and mass production (Raja Santhi & Muthuswamy, 2023).

In the context of the ongoing digital transformation, a review of international policies and European industrial strategies reveals a clear consensus around a core set of eight enabling digital technologies as the foundational drivers for the digitalisation of industry. These technologies form the technological backbone of Industry 4.0 and are actively evolving within the value frameworks of Industry 5.0.

- IoT, IIoT, and IoE, refer to a vast network of physical objects embedded with sensors and connectivity technologies that allow them to collect and exchange data. Within the industrial context, this concept evolves into the Industrial Internet of Things (IIoT), a cyber-physical infrastructure enabling machines, devices, and users to interact and cooperate seamlessly (Jeschke *et al*., 2017). IIoT breaks traditional barriers between B2B and B2C by creating dynamic, data-rich interaction environments across production systems (Celaschi, 2017). The Fourth Industrial Revolution is deeply rooted in this concept of bi-directional communication between humans and machines and between machines themselves. Expanding beyond this, the Internet of Everything (IoE) includes not only devices and systems but also processes, data, and people in a unified ecosystem (Mohd Ali *et al*., 2023). In the context of Industry 5.0, IoE is positioned to enable hyper-personalised user experiences, optimise operational processes, and strengthen customer loyalty through the intelligent use of data (Singh & Kakkar, 2025).
- Cloud Manufacturing integrates distributed design, production, and operational resources through cloud-based platforms. This paradigm, rooted in cloud computing and IoT, transforms manufacturing assets into service-oriented modules that can be accessed, managed, and optimised across global networks (Wu *et al*., 2015). The model supports the "design anywhere, manufacture anywhere" concept originally theorised in the early 2000s, offering manufacturers enhanced efficiency, scalability, and cost-effectiveness (Heinrichs, 2005). As a result, cloud manufacturing allows a complete rethinking of production value chains, moving toward highly adaptable and decentralised industrial ecosystems.
- Additive Manufacturing (AM) commonly known as 3D printing, involves the layer-by-layer construction of three-dimensional objects using materials such as polymers, metals, or ceram-

ics. It is uniquely suited for the mass customisation paradigm central to Industry 4.0, as it enables the production of highly complex and personalised components that are difficult or impossible to achieve with traditional methods (ISO/ASTM, 2015; Dilberoglu *et al*., 2017). Today, AM is a maturing technology adopted across aerospace, automotive, biomedical, and consumer goods sectors, delivering improved performance, reduced waste, and enhanced design freedom.

- Co-robots, or cobots, represent a fundamental evolution from traditional industrial robotics. Designed to safely interact with humans in shared workspaces, collaborative robots integrate advanced sensors, AI-powered control systems, and adaptive learning capabilities (Colgate *et al*., 1996). Unlike previous generations of robots, which were confined to isolated tasks, cobots are flexible, reconfigurable, and capable of performing diverse operations in response to environmental and user inputs. Their increasing role in human-machine collaboration reflects the shift toward Industry 5.0's value-driven, human-centric manufacturing paradigm.
- Big Data Analitics involves the systematic examination of extremely large and diverse datasets to uncover patterns, correlations, and insights that inform strategic decisions (Techtarget, 2017). As the volume of data generated by connected systems and users grows exponentially, the integration of Artificial Intelligence (AI) and Machine Learning (ML) becomes essential. These technologies enable systems to learn from data, adapt to new scenarios, and improve performance over time, making them indispensable for predictive maintenance, customer behaviour analysis, supply chain optimisation, and more. Together, big data, ML and AI represent the cognitive layer of digital transformation, shaping intelligent automation and real-time decision-making.
- Simulation and system integration involve creating digital representations of real-world systems, enabling predictive analysis and operational testing before physical implementation (OECD, 2002). This capability has evolved into the Digital Twin – a dynamic digital counterpart of a physical object, system,

or process. Digital twins are used to monitor, simulate, and optimise operations across their entire lifecycle, from design through to maintenance (Longo *et al*., 2022). System integration ensures interoperability between different components, software platforms, and organisational processes, forming a cohesive, responsive industrial environment.

- Virtual Reality (VR) and Augmented Reality (AR) technologies simulate real or imaginary environments and overlay digital content onto the physical world, respectively (Steuer, 1992). In industrial applications, VR/AR enhance training, remote collaboration, prototyping, and immersive product development. Companies are exploring VR and MR in customer engagement as well as workload training, making possible the multidimensional domain of manufacturing.
- Advanced Human-Machine Interfaces (AHMI) encompass the visual, tactile, voice-controlled, and wearable systems through which operators interact with digital systems (Osservatori.net, 2015). These interfaces are central to the vision of Industry 5.0, where human experience is prioritised alongside technological efficiency. By enabling intuitive control, real-time feedback, and natural interaction, AHMIs enhance not only productivity but also operator well-being and system transparency.

3.4 The information-driven cyber-physical systems and its impact on companies and design systems

As previously described, the current implementation of Industry 4.0 rests on four fundamental pillars: digital design and simulation, highly automated production processes, integrated data management, and interconnected systems across the entire value chain. Two defining features characterise this evolving industrial landscape: its information-driven logic, rooted in real-time awareness and decision-making, and its cyber-physical architecture, which merges the digital and physical worlds through intelligent, responsive systems capable of interaction and autonomy (Herman *et al.*, 2015).

The rise of the information-driven system is closely linked to the emergence of IoT, which enables the tagging, tracking, and communication of *things* through increasingly affordable sensor technologies. This paradigm emerged alongside the growing accessibility of low-cost computing and internet-based communication, further accelerated by the proliferation of smartphones (Thames & Schaefer, 2016). Today, this infrastructure extends far beyond production: customer relations and after-sales services are changing profoundly, allowing companies to access field-generated data and offer predictive, personalised support.

In this context, some authors refer to the concept of the Internet of Services: a shift towards modular, web-accessible service models that allow users and companies to assemble, customise, and deliver value-added solutions with unprecedented agility (Barros & Oberle, 2012). Looking ahead, the information-driven model is expected to move beyond individual factories toward integrated, value-added networks, enabling new forms of distributed production and service delivery. Parallel to this transformation, the development of CPS marks a second cornerstone of Industry 4.0. These systems are defined as «a new generation of systems which integrate physical assets and computational capabilities and are able to interact with humans» (Baheti & Gill, 2011). At their core, CPS is built on two main functional layers: advanced connectivity – ensuring real-time data collection from the physical world – and intelligent data management and analytics, which drive decision-making in cyberspace.

Within manufacturing, CPS is composed of smart machines, storage systems, and production units capable of autonomously exchanging data, initiating actions, and coordinating with one another independently (Kagermann *et al.*, 2013). This evolution enables fundamental improvements in efficiency, flexibility, and responsiveness across engineering, materials usage, logistics, and lifecycle management. Increased decentralisation and machine autonomy, supported by CPS, have proven to be key drivers of industrial resilience and performance (Ivanov *et al.*, 2016).

When the two dimensions of information-driven systems and cyber-physical architectures are combined, manufacturing takes shape as an environment where intelligent, self-organising production becomes possible. This shift requires advanced digital modelling (e.g., the *virtual factory*) and the integration of artificial intelligence to support real-time monitoring, prediction, and control across all stages of production. One of the most significant developments within this framework is the emergence of the Digital Twin (DT). As described by Rodič (2017), the DT acts as a unique digital representation of a product, process, or service system. It reflects the physical counterpart's state, properties, and behaviour through continuous data collection, analysis, and simulation. This digital shadow not only mirrors the real object but also enhances decision-making, as insights from the data allow for optimisation throughout the product's lifecycle – from design and production to maintenance and end-of-life management.

This connection the interconnection between physical and virtual worlds will have a widespread impact in every economic sector, with the transformative potential of Industry 4.0 analysed across four interconnected levels: business, factory, product, customer, and design.

At the business level, the flow of information will no longer be confined within the walls of a single factory. Instead, a broader, integrated network will emerge – one that connects all stakeholders involved in the value chain. These networks will not only facilitate the seamless exchange of data but will also foster real-time responsiveness and increasingly self-organising structures (Kagermann *et al*., 2013). Connected supply chains offer considerable advantages in terms of operational efficiency, especially across organisational boundaries (Hofmann & Rüsch, 2017). As a result, businesses will be compelled to rethink their strategies, moving toward hybrid models that integrate physical and digital infrastructures to enable agile, collaborative workflows spanning the entire lifecycle – from innovation to production and distribution (Gligor & Holcomb, 2012).

Under this paradigm, traditional factories will evolve into Smart Factories, environments defined by real-time communication and autonomous coordination between machines, systems, and human operators. As described by Lucke *et al.* (2008), a Smart Factory is «a factory that context-aware assists people and machines in the execution of their tasks». In such a setting, all resources – tools, machines, data systems – are connected, enabling high levels of automation and responsiveness in production management. This shift has the potential to change existing industrial operations radically. For example, factories capable of receiving consumer orders and producing on-demand goods could bypass traditional sales and distribution channels altogether, redefining the e-commerce landscape (Soori *et al.*, 2023).

The integration of digital technologies across the supply chain also transforms how products are conceived, designed, and produced. One of the most significant advantages is the possibility of mass customisation at a lower cost. Thanks to smart manufacturing intelligence and advanced analytics, product development will increasingly respond to specific user preferences gathered in real-time, feeding insights back into design, innovation, and delivery processes (Chand & Davis, 2010). In this context, products are no longer static artefacts but dynamic, data-informed systems that evolve based on user feedback and system performance.

From the customer's perspective, the value chain integration promoted by Industry 4.0 offers multiple advantages. Greater product customisation and reduced delivery times are only the beginning. The emergence of Smart Products allows users to access real-time information about how products are manufactured and to receive usage recommendations tailored to their individual behaviours (Har *et al.*, 2022). In doing so, the relationship between producer and consumer becomes more interactive, transparent, and personalised.

The reflections on the impact of the current industrial revolution on design could be embedded in the broader area of investigation of Digital Design and Digital Design Thinking. As introduced by Oxman (2006), Digital Design (Thinking) is:

> **non-typological and non-deterministic digitally mediated design (thinking) in supporting the discrete and differentiated process over the generic and the typological. […] Furthermore, the ability of digital models to connect between design and materialization even in conceptual design stages supports a new depth of contextualization and performative design.**

Digital design and manufacturing have been around for several decades from the numerical control of machine tools and automating engineering design in the 1960s, through early Computer-Aided Design (CAD), to modern digital design and manufacturing. Digital design and manufacturing technologies provided significant support for product realization from design conception and engineering to product manufacturing, sales, and services. In the past, the development of the digital design was driven greatly by the technological advances only, such as those in materials, electronics, software, and ICT (information and computing technologies). In the recent debate digitalization, the design discipline face most challenging conditions highlighting the emergence of new theoretical frameworks and novel cross-disciplinary collaboration to constitute the intellectual foundations of Digital Design (Qin *et al.*, 2016). Within this frame, cross-disciplinary connections to the biological sciences are now emerging from a research perspective on cognitive digital enabling technologies, particularly concerning new theories, such as complexity theory, chaos, emergence, catastrophe theory, and bio-mimetics. Furthermore, computational sketching tools – including text-to-image and image-to-image tools – are rapidly emerging and evolving, supporting the creative process by generating unconventional semantic and visual stimuli that foster novel design ideas. Industry leaders such as Adobe and OpenAI are at the forefront of this shift, introducing experimental tools to a broader public, eliciting both enthusiasm and concern within the design community. (Gok, 2023; Bionda & Incitti, 2024).

In conclusion, the integration of digital technologies across industry and design is not only transforming how we produce and interact but also how we think and create. As these tools continue to evolve – from smart factories to generative sketching – they invite us to reconsider established models and engage with new ways of working that are both more connected and more responsive to human needs.

PART 2

Scanning

4. Evolution of Digital Frameworks in the Yachting Sector

4.1 The digital maritime context

The digitalisation of yacht design practices must be seen within the broader evolution of the maritime industry, where digital transformation is reshaping traditional processes across design, construction, operation, and service domains. The implementation of digital technologies – ranging from cyber-physical systems to autonomous navigation tools – marks a systemic shift that goes beyond isolated innovation, calling instead for the reorganisation of industrial workflows, collaborative practices, and conceptual paradigms across the nautical sector. This transformation reflects not merely the integration of digital tools into established practices but a rethinking of how vessels are conceived, produced, and maintained in an increasingly connected and data-driven environment.

Within this framework, the digital transition is not confined to a specific vessel type or market segment but encompasses a broader spectrum of maritime operations, including those related to yachting. The recreational and luxury yachting sectors, while distinct in scale and end-user expectations, are part of this larger industrial transition. To understand this phenomenon, a combination of systematic literature review, industrial survey, and best practice analysis was conducted between 2017 and 2025. These studies, following reported, offer a comprehensive view of the progression of digitalisation in the yacht and broader maritime sectors, capturing technological, operational, and organisational dimensions.

Sullivan *et al.* (2019) define the concept of Maritime 4.0 as the integrated implementation of digital processes and technologies across the entire vessel lifecycle. A critical component of this definition is the emphasis on systemic integration; technologies that are adopted in isolation, without being embedded into the broader system of systems, do not qualify under the Maritime 4.0 framework. This perspective reflects a shift from viewing digitalisation as tool-driven to understanding it as a structural transformation. It also underscores the importance of organisational readiness, data interoperability, and collaborative infrastructures to enable comprehensive digital transformation. Despite its conceptual clarity, the actualisation of Maritime 4.0 remains uneven across different maritime subdomains.

Multiple scholars have identified key factors influencing the pace and depth of digital adoption in maritime industries. As outlined by Gausdal *et al.* (2018) and corroborated by the KPMG International Cooperative (2018), many stakeholders in the maritime transport and yachting sectors face challenges such as limited awareness of digital benefits, lack of strategic alignment, outdated regulatory environments, and fragmented technological infrastructures. These issues are particularly evident in port operations and vessel servicing, where digital maturity varies significantly between actors and geographies. The literature points to four primary drivers of Maritime 4.0: dynamic policy frameworks, market-driven pressures for efficiency and competitiveness, the rapid evolution of enabling technologies, and the necessity for integrated embedded systems that cut across vessel lifecycles (Sullivan et *al*., 2019).

The literature further identifies four core domains in which Maritime 4.0 is developing: vessel design, construction, operation, and service. In the design phase, the incorporation of data from previous and existing vessels allows for more informed and optimised decision-making.

While customer-specific requirements continue to play a central role in design decisions, modern tools such as virtual simulations and real-time performance feedback are becoming more prominent. Nevertheless, as Sanchez-Gonzalez *et al.* (2019) indicate, the integration of artificial intelligence and big data into the design process remains limited. Most applications focus on virtual reality and digital twin simulations, while predictive analytics and machine learning tools are largely unexplored in this context.

The construction phase presents similar asymmetries. While digital manufacturing techniques, including 3D printing and modular construction, hold significant promise, their adoption is still in early stages, particularly in the yacht sector. Luglietti *et al.* (2018) note that although lessons from industrial manufacturing could be transferred to shipbuilding, significant barriers exist, especially regarding cost structures and supply chain complexities. Shipyards face the dual challenge of integrating advanced manufacturing technologies while maintaining the flexibility required for customised builds, a hallmark of the yacht sector.

Operational digitalisation has seen comparatively greater progress. Technologies enabling real-time vessel monitoring, smart port infrastructure, and autonomous navigation are increasingly deployed in both commercial and recreational contexts. According to Thanopoulou and Strandenes (2017), the availability of operational data from sensors, navigation systems, and environmental monitors has grown exponentially. However, despite this surge in data generation, significant challenges persist in transforming this data into actionable design or strategic insights. There is a persistent disconnect between operational data and its integration into design and engineering cycles, which limits the feedback potential of real-world performance metrics.

In the service domain, the deployment of intelligent maintenance systems, specialised maritime software, and environmental monitoring solutions is becoming more widespread. This domain involves not only technological innovation but also the redefinition of service models, including predictive maintenance, remote diagnostics, and digital support networks. Nevertheless, as Jović *et al.* (2022) observe, progress is uneven, primarily due to low interoperability between stakeholders and the absence of shared data standards. Regulatory constraints further exacerbate these issues, with paper-based documentation still prevailing in many jurisdictions, hindering the flow of digital information and slowing innovation adoption.

The academic literature reveals a strong focus on robotics, artificial intelligence, and big data, particularly as they relate to navigation aids and operational efficiency (Pradita, 2025). However, these studies rarely extend to the integration of such technologies into the earlier phases of vessel design or construction. The application of AI in vessel routing, for instance, remains largely decoupled from design optimisation or material selection. Moreover, while big data is recognised as a critical enabler, its use in shipbuilding analytics remains embryonic. In terms of enabling technologies, 3D printing and robotics in construction are identified as promising yet underexplored fields. Similarly, the potential of IoT technologies to transform shipping operations has been recognised, but practical implementation often lags behind academic proposals.

The sector's digital inertia can be partially explained by its structural configuration. Maritime transport involves a multitude of heterogeneous actors – shipbuilders, port authorities, classification societies, regulatory bodies, and service providers – each operating under distinct technological and procedural regimes. As Jović *et al.* (2022) highlight, this fragmentation leads to high costs for achieving information interoperability and weakens the business case for shared investments in digital infrastructure. Moreover, the lack of institutional incentives and collaborative frameworks prevents the consolidation of digital transformation efforts. Laws and regulations often permit only traditional data exchanges, discouraging innovation and reinforcing existing inefficiencies.

Despite these systemic challenges, the urgency to embrace digitalisation is increasingly recognised across the sector. Market competition, environmental regulation, and user demand for smart vessels are driving the need for transformation. In this context, understanding the current state of digital maturity and the barriers that impede progress is essential. The insights derived from the literature suggest that while foundational technologies are available and well-researched, their deployment is hampered by structural, regulatory, and strategic bottlenecks. To address this, a coordinated effort involving technological standardisation, regulatory modernisation, and stakeholder cooperation is needed.

In the specific context of the yacht industry, the digital transition remains nascent but increasingly visible. Yacht builders and designers are beginning to explore smart design environments, digital twins, and connected services. Yet, the sector's fragmentation, focus on bespoke products, and limited economies of scale present unique challenges. The adoption of Maritime 4.0 principles in yachting must therefore be carefully tailored to its industrial and market-specific realities. The following chapter will further analyse these dynamics through a targeted industrial survey and a series of case studies aimed at illustrating the pathways, obstacles, and innovations that define the digital transformation of the yacht sector.

4.2 Maturities of yacht digital framework

The exploration of digital transformation within the yacht sector reveals a notable disparity between conceptual aspirations and practical implementation. At the beginning of 2017, when the first literature review was carried out, only three papers related to yacht design or production were found. The paper's authors confirmed the lack of knowledge on the topic. Liu *et al.* (2017a) described the Intelligent Design of Yacht as a *new paradigma* that needs to be explored systematically to unearth the feasibilities and challenges in scenario development and implementation.

> **Promoting intelligent manufacturing in the luxury yacht industry and achieving high-efficiency and low-cost manufacturing fostered by digitalisation and automation bears special significance in facilitating the market transformation of the shipbuilding industry. The concept of intelligent manufacturing is not limited to *manufacturing intelligence* but has been extended to the corporate level, encompassing the coordination of a *system of intelligence*. The design and manufacturing of luxury yachts entails many optimisation challenges in multidisciplinary collaboration efforts.**

> **These collaboration efforts have to be extended to contain the full life cycle of luxury yacht projects, which fully embodies the organic integration of advanced manufacturing technology, information technology and intelligent technology. (Liu *et al.*, 2017a).**

This articulation not only highlights the complexity of the yacht design ecosystem but also emphasises the systemic nature of digital integration, calling for a life-cycle approach to innovation. The remaining two papers identified in the 2017 review – Liu *et al.* (2017b) and Dogan & Gunpinar (2017) – focused explicitly on the application of digital simulation to yacht performance analysis. Although valuable, these contributions were confined to technical performance modelling and did not engage with broader industrial or organisational implications of digitalisation. This narrow scope highlights the embryonic state of digital maturity in the yacht sector at the time, characterised by isolated technological experiments rather than structured, systemic integration.

A slight shift is observable from 2022 onward, in the post-pandemic period, when a wave of research began addressing the role of digitalisation in nautical tourism. This second wave of scholarship moved beyond design and manufacturing concerns to explore how digital technologies support user experiences, operational optimisation, and sustainable business models. Studies in this period highlighted the emergence of digital business ecosystems capable of delivering joint value creation among stakeholders. These ecosystems facilitate not only efficient operations but also the generation of new service experiences, thereby aligning the digital transition with evolving consumer expectations. The integration of mobile platforms, interactive systems, and digital booking and support interfaces is no longer considered an optional enhancement but a strategic necessity in a competitive market landscape. These transformations have resulted in cost efficiencies, streamlined logistics, and improved customer service delivery, signalling a phase of functional maturity in the service dimension of yachting.

Simultaneously, digital innovation in the luxury yacht market is increasingly shaped by sustainability principles. The demand for reduced environmental impact has directed attention toward advanced monitoring and energy optimisation strategies, particularly within the hotel load segment of yachts. In response to these pressures, new frameworks leveraging artificial intelligence and digital twin technologies have emerged. As demonstrated in the recent work by Dini *et al.* (2024), a modular DT model has been developed, integrating sensor networks, smart energy management systems, and AI-driven automation of environmental controls such as HVAC, lighting, and window shading. This solution directly addresses the challenges posed by limited empirical datasets regarding onboard energy consumption and passenger behaviours. By simulating a wide range of operational scenarios, the system aims to identify optimal energy-saving strategies, thereby contributing to both ecological and economic objectives. This initiative reflects a growing convergence between design intelligence and operational data and suggests the beginning of a digital feedback loop capable of informing future design iterations through real-world performance analytics.

The maturity of digital frameworks in yachting was also be assessed through the lens of industrial insight. To this end, an environmental scanning of the sector was conducted through two rounds of online surveys – first in spring 2018 and again in autumn 2024 – targeting key stakeholders in yacht design studios and shipyards. The first survey (2018) gathered 92 responses, divided between yacht design and naval architecture studios (n=42), and sailing and motor yacht shipyards (n=50). By 2024, a follow-up survey recorded 78 responses (27 from design studios, 51 from shipyards), reflecting a slightly reduced sample size for yacht design and naval architecture studios.

All surveys were conducted internationally, with responses covering a representative sample of the industry's geographical and typological diversity. Italian respondents were primarily drawn from yacht design studios (e.g., Hotlab, M2atelier, Micheletti Yacht Design) and shipyards producing semi-custom yachts across a range of sizes (e.g., Tecnorib, Sacs, Cranchi, Italia Yachts, Sanlorenzo, Benetti, Solaris). The Netherlands and Germany were represented exclusively by super- and megayacht builders such as Amels, Oceanco, and Feadship. At the same time, French responses came from mass-production sailing yacht manufacturers, including Beneteau, Jeanneau, and Dufour. Monaco and the United Kingdom were represented by designers in internationally established studios such as Silver Arrow, Espen Øino International, and Winch Design. Turkish and Greek respondents were primarily from the motor yacht refit and repair sector, with companies like Tecnohull, Karamaci Yachts, Parasiakuo Yacht Design, and Ors Yacht Design participating. Superyacht sailing yacht responses were more globally distributed, consistent with the unique internationalism of the segment, Finnish Swan and South African Southern Wind among them.

From a market segmentation perspective, 51% of all participants operate within the medium-sized yacht category (10 to 24 meters), while the remainder focus on superyachts (up to 45 meters) and megayachts (exceeding 45 meters, up to 100 meters). The market structure revealed a predominance of custom and semi-custom production models. Vessels under 24 meters are mainly delivered as semi-custom (32%) or in low series (34%), while larger vessels are mostly custom-built (53%) or entirely bespoke, one-of-a-kind designs (20%). This distribution has essential implications for digitalisation, as the scalability and reusability of digital workflows often correlate with production volume and standardisation levels.

The 2018 survey revealed a generalised immaturity in the adoption of digital solutions aligned with Industry 4.0 principles. Only eight shipyards reported experimenting with or implementing such technologies, and not a single design studio reported active engagement in ongoing 4.0-related projects. Merely two indicated that they were beginning to evaluate the potential benefits of digitalisation. Geographically, no substantial variation in adoption trends was recorded, confirming that the lag was systemic rather than localised. Critically, 97% of design studios and 70% of shipyards had not evaluated digitalisation opportunities in a systematic, organisation-wide manner, indicating both limited technological penetration and insufficient strategic vision.

By 2024, the landscape had shifted moderately but significantly. While 32% of respondents remained unfamiliar with digitalisation technologies, 49% were actively evaluating or experimenting with digital integration in their workflows, and 19% reported embedding some form of digital innovation into daily operations. The most common areas of implementation included additive manufacturing (used for prototyping and component fabrication), digital simulation and systems integration (particularly in product engineering), and VR/AR tools (primarily in the design and presentation stages). At the same time, collaborative robotics remained marginal, pointing to persistent integration challenges. Emerging technologies, such as the IIoT and big data analytics, were being piloted in two key domains: sailing test monitoring (17%) and manufacturing optimisation (11%). These figures suggest that while early adopters are expanding their digital toolsets, the general industry remains at an exploratory or transitional stage.

The design process itself remains an important indicator of digital maturity. In 2018, 63% of respondents reported using direct drawing and direct modelling tools as their primary design platforms, with negligible differentiation between studios and shipyards. Parametric software, enabling algorithmic geometry generation and seamless communication with digital fabrication tools, was used by only 25% of the sample. A mere 12% described an integrated design process that connected exterior and interior styling with structural simulation, performance analysis, and project management software. Importantly, parametric tools were more prevalent in shipyards, whereas design studios, particularly those involved in superstructure and interior design of large yachts, preferred traditional modelling methods. These patterns reflect deep-rooted disciplinary habits as well as differing demands on design fidelity and flexibility across vessel types.

Also in this matter, in 2024 some progression was recorded. The reliance on direct modelling tools had decreased to 47%, with the use of parametric software holding steady at 25%, and the proportion of respondents reporting integrated workflows – connecting design with engineering, analysis, and management – rose to 28%. This increase, although incremental, indicates a growing recognition of the value of interoperability and data continuity throughout the design, development, and production lifecycle.

Notably, a subset of survey respondents reported concrete progress in digital implementation, citing enhanced cross-departmental data sharing, adoption of cloud-based design collaboration platforms, and initial deployment of digital twin technologies for performance monitoring and predictive maintenance. Yet these advancements remain fragmented and context-dependent, with marked discrepancies in digital maturity across organisational types and yacht segments.

For the first time in 2024, survey participants were asked to evaluate the impact of digital technologies on sustainability. While 79% affirmed familiarity with eco-design principles, only a small subset had explicitly linked digitalisation to environmental strategy. Just six companies declared using digital tools to enable sustainability interventions. Their approaches included simulations and system integration for material selection, IoT and IIoT for manufacturing optimisation, and additive manufacturing for material usage reduction. Respondents were also asked to identify the lifecycle stages where digital technologies played the most significant role in driving sustainability. Optimisation of the initial lifespan, through enhanced durability and performance forecasting, was identified as the most influential (71% average agreement), while optimisation of end-of-life processes (such as recycling or disassembly planning) was largely underexplored, receiving only 8% of responses.

While the conceptual foundations of digital transformation are increasingly acknowledged across the sector, their operational integration remains uneven, often limited to discrete tools or isolated processes. Technological advancements – ranging from additive manufacturing to AI-driven simulation – are outpacing the industry's capacity to absorb them in an orchestrated and systemic manner. A pattern of selective adoption emerges: visualisation tools, rapid prototyping, and elementary system integration are embraced more readily, while technologies requiring cross-functional alignment or reconfiguration of existing workflows encounter greater resistance. This divergence between academic discourse, which increasingly promotes integrative frameworks for digital transformation, and the patchy real-world uptake captured in industry surveys, signals the transitional nature of the sector's digital maturity. On one side, the industry is gradually assembling a toolkit that includes AI, digital twins, simulation-based engineering, and IIoT-enabled monitoring systems. On the other, legacy organisational models, fragmented supply chains, and persistent digital skill gaps continue to obstruct systemic implementation. As a result, the digitalisation of the yachting sector cannot yet be characterised as mature in a comprehensive sense.

Rather, it constitutes a fragmented terrain of incremental experimentation and partial uptake, developing along multiple, often uncoordinated, trajectories.

The maturation of this digital framework remains contingent upon the industry's capacity to articulate shared strategies, enhance collaborative learning, and anchor innovation within both market demands and sustainability imperatives. Real progress will depend not solely on the availability of advanced technologies, but on a broader cultural shift; one that privileges interdisciplinary collaboration, embraces data-informed decision-making, and fosters long-term alignment between design innovation, environmental responsibility, and industrial scalability. The next sections will examine some best practices on the different technologies already explored in industrial or experimental projects in the last 10 years.

5. Case studies in yacht digital manufacturing and design

5.1 Connecting, Manufacturing, Intelligence, digitalizing

Building upon the academic framework introduced in the previous chapters, 27 best practices were identified and analysed across the four core technological families: *connecting*, *manufacturing*, *intelligence*, and *digitalizing*. These categories reflect not only functional distinctions but also the diverse ways in which digital technologies are beginning to shape the design, production, operation, and user experience of contemporary yachts.

The *connecting* family encompasses technologies that create a continuous data infrastructure across the yacht, its operational environment, and the broader service network. Central to this category is the IoE, which involves the deployment of distributed sensors and remote-control units on key yacht components, ranging from propulsion systems and navigation tools to onboard utilities. These technologies enable the acquisition, transmission, and analysis of real-time field data, supporting a range of critical functions: monitoring sailing and mooring operations, facilitating communication between the vessel, shipyards, and marinas, informing predictive and condition-based maintenance strategies, and collecting marine environmental data to support ecological awareness and compliance.

Complementing these onboard systems is Cloud Manufacturing, which represents a broader shift from static, location-bound production to a service-oriented model of distributed industrial capability. Through integrated cloud computing platforms, manufacturing resources – such as tooling, machine time, and design knowledge – can be shared across networks of partners, suppliers, and service providers. While still emerging within the yachting sector, such approaches are increasingly informed by cross-sectorial practices, particularly from the aerospace and automotive industries, where dynamic resource allocation and collaborative engineering have been shown to reduce lead times, improve traceability, and enhance supply chain resilience.

The *manufacturing* family is defined by digital technologies that reconfigure how yachts and their components are physically produced. A key area of innovation is AM, which, within the yachting domain, has been employed both for the rapid prototyping of design concepts and for the production of functional parts, including metal fixtures, hydraulic components, and aesthetic elements. Notable research and industrial experimentation are also underway in the development of full-scale 3D-printed yacht hulls, particularly within the high-performance recreational and military maritime segments. These advancements suggest a future in which design flexibility, material efficiency, and production speed converge to support bespoke, on-demand yacht fabrication.

Another increasingly relevant domain within this family is the use of collaborative robots, which are introduced to perform repetitive or ergonomically demanding tasks, such as sanding, component fitting, or composite layup. While their implementation in the nautical sector is still in the early phases, inspiration is being drawn from mature applications in terrestrial industries – particularly in automotive and motorcycle manufacturing – where collaborative robotics have been instrumental in improving workplace safety and production efficiency without displacing skilled labour.

The *intelligence* family includes the growing use of advanced computational tools to extract meaning from complex data environments and enhance decision-making processes across the yacht's lifecycle. One of the most significant developments in this area is the application of big data analytics. In high-performance sailing, these tools are used to model yacht behaviour under varying wind and sea conditions – optimising sail configurations, foil dynamics, and tactical routing. In commercial and recreational contexts, big data supports voyage planning, traffic management, predictive maintenance, and performance monitoring, drawing from extensive onboard sensor datasets to inform both operational and strategic decisions.

Closely linked to data analytics is the domain of simulation and system integration, which includes tools designed to merge digital design environments with production and lifecycle management (PLM) systems. While a number of experimental projects are attempting to integrate CAD platforms, PLM systems, and ERP (enterprise resource planning) tools into seamless workflows, the reality across many shipyards is still one of fragmented tools and siloed processes. Bridging this divide remains a core challenge for the sector, particularly in light of the increasing complexity of yacht systems and the demand for shorter development cycles.

Finally, the *digitalising* family addresses how digital tools are reshaping the human interface with yacht systems, both in design and in operation. VR/AR technologies have become particularly prominent in recent years, initially as marketing and configuration tools – allowing clients to explore design options and onboard layouts before construction begins virtually – but increasingly also as functional supports for crew training and maintenance inspections. By overlaying digital information on physical environments or creating immersive simulation experiences, these tools enhance spatial understanding, reduce errors, and facilitate faster onboarding of new personnel.

In parallel, developments in AHMI are expanding the modalities through which users interact with onboard systems. These include voice-controlled dashboards, gesture-based controls, tactile feedback devices, and wearable technologies that provide live system updates and environmental readings. Their primary functions include monitoring and managing yacht operations during sailing or mooring, as well as visualising marine environmental data in accessible formats. By prioritising intuitive design and responsive feedback, these interfaces are central to creating safer, more informed, and more user-friendly yachting experiences.

Here below, each best practice provides a concrete example of how Industry 4.0 principles are being implemented in real-world contexts, ranging from sensor-based monitoring systems and distributed manufacturing platforms to predictive analytics tools and immersive human-machine interfaces. Collectively, these 27 cases illustrate the sector's ongoing experimentation with digital innovation, revealing both domain-specific applications and emerging cross-technology synergies.

5.2 Twenty-seven best practices

The identification of the best practices for the case studies analysis was undertaken thanks to the consultation with stakeholders – academics, naval and nautical shipyards, and suppliers, yacht designers, nautical industrial associations – during the international boat-shows and yacht trades between 2017 and 2025. A number of 27 case studies were selected within the nautical, naval, and transportation sectors. Three reference criteria were used to identify good practice examples:

- products/technology/production systems already on the market or in industrial prototyping phases (at least TRL7);
- products/technology/production systems with digital / connected features;
- the established link across different digital technologies.

As well as these key criteria, consideration was made to ensure that the case study groups covered a range of maritime industries branches, digital technologies, and geographical locations.

The case study data was gathered in two stages. First, during the trade events, primary source observations were carried out, complemented by brief meetings with technology developers and company sales representatives. This was then followed by a second stage of desk research, where information was consolidated through the review of online documents.

The purpose of analysing these case studies was threefold: to explore the relationship between Industry 4.0 design principles and digital technologies; to assess the potential impact of digital technologies on yacht design and manufacturing; and, more broadly, to consider how these experiences might be scaled up to support scenario-building activities. Then, each best practice is presented and examined through a three-part profile: (I) brief description including project name, company or industrial cluster, and references; (II) enabling technologies, and sub-technologies applied in UX implementation, (III) impact on design and manufacturing, on communication media, assessed in relation to product and customer journey.

The following section provides a systematic presentation of the selected case studies. The profiles collectively demonstrate the transition from traditional, craft-based processes towards digitally integrated, data-driven systems that combine simulation, connectivity, automation, and immersive interaction. Through this analysis, it becomes possible to observe not only sectoral innovations but also the emergence of cross-cutting patterns that indicate how new technological paradigms may be consolidated and scaled across the marine sector. What emerges is an interconnected landscape in which technical innovation is closely tied to issues of safety, sustainability, and competitiveness. These best practices thus serve as reference points not only for understanding current transformations, but also for informing strategic scenario-building aimed at the future development of the sector.

YachtOnCloud

FAMILY:
CONNECTING

KEYWORDS:
SMART MONITORING/ CLOUD CONNECTIVITY/ IOT/YACHT SECURITY

References: https://yachtoncloud.it.
Company: Pixora S.r.l., Italy.
Year of Market Introduction: 2022.
Overview: YachtOnCloud is a cloud-based mobile application designed to centralise the monitoring and control of yachts, reflecting the broader move towards connected and data-driven marine solutions. The system provides owners with real-time information on vessel location, technical health, and onboard systems, all accessible via an intuitive smart app. Through continuous remote access, users can track operational parameters, anticipate maintenance needs, and ensure the vessel's readiness from any location. The platform embodies the principles of Industry 4.0 by integrating cloud services, data connectivity, and mobile accessibility, enabling greater transparency between owners, operators, and service providers. Introduced in 2022 by Pixora S.r.l. under the YachtOnCloud brand, the application enhances operational confidence, reduces the risks of unexpected failures, and creates opportunities for data-driven decision making in yacht management. Its emphasis on usability and interoperability also highlights its scalability as a tool not only for individual vessel oversight but also for supporting broader fleet management and future scenario planning within the yachting sector.
Enabling Technologies: IoT / IIoT, Big Data Analytics.
Sub-technologies for UX implementation: –
Impact on:

- Client-Design Communication: None.
- Yacht Design and Product Engineering: None.
- Design-Production Integration: None.
- Shipyard-Supplier Integration: None.
- Boat or Part Manufacturing: None.
- Sail Monitoring: Enables real-time monitoring of navigation, safety, and environmental conditions via remote data capture and cloud access.

Besenzoni Unit Control

FAMILY:
CONNECTING

KEYWORDS:
BLUETOOTH CONTROL/
SMART GANGWAY/
LADDERS/MOBILE APP

References: https://www.besenzoni.it/besenzoni-unit-control.
Company: Besenzoni S.p.A., Italy.
Year of Market Introduction: 2018.
Overview: The Besenzoni Unit Control (BUC) exemplifies the growing integration of smart technologies into the leisure marine sector by offering a digital solution for operating yacht boarding systems. Traditionally reliant on dedicated radio or infrared remotes, these systems could be restrictive in terms of convenience and accessibility. The BUC overcomes such limitations by enabling the management of gangways and ladders directly from smartphones or tablets via Bluetooth, through the free Besenzoni Control Device application. Once installed, the receiver can support up to eight registered devices, providing flexibility for both owners and crew, while a unique serial number ensures secure and reliable pairing. The mobile application replicates the full functionality of the original controller in a more accessible format, aligning with broader trends towards user-centred design and mobile integration.
A further strength of the BUC lies in its adaptability: it can be easily retrofitted onto existing Besenzoni systems as well as installed on new builds, extending its relevance across the yacht lifecycle. Importantly, the system is conceived as a complement rather than a replacement, with the traditional remote remaining active as a safety backup.
Enabling Technologies: IoT / IIoT, Big Data Analytics.
Sub-technologies for UX implementation: AHMI.
Impact on:

- Client-Design Communication: None.
- Yacht Design and Product Engineering: None.
- Design-Production Integration: None.
- Shipyard-Supplier Integration: None.
- Boat or Part Manufacturing: None.
- Sail Monitoring: Just a personal digital controller – no data analysis is performed. Enhances client usability and perception by offering no wiring, accessible, and flexible control methods. Improving interaction with onboard systems.

Volvo Easy Connect

FAMILY:
CONNECTING

KEYWORDS:
SMART MONITORING/
ENGINE DIAGNOSTICS/
ROUTE PLANNING/
MOBILE CONNECTIVITY

References: https://www.volvopenta.com/marine/accessories/easy-connect/.
Company: Volvo Penta, Sweden.
Year of Market Introduction: 2018 (first tests).
Overview: Volvo Penta Easy Connect is a digital interface system designed to enhance the boating experience by providing boat owners with seamless access to real-time vessel data through a smartphone or tablet. By connecting the boat's engine and onboard systems via Bluetooth® and Wi-Fi, Easy Connect offers insights into engine performance, fuel consumption, battery status, and navigation routes. The system allows users to monitor and track their journeys, plan future routes, and share experiences with others, while also facilitating proactive communication with Volvo Penta service centres. Diagnostic trouble codes can be shared with dealers in advance, helping prepare maintenance or repairs efficiently. Easy Connect is compatible with a broad range of Volvo Penta engines from 2003 onwards and can be installed easily via the engine's Electronic Vessel Control (EVC) system or harness on non-EVC gasoline engines. Through cloud-based integration, users can securely store and access historical performance data, making it possible to optimise engine operation, improve safety, and streamline maintenance planning.
Enabling Technologies: IoT / IIoT , Big Data Analytics.
Sub-technologies for UX implementation: AHMI.
Impact on:

- Client-Design Communication: None.
- Yacht Design and Product Engineering: None.
- Design-Production Integration: None.
- Shipyard-Supplier Integration: None.
- Boat or Part Manufacturing: None.
- Sail Monitoring: Platform based on a smartphone or tablet app. The system can receive data from a different onboard system. A set of alarms could be set according to personal needs. Data are transmitted seamlessly to the Volvo diagnostic center. Predicted maintenance is managed.

i-Captain

FAMILY:
CONNECTING

KEYWORDS:
BOAT MONITORING/ LIFECYCLE MANAGEMENT/ IOT/PREDICTIVE MAINTENANCE

References: https://www.i-captain.com.
Company: Holonix S.r.l., a spin-off of Politecnico di Milano, Italy.
Year of Market Introduction: 2016.
Overview: i-Captain is a personal Boat Lifecycle Management System developed by Holonix to digitalise and centralise boat ownership experience through IoT. Leveraging a compact onboard device known as the Marine Gateway, i-Captain captures real-time data – including position, acceleration, battery and engine status, and on/off signals from on-board equipment – transmitting this information to a cloud-based platform accessible via web or mobile interface. The system supports antitheft mechanisms, anchoring and geo-fencing alarms, automatic logbook creation, crash detection, and maintenance scheduling, collecting a comprehensive chronological record of both vessel operation and interventions. Originally conceived within the EU-funded BOMA (BOat MAnagement) project to support the digital transformation of small and medium-sized boat builders, i-Captain allows multiple stakeholders – including owners, shipyards, and insurers – to engage with a virtual vessel "avatar" for both monitoring and service planning purposes.
Enabling Technologies: IoT / IIoT, Big Data Analytics
Sub-technologies for UX implementation: AHMI
Impact on:

- Client-Design Communication: None.
- Yacht Design and Product Engineering: None.
- Design-Production Integration: None; however, data insights may inform future engineering improvements.
- Shipyard-Supplier Integration: None; however, sharing of lifecycle and usage data, enabling improved collaboration on maintenance and service.
- Boat or Part Manufacturing: None.
- Sail Monitoring: Enhances communication by providing owners with a comprehensive, real-time interface for interacting with their vessel's status and history. Primar objective: predicted maintenance.

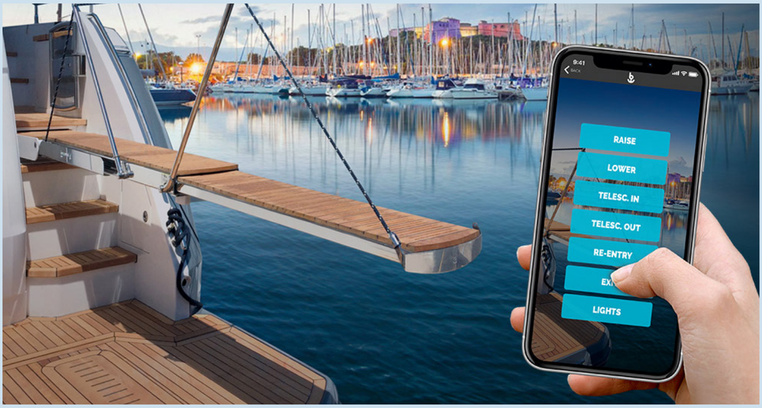


Figure 3.
Case study Besenzoni Unit Control.
Credits: Besenzoni S.p.A.

Figure 4.
EdgeLab Smart Buoys under testing in real-conditions.
Credits: EdgeLab S.p.A.

Figure 5.
Cyclop Marine load sensing technology for standing rigging.
Credits: Cyclop Marine Ltd.

FAMILY:
CONNECTING

KEYWORDS:
ENVIRONMENTAL MONITORING/ MARINE SENSORS/ AUTONOMOUS SYSTEMS/ REAL-TIME DATA/ SMART BUOYS

EdgeLab Smart Buoys

References: https://www.edgelab.eu.
Company: EdgeLab S.p.A., Italy.
Year of Market Introduction: 2021.
Overview: EdgeLab Smart Buoys represent an advanced platform for autonomous marine environmental monitoring, integrating robust sensor networks with real-time data acquisition and cloud-based analysis. Their modular architecture, combined with energy-efficient power systems – including solar panels and high-capacity batteries – ensures extended operational autonomy and minimal maintenance requirements. EdgeLab offers multiple configurations, including the Edge_Smart Buoy for general monitoring, the Edge_Ocean Buoy for high-stability oceanographic measurements, and the Edge_Environmental Buoy optimized for water quality assessment. These platforms complement other industry solutions, such as ReeCoTech Marine Buoys, which provide similar capabilities for monitoring environmental and meteorological conditions, highlighting a growing trend in smart buoy technologies for marine research, environmental management, and sustainable maritime operations. Data collected by EdgeLab systems supports research, predictive modeling, and informed decision-making for ecosystem protection and operational resilience.
Enabling Technologies: IoT / IIoT, Big Data Analytics.
Sub-technologies for UX implementation: –
Impact on:

- Client-Design Communication: None.
- Yacht Design and Product Engineering: None; however, data insights may inform future engineering improvements.
- Design-Production Integration: None.
- Shipyard-Supplier Integration: None.
- Boat or Part Manufacturing: None.
- Sail Monitoring: Data are crowdsourced and (potentially) used to establish a dense cloud of weather parameters close to coasts. Data crowdsourcing should support local weather prediction agencies and weather/climate scientists to improve their models with local data assimilation.

SCAIME FBG Sensors for Yacht Monitoring

FAMILY:
CONNECTING

KEYWORDS:
STRUCTURAL HEALTH MONITORING/ REAL-TIME DATA ACQUISITION/ MARINE SENSORS/ OPTICAL STRAIN SENSING

References: https://scaime.com/marine-and-offshore.
Company: SCAIME sas, France.
Year of Market Introduction: 2021 (on IMOCA IC Foil).
Overview: SCAIME's Fiber Bragg Grating (FBG) sensors are advanced optical sensors designed to measure strain, deformation, and temperature in structures with high precision and reliability. FBG sensors exploit the property of light reflection in optical fibers, enabling robust, electromagnetic-interference-free, and corrosion-resistant monitoring. In the specific case of the IMOCA-class racing yacht Initiatives-Cœur, FBG sensors were embedded within the foils to monitor their structural performance during high-speed offshore navigation. The system consists of two optical sensor lines, each integrating strain gauges and temperature sensors. The data collected is transmitted to an optical interrogator, which converts the optical signals into digital information. This information is then processed and visualized through the onboard navigation system, allowing real-time monitoring of foil deformation and temperature variations.
This integrated monitoring approach enables both immediate operational feedback for the skipper and post-race analysis for engineers and designers.
Enabling Technologies: IoT / IIoT, Big Data Analytics.
Sub-technologies for UX implementation: Simulation and System Integration.
Impact on:

- Client-Design Communication: None.
- Yacht Design and Product Engineering: Data could improve designer datasets for better design and engineering. Several high performance shipyards already use these sensors both in production and in the monitoring/sailing stages.
- Design-Production Integration: None.
- Shipyard-Supplier Integration: None.
- Boat or Part Manufacturing: None.
- Sail Monitoring: Directly benefits from real-time performance tracking of yachts part under load.

Cyclops Marine

FAMILY:
CONNECTING

KEYWORDS:
WIRELESS LOAD SENSORS/
RIG LOAD MONITORING/
FATIGUE MONITORING/
REAL-TIME DATA/
PERFORMANCE ANALYTICS

References: https://www.cyclopsmarine.com.
Company: Cyclops Marine Ltd, UK.
Year of Market Introduction: 2018 (first products), 2023 (full range).
Overview: Cyclops Marine has developed a suite of wireless load-sensing devices designed specifically for sailing yachts, enabling real-time, high-fidelity measurement of rigging loads during sailing operations. These compact sensors can be seamlessly integrated into critical points of the rig (such as halyards, sheets, forestays, and battens), transmitting accurate load data via Bluetooth or proprietary gateways to onboard displays and mobile applications. The sensors also feature embedded fatigue monitoring, capturing cumulative load cycles to inform maintenance schedules more effectively than traditional time- or mileage-based methods.
The integration of Cyclops systems with marine electronics platforms – most notably through the Raymarine LightHouse 3.16 software update – has extended accessibility of load data to mainstream sailors, facilitating real-time display of static and dynamic loads directly on Axiom® multifunction displays. Further, compatibility with Sailmon MAX showcases Cyclops data within broader performance analytics ecosystems, reaffirming its role in democratizing advanced load data for both competitive and leisure sailors.
Enabling Technologies: IoT / IIoT, Big Data Analytics.
Sub-technologies for UX implementation: AHMI.
Impact on:

- Client-Design Communication: None.
- Yacht Design and Product Engineering: Not yet. However, real-time data could improve designer datasets for better design and engineering.
- Design-Production Integration: None.
- Shipyard-Supplier Integration: None.
- Boat or Part Manufacturing: None.
- Sail Monitoring: Monitoring of rig tension, sail batten loads, and responsive tuning during sailing to enhance sail control/ safety.

360° Virtual Yachts

FAMILY:
DIGITALISING

KEYWORDS:
VIRTUAL TOURS/AR/
CLIENT ENGAGEMENT

References: http://360virtualyachts.com.
Company: 360VY, The Netherland.
Year of Market Introduction: 2017.
Overview: 360 Virtual Yacht is a platform designed to present your superyacht (alerady built) in a unique Virtual Reality View. It is accessible to everyone with a smartphone just placing the smartphone in the VR Goggles and stepping into the experience through a internet URL. The platform uses authentic 360 photos instead of 3D renders and adding hotspots with interactive content to provide information on specific furniture, materials, technology or other notable features of your yacht. A Technical Timeline, an interactive map of the yacht in different time phases according to the different building phases of the yacht, allows onwner and crew to accurately visualize where the frame, isolation, piping and wiring are during maintenance needs. All the Virtual Tours and Technical Timelines are available in Virtual Reality for a unique experience. By simply entering the specific URL in a smartphone's web browser, the Virtual Tour immediately launch without downloading anything.
Enabling Technologies: AR/VR, Simulation and system integration.
Sub-technologies for UX implementation: AHMI.
Impact on:

- Client-Design Communication: Accessible to everyone with a smartphone, it allows an immersive onboard experience. It is also used in maintenance and technical service thanks to the Technical timeline feature. It could be implemented in the communication shipyard-supply chain.
- Yacht Design and Product Engineering: None.
- Design-Production Integration: None.
- Shipyard-Supplier Integration: None.
- Boat or Part Manufacturing: None.
- Sail Monitoring: None.

AC Sailing

FAMILY:
DIGITALISING

KEYWORDS:
ESAILING/
VIRTUAL RACING/
SIMULATION

References: https://www.acsailing.com.
Company: Emirates Team New Zealand, New Zealand.
Year of Market Introduction: 2024.
Overview: AC Sailing is the official sailing simulation game of the 37th America's Cup, developed by Emirates Team New Zealand. Launched in April 2024, the game offers an ultra-realistic experience of high-speed foiling yacht racing, utilizing the same simulation technology employed by America's Cup teams. Players can take the helm of AC40 yachts, racing in iconic venues such as Barcelona, and compete against others in online multiplayer modes or practice solo to refine their skills. The game features ranked matches, leaderboards, and a sailing school to aid both beginners and seasoned sailors in mastering the art of foiling and maneuvering. AC Sailing also serves as the platform for the America's Cup E-Series, an esports league that brings the excitement of virtual yacht racing to a global audience. The inaugural season of the E-Series culminated in a groundbreaking "Gamer to Sailor" race, where the top two virtual sailors raced against a real-world America's Cup team, demonstrating the game's authenticity and the transferable skills between virtual and real-world sailing.
Enabling Technologies: AR/VR, Simulation and system integration.
Sub-technologies for UX implementation: AHMI, AR/VR.
Impact on:

- Client-Design Communication: Facilitates engagement. Able to predict sail performance and to virtually test the behaviors of the yacht. Nowadays it is not connected with real data (weather forecasting or on-board sensors).
- Yacht Design and Product Engineering: None.
- Design-Production Integration: None.
- Shipyard-Supplier Integration: None.
- Boat or Part Manufacturing: None.
- Sail Monitoring: None.

VR4YD (Virtual Reality for Yacht Design)

References: https://caputistudio.com.
Company: Caputistudi, Italy, in partnership with Oniride.
Year of Market Introduction: 2016.
Overview: VR4YD embodies an advanced application of virtual reality within yacht design, functioning as an immersive platform that extends the concept of Digital Mock-Up (DMU) to enable thorough evaluation and communication of vessel geometries, spatial configurations, and design intent. Born from a collaboration between Caputistudio and Oniride, VR4YD offers a refined design visualization environment wherein stakeholders – including architects, naval engineers, clients, and shipyards – can experience yacht interiors and exteriors in an immersive, interactive context. Utilising CAD-based solid models, VR4YD supports simultaneous architecture (SA), facilitating real-time navigable walkthroughs and enabling users to explore layout, scale, and materiality with unmatched clarity. The first application of this technology was the EUR 43, a 43 metre yacht designed for the under-500 GT segment. In this pilot, VR4YD allowed preview of architectural space and aesthetic detailing. Beyond aesthetic immersion, VR4YD contributes to improved design control, client approval processes, and iterative feedback, reducing reliance on physical mock-ups.
Enabling Technologies: AR/VR.
Sub-technologies for UX implementation: AHMI.
Impact on:

- Client-Design Communication: It allows an immersive onboard experience. Clients could personalize their boats using a pre-defined set of chooses. Not for fully custom boat.
- Yacht Design and Product Engineering: Visualization purpose, only. It is not connected with parametric design and with project management software.
- Design-Production Integration: None.
- Shipyard-Supplier Integration: None.
- Boat or Part Manufacturing: None.
- Sail Monitoring: None.

FAMILY:
DIGITALISING

KEYWORDS:
VIRTUAL REALITY/ YACHT DESIGN DIGITAL MOCK-UP/ IMMERSIVE VISUALIZATION

Figure 6.
AC Sailing simulation game platform.
Credits: AC Sailing Epic games.

Figure 7.
VR4YD interacting scenario.
Credits: Caputi studio.

Figure 8.
OPTIP Ololens technology for smart shipbuilding and maintenance operations.
Credits: Predict S.p.A.

OPTIP Holoassistance

FAMILY:
DIGITALISING

KEYWORDS:
AUGMENTED REALITY/
REMOTE ASSISTANCE/
MIXED REALITY/
HOLOLENS/
YACHT MAINTENANCE

References: https://www.optip.it.
Company: Predict S.p.A., Italy.
Year of Market Introduction: 2021.
Overview: OPTIP Holoassistance represents a refined application of mixed reality technology aboard superyachts, facilitating remote technical assistance, immersive training, and virtual prototyping. Deployed through Microsoft Hololens, OPTIP uses advanced optical projection and environmental mapping to overlay real-time 3D holograms directly within the user's field of view. This capability allows onboard operators to receive step-by-step guidance from shore-based technical specialists – complete with schematics, video tutorials, manuals, and dynamic visual cues such as arrows and overlays – without the need for physical presence.The first prototype was installed on Cantiere delle Marche vessels (MY Crowbridge and MY Aurelia) to empowers remote crew training, targeted inspections and refit planning by visualizing internal systems (e.g. piping and cable routes) hidden behind furnitures and finishes. Furthermore, owners benefit from an immersive customer experience, with virtual walkthroughs of construction progress, interior layout visualization in 3D, and lighting mood previews.
Enabling Technologies: AR/VR.
Sub-technologies for UX implementation: AHMI.
Impact on:

- Client-Design Communication: Immersive onboard experience. Clients can experience virtual walkthroughs and furniture layouts interactively during build stages.
- Yacht Design and Product Engineering: visualization purpose.
- Design-Production Integration: None; however, it could have potential use in communication.
- Shipyard-Supplier Integration: None.
- Boat or Part Manufacturing: Use of Hololens hardware for overlaying spatially anchored 3D content within the physical environment could help in shipbuilding operations.
- Sail Monitoring: None.

Ramlab WAAMpeller

FAMILY:
MANUFACTURING

KEYWORDS:
3D PRINTING/
SHIP PROPELLER/
ADDITIVE
MANUFACTURING

References: https://www.ramlab.com.

Company: RAMLAB (Rotterdam Additive Manufacturing LAB), The Netherland, in collaboration with Valk Welding, Damen Shipyards Group, Promarin, Autodesk, and Bureau Veritas.

Year of Market Introduction: 2017.

Overview: The WAAMpeller project represents a pioneering application of additive manufacturing in the maritime sector. Using Wire Arc Additive Manufacturing (WAAM), RAMLAB successfully produced the world's first 3D-printed ship propeller, demonstrating both the feasibility and advantages of large-scale metal additive manufacturing. The WAAMpeller was installed on a Damen tugboat, providing real-world validation of the process under operational conditions. The project highlights key benefits of additive manufacturing, including reduced lead times, on-demand production, and the potential to create complex geometries that are difficult to achieve with conventional casting. Beyond its immediate technical success, the WAAMpeller exemplifies the potential to reshape supply chains by localising production and enabling rapid, flexible responses to maintenance and repair.

Enabling Technologies: AM.

Sub-technologies for UX implementation: Co-robots.

Impact on:

- Client-Design Communication: None.
- Yacht Design and Product Engineering: Design for additive manufacturing. Topology optimization for lightweight additive production.
- Design-Production Integration: Streamlined the transition from design to production by reducing the need for traditional tooling and allowing for rapid prototyping and iteration.
- Shipyard-Supplier Integration: None.
- Boat or Part Manufacturing: Additive manufacturing in BAAM with robotic arms enables the production of complex parts with reduced lead times and material usage.
- Sail Monitoring: None.

Green Ship of the Future

References: https://greenship.org/.
Company: Create it REAL, Denmark, in collaboration with the Green Ship of the Future consortium.
Year of Market Introduction: 2017 (pilot project lunch).
Overview: The Green Ship of the Future's on-board 3D printing pilot, led by Create it REAL, marks a notable milestone in maritime additive manufacturing: the secured, on-demand production of spare parts aboard ships. This initiative responds to the logistical, environmental, and cost challenges of delivering parts to vessels at sea – often via costly helicopter or boat dispatch – by enabling fabrication at point of need. Crucially, Create it REAL's platform integrates a real-time processor into standard FDM or SLA 3D printers, enabling high-speed printing (up to five times faster than typical FDM) alongside end-to-end file encryption. Users aboard vessels can print parts without accessing or exposing intellectual property – files are decrypted securely within the printer, protecting design rights consistent with streaming models akin to encrypted music platforms.
Enabling Technologies: AM.
Sub-technologies for UX implementation: Cloud Manufacturing.
Impact on:

- Client-Design Communication: None.
- Yacht Design and Product Engineering: Design for additive manufacturing. Topology optimization for lightweight additive production. Possibility to couple with 3D scan for (broken-damaged) component replacing or on-board maintenance. Technical office on demand: decentralization of design expertise.
- Design-Production Integration: Design engineering takes into account the logic of production. A shared library between different companies (ships).
- Shipyard-Supplier Integration: None.
- Boat or Part Manufacturing: Additive/digital manufacturing and rapid prototyping.
- Sail Monitoring: None.

FAMILY:
MANUFACTURING

KEYWORDS:
ON-BOARD 3D PRINTING/ ADDITIVE MANUFACTURING/ SPARE-PARTS LOGISTICS

Mambo

FAMILY:
MANUFACTURING

KEYWORDS:
ADDITIVE MANUFACTURING/ ROBOTIC 3D PRINTING/ 3D CONTINUOS FILAMENT FIBERGLASS

References: https://www.moicomposites.com.
Company: Moi Composites, Italy, in collaboration with KUKA Robotics, UK.
Year of Market Introduction: 2020.
Overview: MAMBO represents a pioneering advancement in the field of boatbuilding, being the first continous filament fiberglass boat produced entirely through robotic 3D printing. The project aimed to explore the potential of additive manufacturing in creating lightweight, complex geometries that traditional boatbuilding methods cannot easily achieve. The boat measures 6.5 meters in length, 2.5 meters in width, and weighs approximately 800 kilograms. Its construction utilized KUKA's KR QUANTEC robots, which employed a patented Continuous Fiber Manufacturing (CFM) process developed by Moi Composites. This process involves the deposition of continuous fiberglass filaments impregnated with thermosetting resin, layer by layer, to build up the boat's structure. Production was carried out across two sites: the first half of the boat was printed at Autodesk's facility in Birmingham, UK, while the second half was printed at Moi Composites' workshop in Milan, Italy. The use of cloud-based monitoring allowed the teams to coordinate and oversee the printing process remotely.
Enabling Technologies: AM.
Sub-technologies for UX implementation: Simulation and System Integration.
Impact on:

- Client-Design Communication: None.
- Yacht Design and Product Engineering: Freeform design. Topology optimization for production.
- Design-Production Integration: Design engineering takes into account the logic of production.
- Shipyard-Supplier Integration: None.
- Boat or Part Manufacturing: Direct impact by introducing a new method of manufacturing boat hulls and components, potentially reducing material waste and production time.
- Sail Monitoring: None.

GEBE2 Smart Co-robot for Composite Sanding

FAMILY:
MANUFACTURING

KEYWORDS:
ROBOTIC SANDING/
COMPOSITE MATERIALS
SURFACE FINISHING/
CAD-CAM
PROGRAMMING

References: https://gebe2-et.com/.
Company: GEBE2, France.
Year of Market Introduction: 2023 (Smart Co-robots).
Overview: GEBE2 has developed a robotic sanding solution that reproduces the operator's gestures and sensitivity. The central element, the effector, is equipped with a random orbital electric sander and a compliant de- vice that applies a constant force in all directions, to the nearest N. The robots are equiped with automatic disc changers for using a range of grain sizes. GEBE2 provides also a custom-engineered CAD/CAM software for robotic sanding that programs trajectories in hidden time based on the CAD file of the part. The graphic display of material removal guides the programmer and helps him obtain a smooth surface. In working on refitting boat, the sanding robot can be semi-automatic programmed in order to sand the shell by windowing. The operator only needs to learn the 4 points that delimit the work area, after which the robot automatically calculates its trajectories whatever the shape of the part. Furthermore, GEBE2 provides custom-engineered CAD/CAM software for robotic sanding that programs trajectories in hidden time based on the CAD file of the part. The graphic display of material removal guides the programmer and helps him obtain a smooth surface. AHMI interface (such as virtual reality goggle and personal tablet) are used to manage/verify the robot path during the manufacturing stage.
Enabling Technologies: Co-robots.
Sub-technologies for UX implementation: Simulation and System Integration, IoT/IIoT, VR/AR.
Impact on:

- Client-Design Communication: None.
- Yacht Design and Product Engineering: None.
- Design-Production Integration: None.
- Shipyard-Supplier Integration: None.
- Boat or Part Manufacturing: Robotic-assisted manufacturing in a collaborative environment (no fences or alarms setting).
- Sail Monitoring: None.

Kleven Shipyard Welding Corobot

<u>FAMILY:</u>
MANUFACTURING

<u>KEYWORDS:</u>
AUTOMATIC WELDING/
CO-ROBOTS/
METAL VESSEL
PRODUCTION

References: https://en.greenyard.no.

Company: Greenyard Kleven, Norway.

Year of Market Introduction: 2015.

Overview: The Norwegian shipyard Kleven, specialized in commercial boats and work-boats, launched in 2015 and 2018 the two 116m explorer superyachts Ulysses. The Hull construction was made by two collaborative welding robots. The cobots were directly controlled by the design softwar, interacting with the operator and modifying their welding paths according to the components and workers positions. The main factor influencing quality of robotic operation in the shipbuilding industry is the consistency. The collaborative welding robot always performed the operation exactly as programmed. They improved the quality of the welding seems, and reduce the use of welding wire, which then reduces the overall weight of the construction. Kleven reports as much as 80-90% reduction in welding wire consumption, as well as 10% deformation compared to conventional welding. This consistent quality can also affect the throughput time at the yard. Rework to adjust for heat distortions is part of the problem, and can be eliminated by use of automation technology with modern welding equipment. The use of welding robots also enables thinner plating on the steel structure, below 10 mm. According to Kleven yacht, is possible to reduce up to 70% the planting thickness, as most of the plates are not a load-carrying element.

Enabling Technologies: Co-robots.

Sub-technologies for UX implementation: Simulation and System Integration.

Impact on:

- Client-Design Communication: None.
- Yacht Design and Product Engineering: Parametric design. Design engineering considers the logic of robotic production.
- Design-Production Integration: None.
- Shipyard-Supplier Integration: None.
- Boat or Part Manufacturing: Robotic-assisted manufacturing in a collaborative environment (no fences or alarms setting).
- Sail Monitoring: None.

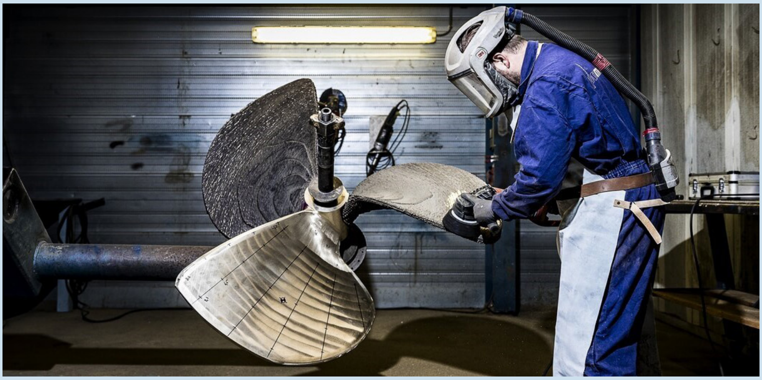


Figure 9.
RAMLAB WAAMpeller during finishing stage. Credits: RAMLAB.

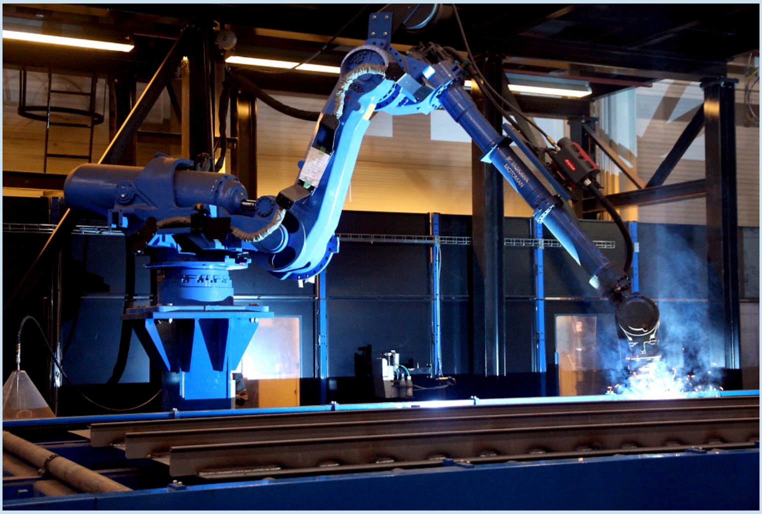


Figure 10.
Klevenwelding robot. Credits: Superyacht Technlogy Hub.

Figure 11.
3D printed Mini 650 Sailingboat portion by Nugæ. Credits: *Il giornale della Vela*.

Nugæ 3D-Printed NUDGE

<u>FAMILY:</u>
MANUFACTURING

<u>KEYWORDS:</u>
LARGE-FORMAT 3D PRINTING/ COMPOSITE THERMOPLASTICS/ ONE-OFF MARINE PARTS/ ROBOTIC ADDITIVE MANUFACTURING

References: https://www.nugae.tech/en/.

Company: Nugæ, Italy.

Year of Market Introduction: 2023 (previously Ocore).

Overview: Nugæ has developed a cutting-edge robotic 3D printing system capable of fabricating large-scale composite thermoplastic components with up to 80% weight reduction compared to conventional methods, 20% greater resistance to marine environments, and approximately five times faster production turnaround. The process includes the use of parametric and generative design to supports complex, performance-optimised 3d printed geometries. Thes allows to dramatically reducing material use, highlighting advancements in sustainability and structural efficiency. The printing system is mounted on anthropomorphic robots and comprises integrated hardware and software for extrusion control, slicing, and real-time monitoring. One illustrative case is a one-off stern hatch for a 13 m sailing vessel: printed in five modular, structurally reinforced sections with internal grid infill, achieving perfect fit, stiffness, and compatibility with lamination and finishing processes.

Enabling Technologies: Co-robots, AM.

Sub-technologies for UX implementation: Simulation and System Integration.

Impact on:

- Client-Design Communication: None; however it allows flexible customization.
- Yacht Design and Product Engineering: Enables close collaboration through rapid prototyping, modular design validation, and iterative fit adjustments.
- Design-Production Integration: Streamlines the transition from CAD to physical part, eliminating mould constraints.
- Shipyard-Supplier Integration: None.
- Boat or Part Manufacturing: Large Robotic-assisted AM.
- Sail Monitoring: None.

Xometry

References: www.xometry.com.
Company: Xometry, USA.
Year of Market Introduction: 2014.
Overview: Xometry is an on-demand manufacturing platform that enables companies to leverage digital technologies for rapid production and distributed manufacturing. The network provides faster lead times, competitive pricing, and a significantly expanded capacity and range of capabilities compared to traditional manufacturing approaches. In 2018, Xometry strengthened its position in the manufacturing-on-demand sector through the acquisition of MakeTime, another leading platform, thereby creating the largest partner network in the industry. This extensive network supports both customer demands and the business development of local machine shops and manufacturing facilities. The combined Xometry + MakeTime portfolio includes advanced manufacturing processes such as CNC machining, sheet metal fabrication, Direct Metal Laser Sintering (DMLS), Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), PolyJet 3D printing, urethane casting, and injection molding.
Enabling Technologies: Co-robots, AM, Cloud Manufacturing.
Sub-technologies for UX implementation: Simulation and System Integration.
Impact on:

- Client-Design Communication: None.
- Yacht Design and Product Engineering: The engineering phases are guided by the parametric/generative design software embedded in the web platform.
- Design-Production Integration: Design engineering takes into account the logic of production.
- Shipyard-Supplier Integration: on-demand manufacturing platforms for sharing digital technologies. Unified web platform for design engineering and project management.
- Boat or Part Manufacturing: Additive /digital manufacturing shared within a community of suppliers/yards.
- Sail Monitoring: None.

<u>FAMILY:</u>
MANUFACTURING

<u>KEYWORDS:</u>
3D PRINTING/
CLOUD
MANUFACTURING/
SHARED TECHNOLOGY/
SERVICE ORIENTATION/
CUSTOMIZATION

Autodesk SSI - ship constructor

FAMILY:
INTELLIGENCE

KEYWORDS:
SHIPBUILDING SOFTWARE/
3D MODELLING/
PRODUCTION ENGINEERING/
CAD-BASED DESIGN

References: https://www.ssi-corporate.com.
Company: SSI (ShipConstructor Software Inc.), Canada.
Year of Market Introduction: 1990 (as Albacore Research Ltd.) – 2015.
Overview: ShipConstructor, developed by SSI, is a specialised CAD/CAM software suite designed for the shipbuilding industry, providing a comprehensive environment that integrates design, engineering, and production. First introduced in 1990 and continuously developed, the platform leverages the AutoCAD environment to support the creation of intelligent 3D models encompassing structural components, piping, electrical, and HVAC systems. These models form the basis for coordinated workflows that extend across the entire vessel lifecycle, from concept design through detailed engineering to construction and maintenance. Key features such as clash detection, user-defined attributes, and integration with Product Lifecycle Management (PLM) systems enhance accuracy, traceability, and collaboration among design teams, shipyards, and suppliers.
Enabling Technologies: Simulation and system integration.
Sub-technologies for UX implementation: –
Impact on:

- Client-Design Communication: None.
- Yacht Design and Product Engineering: Parametric design for engineering and nava architecture optimization.
- Design-Production Integration: Facilitated seamless integration between design and production phases.
- Shipyard-Supplier Integration: Improved coordination with suppliers through standardized data formats and real-time updates, ensuring timely delivery of materials and components.
- Boat or Part Manufacturing: None.
- Sail Monitoring: None.

Cost fact

References: https://costfact.com.
Company: COSTFACT GmbH, Germany.
Year of Market Introduction: 2003 (first esperimenting) – 2018.
Overview: CostFact is a specialised cost management software suite designed explicitly for the shipbuilding industry, supporting comprehensive cost planning from the earliest tender phases through detailed engineering and lifecycle scrutiny. The system enhances efficiency, speed, and accuracy in cost estimation by employing a three-step approach that combines top-down and bottom-up planning, parametric and regression-based forecasting, integrated data input, and multi-user collaboration. Moreover, CostFact supports advanced cost controlling through risk analysis and life-cycle cost modelling, enabling users not only to forecast costs but also to evaluate in-service operational expenditures and compare technical alternatives using actual cash values and sensitivity analyses. Having been deployed by major industry players – including Ferretti Group and Blohm+Voss – the software remains a standard tool in maritime cost engineering, celebrated for delivering consistent transparency and enabling rapid, reliable quotations with end-to-end traceability.
Enabling Technologies: Simulation and system integration, Big Data Analitics.
Sub-technologies for UX implementation: –
Impact on:

- Client-Design Communication: None.
- Yacht Design and Product Engineering: Indirect influence; by supplying cost insights early in the design process, enables engineering decisions to be better informed by financial feasibility.
- Design-Production Integration: A unique platform for shipyard and supply chain management used to support the design stage (also).
- Shipyard-Supplier Integration: Supports smoother collaboration by consolidating cost data across stakeholders.
- Boat or Part Manufacturing: None.
- Sail Monitoring: None.

FAMILY:
INTELLIGENCE

KEYWORDS:
COST ESTIMATION/
SHIPBUILDING
LIFECYCLE/
RISK ANALYSIS

FAMILY:
INTELLIGENCE

KEYWORDS:
MARITIME INTELLIGENCE/ VESSEL MONITORING/ VOYAGE OPTIMIZATION/ EMISSIONS REPORTING/ FLEET MANAGEMENT

Podium Platform

References: https://www.polestarglobal.com/podium-platform.
Company: Pole Star Global, Hong Kong.
Year of Market Introduction: 2024.
Overview: Podium consolidates a wide array of maritime data streams – including AIS tracking, satellite communications, and proprietary onboard sensors – into a single, coherent, and user-friendly interface. This integration allows operators, charterers, and maritime authorities to access real-time vessel positions, voyage performance metrics, and environmental monitoring data with unprecedented accuracy. Beyond basic vessel tracking, Podium provides AI-driven voyage optimization, predictive maintenance insights, and detailed emissions reporting in line with international regulations such as IMO's MARPOL Annex VI. The platform supports advanced analytics, enabling users to evaluate operational efficiency, reduce fuel consumption, and anticipate potential delays or hazards. Podium is designed with scalability and interoperability in mind, supporting integration with existing shipboard systems and third-party applications to enhance decision-making across the entire supply chain. By providing continuous data visibility, the platform facilitates collaboration among stakeholders, promotes proactive risk management, and supports sustainable operational strategies.
Enabling Technologies: IoT / IIoT, Simulation and system integration, Big Data Analitics.
Sub-technologies for UX implementation: –
Impact on:

- Client-Design Communication: None.
- Yacht Design and Product Engineering: None.
- Design-Production Integration: None.
- Shipyard-Supplier Integration: None.
- Boat or Part Manufacturing: None.
- Sail Monitoring: Collection of near-real-time data on vessel location and movement to monitor vessel performance, emission and safety. Possibility to use for remote and automated routing (self-driving/autonomous shipping tests).

SIMULIA Marine & Offshore Solutions

FAMILY:
INTELLIGENCE

KEYWORDS:
MARINE SIMULATION/ MULTIPHYSICS SIMULATION/ STRUCTURAL ANALYSIS/ FLUID-STRUCTURE INTERACTION/CFD

References: https://www.3ds.com/products/simulia/marine-offshore.
Company: Dassault Systèmes, France.
Year of Market Introduction: 2019.
Overview: SIMULIA Marine & Offshore Solutions, developed by Dassault Systèmes, provide a comprehensive suite of simulation tools specifically tailored to the design, analysis, and optimization of marine vessels and offshore structures. By integrating multiphysics simulation capabilities it enables engineers to evaluate complex interactions between hydrodynamic forces, structural stresses, and onboard systems under realistic operational conditions. The platform allows for detailed FEA and CFD simulations, supporting the assessment of hull performance, structural integrity, vibration, fatigue, and fluid-structure interactions. Its advanced simulation environment supports performance optimization, risk assessment, and design innovation, enabling naval architects and marine engineers to refine vessel concepts, enhance hydrodynamic efficiency, and predict system behaviour under diverse environmental and operational scenarios.
Enabling Technologies: Simulation and system integration, Big Data Analitics.
Sub-technologies for UX implementation: –
Impact on:

- Client-Design Communication: Real time visualization of predicted performance.
- Yacht Design and Product Engineering: Significantly impacting by enabling virtual testing of various design scenarios, leading to optimized performance and reduced design cycles.
- Design-Production Integration: None.
- Shipyard-Supplier Integration: None.
- Boat or Part Manufacturing: None.
- Sail Monitoring: None.

K-IMS

FAMILY:
INTELLIGENCE

KEYWORDS:
MARITIME DATA INTEGRATION/
FLEET MONITORING/
CYBERSECURITY/
ONBOARD-ONSHORE SYNCHRONISATION

References: https://www.kongsberg.com/maritime.
Company: Kongsberg Maritime, Norway.
Year of Market Introduction: 2014.
Overview: The KONGSBERG Information Management System (K-IMS) is a collaboration platform developed for the offshore and maritime industry. K-IMS is designed to enable continuous access to data both onboard and onshore through an interactive web-based solution and to provide an efficient information flow. The main purpose of the system is to share data and information between users and systems involved in offshore and onshore vessel operations. Information is collected from multiple sources and presented to multiple users via a secure infrastructure and a web-based portal. The solution solves the increasing challenge of connecting fleet owner and sub-supplier on vessel and route data recording and management with a single communication infrastructure. The system unites all data logging and communication into a single, secure and maintainable solution. It gives the fleet owner control of the information flow and security. A common solution for all roles in owner and 3rd party supplier organization enables collaboration and improved decision processes.
Enabling Technologies: IoT / IIoT, Big Data Analitics.
Sub-technologies for UX implementation: Simulation and system integration.
Impact on:

- Client-Design Communication: None.
- Yacht Design and Product Engineering: None.
- Design-Production Integration: None.
- Shipyard-Supplier Integration: None.
- Boat or Part Manufacturing: None.
- Sail Monitoring: Collection of near-real-time data on vessel operation to monitor shipping operations and ship status/ maintenance. Collaborative tools. It allows companies to optimize fuel consumption and routing according to real-time sea and weather conditions. In the future, the possibility to use for remote and automated routing.

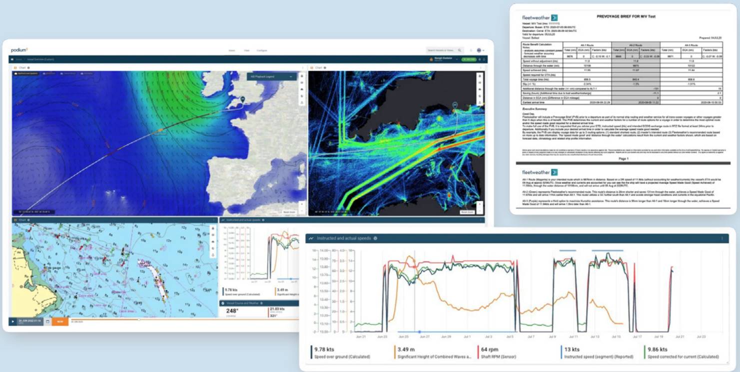


Figure 12.
Podium Platform user interface.
Credits: Pole Star Global.

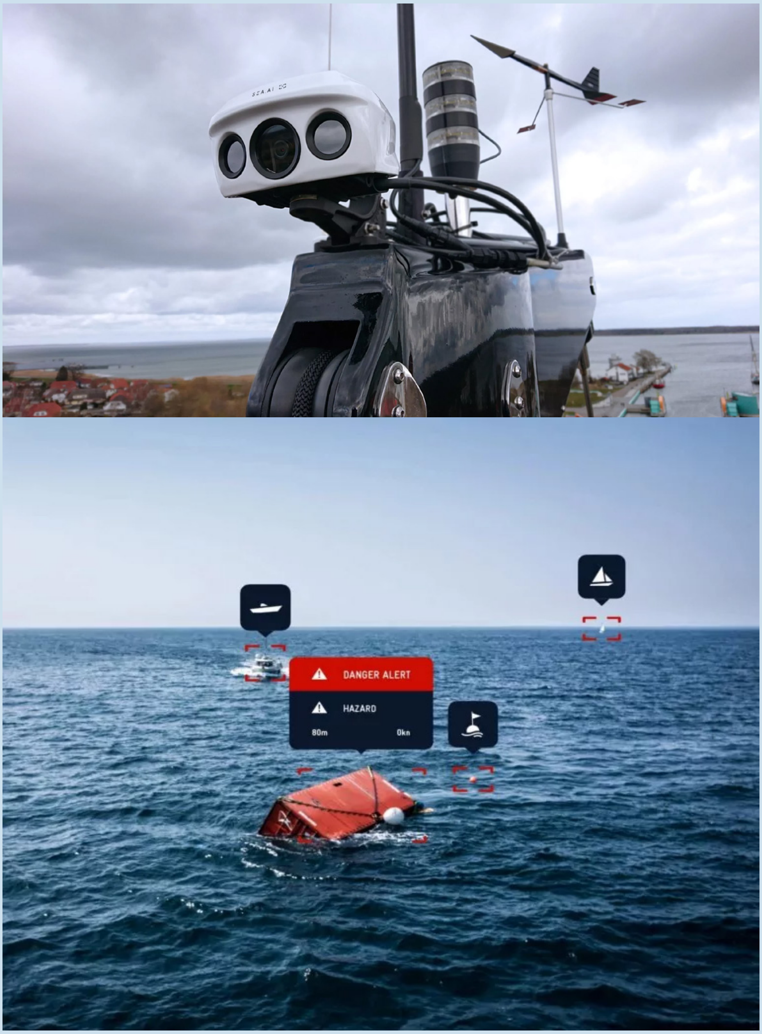


Figure 13.
SEA.AI equipment at the top of a racing sailingboat, and its reported images in AR.
Credits: SEA.AI.

SEA.AI

FAMILY:
INTELLIGENCE

KEYWORDS:
MACHINE VISION/
THERMAL IMAGING/
COLLISION AVOIDANCE/
AI-BASED DETECTION/
MARITIME SAFETY

References: https://www.sea.ai.
Company: Sea.AI, France.
Year of Market Introduction: 2019 (first tests), 2023 commercial use.
Overview: Sea.AI represents an advanced application of artificial intelligence and computer vision in the maritime domain, specifically designed to extend situational awareness and safety capabilities beyond the limitations of conventional navigation systems such as radar and AIS. The system combines high-resolution optical and thermal cameras with embedded image-processing units capable of executing deep learning algorithms for real-time object detection, tracking, and classification. By leveraging a training dataset containing millions of annotated maritime objects, the system is able to identify both cooperative and non-cooperative targets, including small vessels, buoys, debris, and even people in the water, under conditions of reduced visibility such as night-time sailing or adverse weather.
In practical deployment, Sea.AI has demonstrated strong operational value in offshore racing contexts, where reaction times are limited, and human vigilance is heavily strained. Empirical reports from professional skippers highlight its capacity to provide early warnings in situations where traditional instruments would have failed to detect a threat, thereby preventing potential accidents. The system also introduces an AHMI layer by delivering multimodal feedback optimised for intuitive decision support.
Enabling Technologies: IoT / IIoT, Big Data Analitics, Simulation and system integration.
Sub-technologies for UX implementation: AHMI, VR/AR.
Impact on:

- Client-Design Communication: None.
- Yacht Design and Product Engineering: None.
- Design-Production Integration: None.
- Shipyard-Supplier Integration: None.
- Boat or Part Manufacturing: None.
- Sail Monitoring: collect environmental and sailing data to simulate sailing scenarios; improving navigation awareness.

Odyssee

FAMILY:
INTELLIGENCE

KEYWORDS:
AI-DRIVEN CAE/
DESIGN OPTIMISATION/
COMPOSITE MATERIAL
SIMULATION/
DIGITAL TWIN

References: https://hexagon.com/products/odyssee.
Company: Hexagon AB, Sweeden.
Year of Market Introduction: 2022.
Overview: The ODYSSEE platform introduces a transformative approach to engineering simulation by integrating advanced AI and machine learning techniques with traditional CAE workflows. Its ODYSSEE CAE module allows engineers to construct highly accurate reduced-order models – or digital twins – through real-time predictive simulation, even when only limited prior FEA analysis or physical test data are available. This real-time capability dramatically reduces computational resources and accelerates design iteration. The platform module extends innovation further by enabling image- and CAD-based learning: non-specialists can feed the system with visual or CAD inputs to rapidly generate simulation predictions without complex setup. Core to both modules is the Quasar AI engine, which supports operations like interpolation, classification, and optimization, and integrates with leading CAE tools including MSC Nastran, Adams, Marc, and Cradle CFD via smart elements or FMU models.
Enabling Technologies: Big Data Analitics, Simulation and system integration.
Sub-technologies for UX implementation: AHMI.
Impact on:

- Client-Design Communication: None.
- Yacht Design and Product Engineering: Facilitates early exploration of composite structures and structural configurations, supporting lightweight and efficient design through fast, accurate CAE feedback. Plus, offers potential to simulate composite material behaviour.
- Design-Production Integration: Smoother transitions from design to prototyping, with predictive models guiding early optimization and reducing prototype physical testing.
- Shipyard-Supplier Integration: None.
- Boat or Part Manufacturing: None.
- Sail Monitoring: None.

Sail Insight

FAMILY:
INTELLIGENCE

KEYWORDS:
SAILING ANALYTICS/
REGATTA TRACKING/
MOBILE APP/
REAL-TIME DATA/
CLOUD IN-MEMORY
PROCESSING

References: https://sail-insight.com.
Company: SAP SE, Germany, in partnership with the Sailing Yacht Research Foundation (SYRF).
Year of Market Introduction: 2020.
Overview: Launched in 2020 and endorsed by World Sailing, the app allows sailors, coaches, clubs, and fans to create, track, and manage races in real time – providing live performance data, leaderboards, and predictive handicap scoring via GPS and wind data streams. Leveraging SAP Sailing Analytics – the world's most comprehensive sailing database – and in-memory cloud computing, the app processes and visualises data instantly on smartphones and tablets. It thus bridges a long-standing gap in accessibility: previously cost-prohibitive tracking and analysis of regatta actions are now available at club and grassroots levels. Sail Insight supports diverse race formats – from one-design classes to performance cruisers – allowing broader participation and engagement. The platform enhances coaching and competition through immediate feedback, enriches fan and media experience with live tracking, and has laid the groundwork for subscription-based advanced features following its initial free release.
Enabling Technologies: IoT / IIoT, Big Data Analitics, Simulation and system integration.
Sub-technologies for UX implementation: AHMI.
Impact on:

- Client-Design Communication: real-time visualization of sailing data. Virtualization of racing.
- Yacht Design and Product Engineering: None; however, there could be the possibility of exploit data for the design concept stage.
- Design-Production Integration: None.
- Shipyard-Supplier Integration: None.
- Boat or Part Manufacturing: None.
- Sail Monitoring: Indirect; focus is on race performance tracking and analytics rather than direct sail diagnostics.

IYC Blue

References: https://iyc.com/blue/.
Company: International Yacht Company, USA.
Year of Market Introduction: 2023.
Overview: BLUE is a comprehensive digital platform engineered to streamline yacht and fleet operations by integrating real-time tracking, predictive maintenance, crew oversight, compliance management, inventory control, and documentation into a unified interface. The system centralizes operational workflows into a coherent framework, significantly reducing administrative complexity and enhancing decision support through proactive issue identification, compliance monitoring, and streamlined reporting. The platform's architecture reflects advanced digitalization within yachting infrastructure, incorporating AI driven automation via a virtual manager: Anna. This functionality reportedly transforms up to 30 human administrative hours into one minute of AI processing, spanning tasks from crew certification tracking and logistics coordination to weather-informed itinerary optimization and regulatory monitoring. This represents a tangible embodiment of Industry 4.0 principles, wherein cognitive automation augments human operational capacity, delivering higher reliability and reduced risk in high-stakes maritime environments.
Enabling Technologies: IoT / IIoT, Big Data Analytics.
Sub-technologies for UX implementation: AHMI.
Impact on:

- Client-Design Communication: None.
- Yacht Design and Product Engineering: None; however, data-driven insights may gradually influence operational design decisions and layout improvements.
- Design-Production Integration: None.
- Shipyard-Supplier Integration: None.
- Boat or Part Manufacturing: None.
- Sail Monitoring: Indirect; the focus is on yacht operations, not sailing monitoring/performance.

FAMILY:
INTELLIGENCE

KEYWORDS:
YACHT MANAGEMENT/
REAL-TIME OPERATIONS/
PREDICTIVE MAINTENANCE/
AI VIRTUAL ASSISTANT

5.3 Case studies map

A case studies map is here presented to provide a synthetic overview of the best practices analysed in this chapter. While each case illustrates a specific trajectory in the digitalisation of yacht design and manufacturing, their collective reading highlights recurrent drivers, cross-cutting strategies, and emerging systemic patterns.

The enabling technologies of the Fourth Industrial Revolution often show overlapping fields of application. To avoid grouping projects only by the technologies they employ, a card-sorting method was used to cluster them according to shared behaviours. The resulting map organises these clusters to highlight their relationships and, above all, their impact on design processes and tools.At its centre, the map places five progressive levels of digital technologies integration: digital data gathering, simulation, optimisation, system integration, and generative design. These levels are related to two cross-cutting dimensions: communication and collaboration. From this framework, the following groups of case studies emerge:

- Digital data gathering: projects using IoT and HMI systems to monitor yacht assets. This cluster includes digital gateways, onboard electronic logs, and platforms for vessel system control and automation. This cluster includes, for example, YachOnCloud and Volvo Easy Connect digital platforms for real-time monitoring, both based on digital gateways, electronic logs, and automation platforms for vessel control.
- Environmental digital data analysis: projects combining IoT, big data, simulation, and AHMI to collect and analyse environmental and vessel-related data. These are mainly focused to develop predicted maintenance data. Representative of this category is, for example, the platform i-Captain. Only one case explores comparing field data with design data (i.e. Sail Insight), and none within the selected corpus demonstrate systematic use of field data in design development.
- Data simulation for communication: projects not, or only partially, informed by field data. They integrate big data, simulation, VR, and AHMI to support communication strategies,

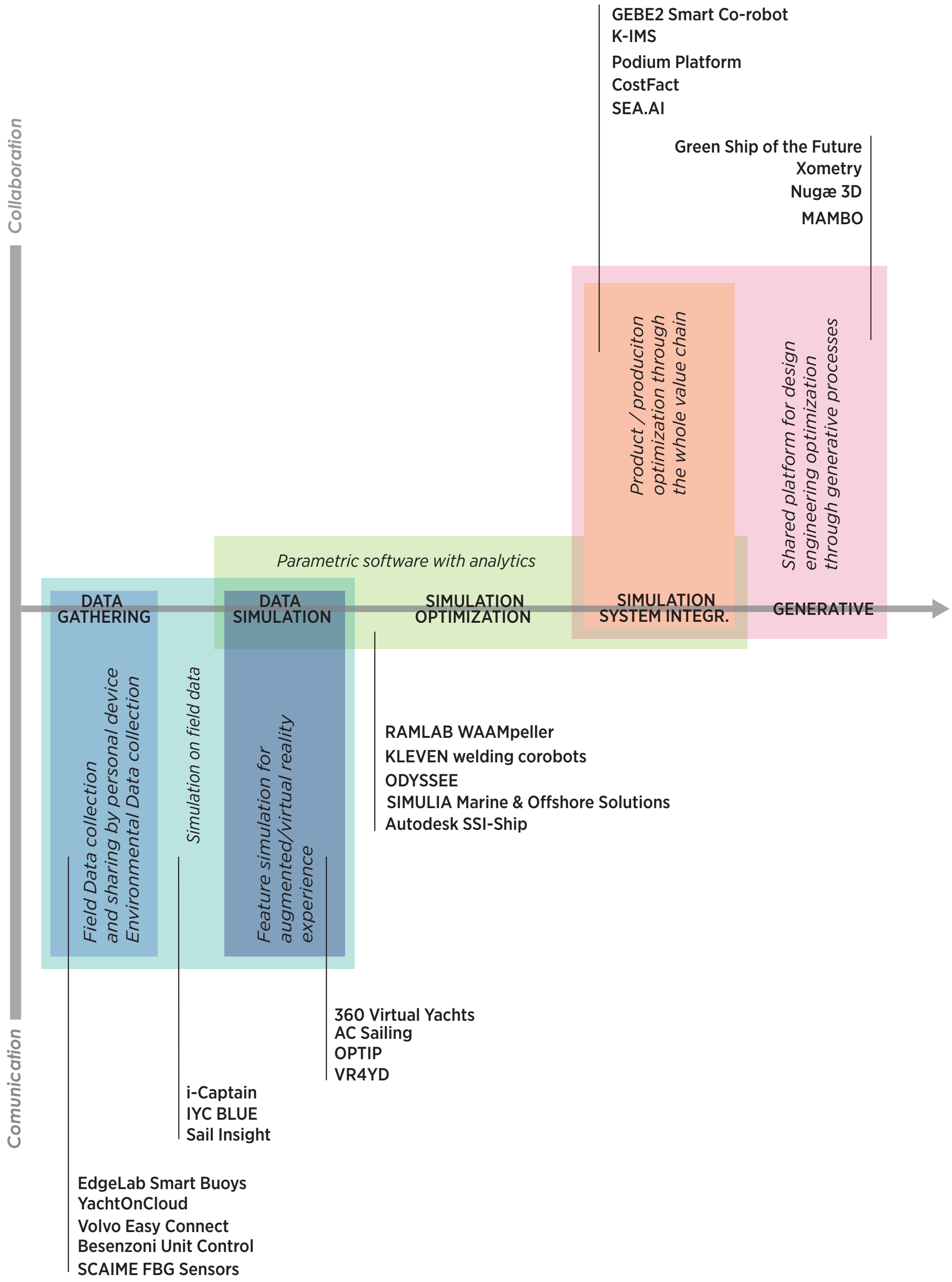


Figure 14.
Case studies map.

such as virtual reality for marketing (i.e. VR4YD and 360 Virtual yacht) or virtual sailing testers/racers (i.e. AC Sailing).

- Simulation analysis and optimisation: projects using simulation tools to predict performance or optimise manufacturing processes, yet within non-integrated ecosystems and without field data inputs. Notable cases are Odyssee software pack for hull composite design optimisation and Dassault Systems' SIMULIA Marine & Offshore Solutions applied to naval architecture.
- Optimisation through integration: collaborative projects aimed at optimising both product and process across the value chain. Examples include collaborative platforms for managing design phases and supply chains (i.e. Cost Fact), and fleet sailing or offshore operations (i.e. K-IMS and Podium Platform).
- Optimisation through generative approaches: projects adopting generative design tools to create self-configuring product forms in line with manufacturing processes. This cluster includes additive manufacturing like Mambo, collaborative robotics and cloud manufacturing initiatives (i.e. Xometry). In addition, some of them reveals a collaborative nature (Green Ship for the Future) directed towards generative optimisation (Nugæ).

The map shows a clear distinction between communication-oriented strategies, which tend to be associated with lower levels of integration, and collaboration-oriented strategies, which underpin more advanced systemic integration and self-configuring processes. Technologies positioned on the left side of the map reflect the design principles of virtualisation, service orientation, and decentralisation. At the same time, those on the right embody principles of flexibility, self-configuration, and real-time capability.

Overall, the case study map suggests the possibility of a vertical integration of data gathering and simulation processes across the yacht industry. At the same time, it highlights how collaborative platforms for generative design, despite their advanced optimisation potential, still lack a systematic use of field data along the entire value chain.

PART 3

Forecasting, Visioning and Planning

6. Drivers for the digitalization of yachting industries

6.1 The yachting digital forecasting framework

In the previous chapter, the case studies map was presented as a tool to visualise the diffusion and applications of digital technologies in the field of yacht design, shipbuilding, and onboard experiences. From its analysis, a clear distinction emerges between communication-oriented strategies, which tend to be associated with lower levels of integration, and collaboration-oriented strategies, which underpin more advanced systemic integration and self-configuring processes. The technologies positioned on the left side of the map largely reflect the design principles of virtualisation, service orientation, and decentralisation, whereas those on the right embody principles of flexibility, self-configuration, and real-time capability.

Overall, the map suggests the possibility of a vertical integration of data gathering and simulation processes across the yachting sector. At the same time, it highlights a persistent gap: collaborative platforms for generative design, despite their optimisation potential, still lack a systematic use of field data along the entire value chain. To further investigate these opportunities, a series of scenario-building workshops based on co-design practices was organised. This chapter summarises the results of those activities, presenting the forecasting framework and seven scenarios for the development of the yachting sector within a broader digital ecosystem.

In constructing the forecasting framework for the scenario-building phase, the findings from the case studies were analysed through the lens of the ecosystem approach proposed for Industry 4.0 scenarios by PwC (2016). As stated in that report:

> **Industry 4.0 needs to extend far wider than horizontal and vertical integration within your own organisation. First movers achieve breakthrough performance by going a step further to understand consumer needs and use digital technologies to create and deliver value to the customer in an integrated, innovative solution.**

The PwC Industry 4.0 scenario framework identifies four steps in moving from a product-oriented to a platform-focused approach. The first is the *core product*, the traditional base offering, which may be digitised by adding digital layers around it. This is followed by d*igital augmentation*, where customer interfaces, visualisation, touchpoints, and channels enhance the experience and open a variety of interaction models. The third step is *digital services*, in which digitally enabled services are added to the physical core product, providing an end-to-end solution to a broader customer need. The final phase is the *digital ecosystem*. Here, through interfaces with suppliers, partners, and customers, the product becomes embedded in a wider system of co-creation and value capture.

In this study, the PwC framework was expanded to encompass not only the product dimension but also the manufacturing process and the post-launch stage. As illustrated in Figure 15, the resulting background scheme is represented by four concentric circles, divided into four sectors by horizontal and vertical axes. The horizontal axis distinguishes a focus on product from a focus on production, while the vertical axis separates the phases before launch from those after launch. The resulting quadrants are: Design (product before launch), Manufacturing (production before launch), Sailing (product after launch), and Maintenance (production after launch).

The Yachting digital forecasting framework was constructed by overlapping the groups identified in the case studies map with this scenario-based scheme. In doing so, it became clear that the structure of the map retains the sequence and interrelation of clusters previously described. However, a significant barrier persists between the *pre-launch* and the *post-launch* sectors.

This reflects the earlier distinction between communication and collaboration: data generated in real contexts are not yet systematically integrated into the design phases, and the results of engineering and software analyses are not confirmed by feedback from the sailing stage. Likewise, the *post-launch* manufacturing area, represented by maintenance, is only marginally influenced by digitally embedded

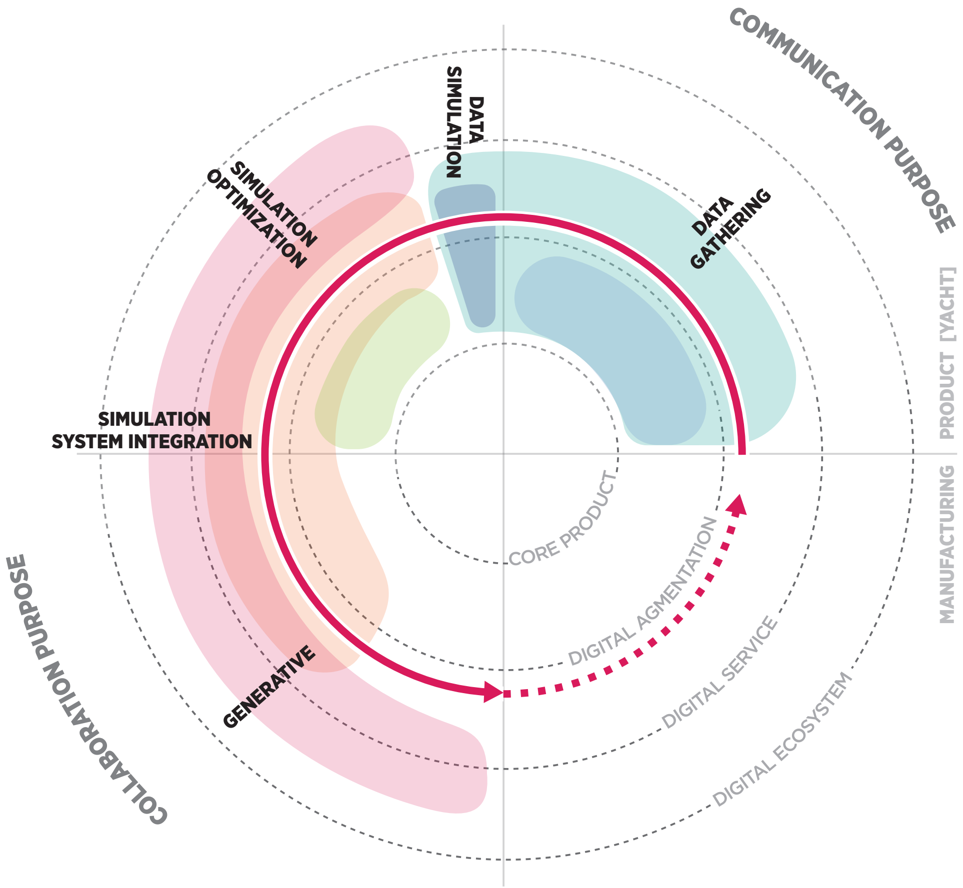


Figure 15. Yachting digital forecasting framework.

technologies and is not yet effectively connected to the other three sectors.

The analysis therefore reveals numerous unexplored opportunities in the yachting sector and a general lack of systemic vision regarding digital technologies. The projects examined nevertheless confirm the high potential of digital enabling technologies to enhance awareness and interoperability throughout the design and manufacturing processes, with significant implications for communication media across the entire customer journey.

From the relation between embedded digital technologies and the design principles identified in the case studies, together with the systemic perspective provided by the Yachting digital forecasting framework, it is possible to extrapolate the main drivers, challenges, and uncertainties of the emerging digital yacht ecosystem. The principal drivers are aligned with the design principles of Industry 4.0: virtualisation, service orientation, flexibility, and self-configuration. In particular, new forms of communication media are emerging between companies and end users. These allow, first, a more immersive experience and, second, quicker and easier access to information through digital platforms and personal devices. Such media could also embed digitally enabled services to provide end-to-end solutions addressing broader customer needs.

Despite these advancements, digital data from field operations and user engagement remains underutilised in design phases and is only partially integrated into maintenance. This leads to a disconnection between the *pre-launch* and *post-launch* stages, ultimately affecting both the quality and quantity of design input data. However, data gathered from user experience and field measurements could support not only communication between users, yachts, and companies for maintenance and service-oriented purposes, but also inform the design process itself, thereby enhancing virtualisation in project development.

At present, digital communication media are primarily employed for marketing purposes and are rarely integrated into design, manufacturing, or maintenance. However, the positive results of experimental projects with virtual reality and advanced human-machine interfaces documented in the case studies suggest that these technologies should be scaled up and extended to other areas of the yachting sector. On the design and manufacturing side, horizontal integration of digital data is increasingly applied to simulation, optimisation, and generative processes. Whereas communication strategies tend to focus on interoperability, collaborative strategies drive projects towards a higher level of awareness and systemic horizontal integration. Nonetheless, the use of collaborative platforms for optimisation and generative design processes remains limited, as field data are not yet consistently employed along the entire value chain.

The visual representation of the Yachting digital forecasting framework reveals a lack of experience in the final layer, the digital ecosystem, as well as insufficient connections between the four quadrants. This finding further confirms the immaturity of the yachting sector with regard to digital technologies and reinforces the need for systemic visions to harness the opportunities offered by the fourth industrial revolution. To address these gaps, a series of co-design scenario-building workshops was organised, the results of which are discussed in the following section.

6.2 Co-design scenario-building workshops

Between 2020 and 2024 a series of co-design scenario-building workshops was organised to address the central question: «How might digitally enabled technologies be more effectively implemented within a Yacht Industry digital ecosystem?». These activities were conceived to foster an iterative approach, balancing the exploration of opportunities through scenario building with systemic analysis, while simultaneously generating knowledge through structured discussions among stakeholders.

Participants were engaged as co-creators in the design process, thereby enabling the identification of systemic challenges too complex to be understood from a single disciplinary perspective. A systemic lens was essential, since drivers of change act within a network of interactions that spans design and production processes as well as user experience and maintenance. Consequently, while the research aimed to investigate transformations in yacht design processes and tools, it was necessary to position the broader Yacht Industry at the centre of the strategic forecasting activity.

The workshops gathered participants from three domains:

- within the focus of study – yacht designers and draftsmen within shipyards;
- at the edge of the study – shipyard project and production managers, together with representatives from yacht industry associations;
- outside the immediate focus – experts in digital transformation and policymakers.

To support strategic conversations, a properly-designed toolkit was employed, drawing on the Future Technology Workshop (FTW) method (Vavoula *et al*., 2002). The sessions followed four phases: (I) introduction to the research aims and the forecasting framework developed in previous stages; (II) structured brainstorming; (III) free envisioning exercises; and (IV) scenario model-building, identifying gaps between current and anticipated technologies. The FTW approach guided participants through a grid exploring everyday technologies and activities, current technologies applied to new activities, new technologies supporting existing activities, and entirely new activities enabled by new technologies. This methodology enabled participants to articulate visions of the *desired future* and to position experimentation within an industrial perspective. Notably, the visions generated in 2020 were subsequently used by some shipyards as references for project proposals, several of which are discussed in *Chapter 8 – Emerging Approaches in Designing for Sustainability and Customisation*. The most recent workshops in 2024 also began experimenting with AI generative tools as active members of the co-design process.

During the workshops, professionals envisioned alternative scenarios that situated digital technologies within a potential yacht industry ecosystem. They identified gaps between current practices and future possibilities, and outlined critical aspects, challenges, and opportunities for technology application. Seven systemic visions emerged, each addressing distinct but interconnected aspects of design, production, communication, and service.

6.3 Emerging scenarios

6.3.1 Vision 1: Computational yacht design process

This vision emerged from a provocative question raised during the workshop: «Can we record data while sailing and use that to generate optimised shapes?». It envisaged a continuous cycle where sailing data – performance metrics, environmental conditions, and user interactions – were fed back into computational and generative design tools.

At its core, this vision imagined sensors and digital gateways onboard yachts, generating datasets processed by optimisation algorithms and big-data platforms. Over time, self-configuring generative design tools, linked to additive manufacturing, could create yachts whose forms evolve in response to real-world feedback. Two critical issues were emphasised: the selection and interpretation of input data, and the role of the designer. Participants stressed that designers must mediate between raw data and design decisions, deciding at which stage of the design spiral generative tools are most valuable.

The idea of feeding sailing data into computational and generative design tools, first seen as speculative in 2020, has become increasingly plausible by 2024. Advances in AI-based optimisation have made this vision increasingly plausible. Machine learning now enables near real-time analysis of hydrodynamic, energy, and user comfort data. Generative AI can propose multiple alternatives in hours rather than weeks. Yet the role of the designer remains central. Algorithms are seen as augmenting, not replacing, human expertise. Designers now use AI earlier in the process to test scenarios, while reserving their judgment for trade-offs and creative synthesis.

6.3.2 Vision 2: Collaborative knowledge management platforms

Running in parallel to Vision 1, the second vision extended the concept of data use to a shared, industry-wide scale. Rather than each shipyard or design office operating in isolation, participants envisaged a collaborative Knowledge-Based Engineering (KBE) platform. This digital infrastructure would store, organise, and analyse data generated during sailing, design, and maintenance, making it available across the sector.

The potential benefits were significant: improved integration of diverse datasets, greater reuse of components and design experiences, and automated decision-support tools based on accumulated knowledge. Importantly, maintenance operations could be informed by a historical record of component performance, usability issues, and previous failures, thus creating a feedback loop across the vessel lifecycle.

Yet this vision also surfaced tensions. Who owns the data? Should platforms be managed by industry associations to guarantee neutrality, or would competitive pressures make companies reluctant to share? Concerns over confidentiality and intellectual property were central, reflecting wider debates across digital industries. Despite these issues, participants broadly agreed on the need for shared knowledge infrastructures. Without them, the promise of computational design (Vision 1) remains limited, as data will continue to be fragmented and underutilised.

Nowadays, the debate over shared knowledge infrastructures remains unresolved, but some progress has been made. Industry associations and EU-funded projects have begun experimenting with sector-wide platforms for data exchange, particularly in areas such as sustainability reporting and safety compliance. The technical feasibility of large-scale knowledge management systems is no longer in doubt, thanks to interoperable cloud services and advances in semantic data modelling.

The challenge today lies in governance. While some shipyards and design studios have started to share anonymised sailing data, competitive pressures still restrict transparency. Nevertheless, there is growing recognition that without sector-level collaboration, individual efforts in AI design or predictive maintenance will remain fragmented.

6.3.3 Vision 3: Digital/augmented communication media for customer co-creation

This vision shifted the focus towards the relationship between shipyards and clients, exploring how virtual and augmented reality could become tools of co-creation. By enabling clients to interact with digital models in immersive environments, shipyards could offer richer experiences and gain deeper insights into user expectations.

However, the workshop internal discussions revealed differences of opinion. On one hand, some argued that opening the design process to greater client involvement could lead to innovation and improved satisfaction. On the other hand, many design studios, particularly those specialising in superyachts, expressed a need of caution. As one participant observed: «An owner does not know what he wants – if we leave everything open, the project will change every week!».

A compromise position emerged: customer involvement could be structured through controlled options, supported by parametric models that allow limited customisation within predefined boundaries. Such systems could serve as powerful market research tools while protecting the integrity of the design process.

The key enabler here would be linking VR platforms to digital twins, ensuring that client modifications are immediately reflected in engineering models.

From 2020 to 2024, immersive technologies have matured rapidly and virtual configurators are now so common that their use in yachting is much more appreciated. The pandemic period, in fact, represented a real turning point in this. VR headsets and AR applications are increasingly used in early design reviews, allowing customers to walk through digital twins of yachts before construction.

However, the tension between openness and control persists. Superyacht designers remain cautious about granting clients too much agency, but parametric configurators are now widely used to manage customisation in structured ways. In this updated scenario, customer co-creation is no longer a futuristic option but a growing industry expectation, albeit one carefully mediated by professional boundaries.

6.3.4 Vision 4: Digital/augmented communication media for manufacturing system

While Vision 3 focused on customer interaction, Vision 4 applied AR/VR technologies to the manufacturing domain. Here, augmented reality becomes a bridge between design studios, technical offices, and production sites, offering real-time guidance for assembly, installation, and maintenance. By visualising components and procedures, technicians could reduce errors, accelerate processes, and access yacht-specific data through interactive logs.

Unlike the customer-focused vision, this scenario faced relatively little resistance. Confidentiality was not seen as a barrier, and the main challenges concerned training and the adoption of new tools. Indeed, participants highlighted strong synergies with other visions, particularly computational design (Vision 1) and integrated management (Vision 5). In this scenario, AR/VR was not just a communication tool but a mechanism for embedding digital twins into the daily operations of shipyards and service providers.

By 2024 AR/VR applications in production have gained traction. Some shipyards now use augmented reality for assembly guidance, overlaying digital models onto physical structures to reduce errors. Maintenance processes increasingly rely on AR-enabled manuals accessible via tablets or smart glasses, improving accuracy and efficiency in complex repairs.

New most recent visions forecast the integration of digital twins to link design models with production workflows. This updated vision emphasises the potential for a *closed-loop* systems, where real-world assembly data feed back into design standards. Training remains a barrier, but the benefits of visualisation and interoperability have been widely acknowledged.

6.3.5 Vision 5: Virtual integrated management

This vision was triggered by a key question raised during one of the firsts workshops: «What happens to the entire project management process if an integrated system for yacht design and production management is developed?». The discussion pointed towards a holistic digital ecosystem where every stage of the yacht lifecycle could be coordinated through a single platform.

At the centre of this vision lies the digital twin, not as a static model but as the core of a broader project management environment. Inspired by Building Information Modelling (BIM) in architecture, the proposed platform would converge engineering technologies, operational processes, and information systems into a unified portal. By linking these domains, the system would ensure consistency, improve transparency, and reduce redundancy across the project.

In practice, this meant extending digital augmentation from design into production, allowing virtualisation of all design and manufacturing processes. In the digital service layer, vertical supply chain integration would be enabled, with suppliers and subcontractors feeding real-time data into the platform. The final loop of the digital ecosystem envisioned real-time feedback from production and sailing, supported by sensors on tools, workstations, and yachts in operation, thus closing the cycle with maintenance and lifecycle management.

Yet concerns were also raised. The use of field data to monitor workers or track yacht activity raised ethical issues, echoing broader debates around privacy in the digital ecosystem. While the benefits of real-time integration were recognised, trust and confidence were seen as essential, with clear governance and data protection policies considered crucial to prevent misuse.

In the last workshops, integrated platforms are increasingly gaining attention, especially for environmental performance tracking and project coordination. However, BIM-inspired approaches have maturated in the yachting sector, yet, remaining nowadays just at prototyping phases.

6.3.6 Vision 6: Rapid prototyping and flexible/cloud manufacturing for high customization

This vision addressed the rising demand for personalisation in yachting by considering how additive manufacturing, collaborative robots, and cloud-based systems could create a highly flexible production model. The focus was not on entire yachts but on components, where rapid prototyping and decentralised production could deliver the greatest benefits.

In this scenario, additive manufacturing was seen as more than a prototyping tool: it could produce lightweight, customised, and functional parts, while co-robots would assist operators in assembly and finishing. Maintenance was reimagined as both repair and aesthetic refitting, supported by on-demand local production through cloud manufacturing networks.

Over the years, this vision has also expanded to encompass the use of computational and generative design to develop new component geometries optimised for additive manufacturing. This opened opportunities for aesthetic innovation and material efficiency, but also highlighted a skills gap, since many designers lacked experience with parametric and generative tools. Concerns were also raised about material certification and durability in the marine environment.

Despite these challenges, participants considered more and more the vision realistic, especially given parallels with aerospace and automotive sectors. Importantly, it connected strongly to Vision 3 (customer co-creation), suggesting that personalised elements could be designed collaboratively with clients and produced economically using additive technologies.

6.3.7 Vision 7: Personalized predicted services

The final vision focused on post-launch activities, imagining a yacht ecosystem where real-time sailing and mooring data would support highly personalised services. This vision expressly focuses on the charter yacht market. In here, sensors, digital gateways, and electronic logs would gather information such as routes, speeds, and environmental conditions, feeding platforms designed to enhance both user experience and operational efficiency. Insurance models based on real data were also envisaged, offering tailored packages for charter companies and multi-owner yachts.

At the core of this vision was the idea of a unified platform accessible through personal devices, capable of integrating diverse services into a seamless interface for owners, operators, and service providers. Participants noted its potential to extend the value of yachting beyond the vessel itself, embedding it within a broader product–service ecosystem.

The scenario of predictive, data-driven services has evolved into one of the most active areas of experimentation in recent years. Electronic logbooks, voyage optimisation tools, and integrated marina platforms are being piloted across Europe, as demonstrated by the selection of best practices. Charter companies increasingly demand digital platforms for fleet monitoring and predictive maintenance; nevertheless, a unique standard offer for companies is not yet implemented. Plus, insurance providers are not yet exploring dynamic pricing models based on real sailing data.

Significant concerns were here raised about data security. While privacy was acknowledged, the priority was seen in safeguarding the integrity of digital infrastructures against cyberattacks. Low awareness of cybersecurity in the yachting and wider maritime sectors was highlighted as a critical weakness, with participants stressing that resilience measures would be essential for such services to become viable.

6.3.8 Reflections

The visions elaborated through the scenario-building workshops show how different trajectories – from computational design processes to knowledge-sharing platforms, from immersive communication tools to predictive services – contribute to an increasingly interconnected ecosystem where design, production, operation, and maintenance are no longer separate domains but part of a continuous cycle. Nowadays, the technological foundations are already established: computational tools are rapidly advancing, immersive media are becoming more accessible, integrated management systems are gaining maturity, and predictive services are moving from prototypes to early applications.

Despite evident progress in technology from the first workshop session in 2020 to the last one, the discussions also revealed unresolved issues. Questions of governance, the development of new skills, and the ethical management of data remain central challenges. The sector is therefore faced with a decisive shift: it is no longer a matter of asking whether such futures are possible, but of understanding how they can be implemented responsibly and strategically.

The next chapter takes this reflection one step further. Chapter 8 introduces the roadmaps toward a computational morphology system, translating the visions into concrete strategies and highlighting their implications for future yacht design practices.

7. Toward a computational morphology system

7.1 Roadmaps to yacht digital design

The first attempt to design roadmaps for the digitalisation of the yacht sector was undertaken in 2020, as an elaboration of the initial results of the co-design workshops. Roadmaps were conceived as the bridge between forecasting and the present gap, guiding the transition from imagined futures to concrete actions (Hines & Bishop, 2006). The three developed roadmaps represent the translation of scenario-building results into a practical understanding of novel yacht design approaches, processes, and tools shaped by the current framework of the yacht industry.

Although the scenario-building activity was carried out with a systemic approach, the design of the roadmaps focused specifically on yacht design processes and tools, spanning from data input to communication strategies with customers and production sites. A temporal division structured the progression of each roadmap into three phases, also reflecting the introduced PwC Industry 4.0 scenario framework (PwC, 2016):

- current: digital augmentation (within five years);
- near future: digital services (within ten years);
- future: digital ecosystem.

Here following the roadmaps are presented, referring to a specific cluster within the yachting sector (as described in Chapter 3): series-produced yachts, semi-custom yachts, and custom yachts. As each cluster exhibits distinct design logics and market demands, a differentiated approach to digitalisation is proposed.

7.1.1 The Digital Product–Service Ecosystem

The first roadmap addresses the superyacht and mega yacht segments, representing companies operating at the top of the market. Here, the defining element is extreme customisation, with projects deeply influenced by the personality and culture of the client (Celaschi *et al*., 2005). Within this cluster, luxury design is increasingly oriented towards rare, tailor-made experiences rather than standardised objects. Against this background, the roadmap proposed here responds to the peculiarities of the superyacht cluster by outlining a journey towards a digital product–service ecosystem. In such an ecosystem, services and components are no longer designed solely according to static specifications; instead, they evolve dynamically from real user data, continuously collected and processed through a digital experience platform. The roadmap is articulated into three progressive stages: current, near future, and future.

Current (digital augmentation)

The first step of this transition is the digital augmentation of both the design project and the yacht itself. On the design side, the traditional CAD model gives way to parametric modelling. In this framework, project dimensions are no longer drafted directly in a digital continuum space; instead, they are controlled by parameters that define relations between shapes and components. The designer interacts with a digital structure that emerges from predefined rules, rather than from direct drawing. This enables the preliminary concept design phase to embed engineering logic from the outset, permitting rapid and flexible modification of the design dimensions and structural organisation. On the product side, vessels are equipped with sensors and remote-control networks, transforming them into connected objects. Initial services become available through this connectivity: automated sailing data recording via an electronic logbook, access through a universal system gateway, and integration with social media platforms. These services are modest but represent an important first step, as the user experience data they generate are stored within a knowledge management platform for later use in both design and operational phases.

Near future (digital services)

The second stage deepens this integration by connecting the knowledge management platform to both the design project and the physical product. At this point, the platform is enhanced with big data real-time analytics, enabling it to process large and heterogeneous field datasets. Through this analysis, hidden patterns can be uncovered and represented as formal, computer-interpretable rules. Design projects then benefit from this iterative loop: simulations and verifications are continuously informed by the outcomes of data analysis, ensuring that project assumptions are validated against real-world evidence. In parallel, the three-dimensional yacht model evolves into a non-living digital twin: a digital replica of all the vessel's physical and IoT assets, capable of direct communication with the production site and supply chain partners.

From the perspective of customer engagement, augmented and virtual reality, together with AHMI, provide immersive environments in which clients can explore preliminary design concepts. This approach reduces reliance on physical mock-ups while allowing verification of features at a much earlier stage.

The near future also introduces novel digital services on board. By combining sailing analytics, environmental and weather data, and information from other vessel routes, routing becomes optimised and, in part, automated. Real-time field data inform maintenance schedules and marina services, while legal and insurance services are integrated into the digital ecosystem. Together, these services reflect the convergence of design, operation, and user experience within a single data-driven framework.

Future (digital ecosystem)

In the long-term vision, the roadmap culminates in the establishment of a comprehensive digital product–service ecosystem. Here, the boundaries between the physical and the virtual worlds dissolve, with data flowing seamlessly and bidirectionally between the yacht and a living digital twin. Unlike the earlier static versions, the living twin is not only a mirror of the vessel but also a dynamic project in its own right. It incorporates both field data and design project information, enabling full interoperability and vertical system integration across yacht components.

This parametric digital twin offers insights not just into the individual elements but also into the dynamics of how digital devices interact and evolve throughout the entire yacht life cycle. Annual maintenance and refit operations are therefore no longer reactive but proactively shaped by accumulated field data, allowing yachts to be optimised continuously according to real customer needs. At the same time, advanced human–machine interfaces enable both owners and project managers to engage with complete, augmented visions of the yacht in a virtual environment, bridging customer experience, design verification, and operational management.

Implications for yacht design

Within this scenario, the yacht design process preserves its iterative character but acquires new layers of integration. The adoption of parametric design tools allows the creation of living digital models governed by predefined relations. Simulation and optimisation no longer stand apart as subsequent phases; rather, they merge into a unified analytical process operating directly on geometrical models.

This approach corresponds to what Oxman (2006) describes as predictive modelling. In such systems, relationships between objects are explicitly defined, establishing interdependencies that can be activated to produce variations. Once generated, these variations are easily transformed and manipulated, while maintaining the topological integrity of the model.

In this context, the living digital twin acts as the central hub. Managed by parametric technologies and continuously optimised by the outputs of the digital experience platform, it provides designers with an integrated tool powered by real-time field data. Designers can define the general properties of geometrical structures within a user-defined framework, while the platform supports multiple evaluative analyses and facilitates collaboration between design and engineering teams.

Moreover, the living twin embedded in the digital experience platform can be visualised through virtual reality devices. This visualisation not only enhances customer engagement but also assists manufacturing and maintenance teams by representing the yacht's features, systems, and operational dynamics across its entire life cycle.

Critical aspects

The possibility of using a sensor to control and manage the yacht journey raises ethical concerns about confidence and privacy that must be carefully addressed. According to a recent literature review (Flyverbom *et al.*, 2019; Radulovic, 2022; Gai *et al.*, 2022; Durlik *et al.*, 2023), the scenario shares the challenge of data and privacy protection with the broader Industry 4.0 development. Even if the ethical challenges created by mass data gathering through online interactions are scientifically reported, there is no clear policy or ethical framework on digital technologies due to the rapid and disruptive changes in the information technology environment (Sun *et al.*, 2024). For the yachting sector, the success of this roadmap will depend not only on technological advances but also on building confidence through responsible data governance.

7.1.2 The Generative-Integrated Ecosystem

The second roadmap addresses the semi-custom yacht sector, which represents a significant share of the industry. These companies operate with model-based production processes that allow for high levels of flexibility and personalisation. Unlike the fully customised world of superyachts, semi-custom projects typically rely on a predefined base model that is adapted to meet client requirements. Within this context, design and engineering phases are closely interconnected from the outset, and parametric modelling tools are already common. In several cases, these are integrated with structural analysis, performance simulation, project management, and supply chain systems.

The prevailing approach is therefore to embed constraints and material limits within the earliest concept stages, rather than dealing with them only later in the design spiral.
The roadmap for this cluster plots a transition from optimisation-based approaches to a generative-integrated ecosystem, where design knowledge, computational processes, and advanced manufacturing converge into a unified platform.

Current (digital augmentation)
At present, the semi-custom segment benefits from the introduction of knowledge management platforms that span both production and sailing stages. These platforms record and analyse data generated by digital augmentation of yachts and production tools, producing computer-interpretable rules that can directly inform parametric design models.

While such knowledge-based methods are widely applied in other transport industries – including ship engineering, automotive, and aerospace (Chapman & Pinfold, 1999, 2001; Munjulury *et al*., 2016; Koh *et al*., 2024; Zhang *et al*., 2025) – the yachting sector has lagged behind. Its fragmented structure, characterised by small and medium-sized enterprises and low production volumes, has hindered adoption. Nevertheless, the significant body of formalised engineering knowledge available in maritime regulations and design codes represents an untapped resource that could be incorporated into yacht design through digital platforms.

Near future (digital services)
In the second stage, knowledge management is integrated directly into the digital twin of the yacht. Optimisation and refinement steps are managed within this digital replica of physical and IoT assets, which acts as a shared environment for designers, production sites, and supply chain partners. The twin becomes an interactive interface accessible through personal devices, where work teams can test features, exchange feedback, and validate assembly operations. Augmented and virtual reality play a key role, enabling verification of onboard components and immersive evaluation of optimised solutions.
Future (digital ecosystem). The long-term vision involves embedding

generative design tools into the knowledge management platform, transforming field data and user experience into alternative design solutions. Here, parameters defined by both design constraints and project requirements are combined with associative algorithms to generate multiple valid configurations. Designers interact with these generative structures by defining shape grammars and design logic, while algorithms explore variations that would be difficult or impossible to conceive manually.

This process allows quantitative computational analyses (e.g., finite element methods) to be translated into qualitative alternatives, broadening the design space. Once generated, selected solutions are integrated into the digital twin and channelled directly into the production and supply chain system. Importantly, the adoption of additive and cloud manufacturing within this roadmap enables the realisation of components with greater flexibility, strength, and lightness, as shown in other industries where generative design combined with 3D printing has proven effective in the last ten years (AMFG, 2018).

Implications for yacht design

This roadmap represents a paradigm shift in the yacht design process. The parametric approach, in which designers manually adjusted variables to explore alternatives, evolves into computational morphogenesis, driven by new associative algorithms. The iterative cycle of design, simulation, optimisation, and evaluation no longer occurs in sequence but is unified in a designer-scripted process.The integration of additive manufacturing and collaborative robotics extends the design domain to include the *making level*, where production is no longer external to design but part of a continuous feedback loop. The design process in this scenario can be summarised in three steps:

1. defining constraints and requirements: designers set qualitative project rules and shape grammars, while field data provide quantitative parameters;
2. exploring alternatives: algorithms generate multiple design options, supported by AI-powered evaluation tools;
3. selecting and integrating solutions: chosen options are embedded into the digital twin and managed by the integrated production platform.

Critical aspects
Alongside privacy and cybersecurity issues already noted in the previous roadmap, this scenario raises questions about the shifting role of the designer. While parametric tools enhanced flexibility and interoperability, exploration of alternatives was still constrained by manual control. Generative approaches instead delegate much of this exploration to algorithms, positioning designers primarily at the beginning (in defining the rules) and at the end (in evaluating outcomes). This transformation requires not only new digital skills but also a cultural shift towards what has been described as digital design thinking (Oxman, 2006).

7.1.3 The Co-Modular Digital Ecosystem

The third roadmap addresses the cluster of companies involved in series-produced yachts, generally characterised by lower levels of customisation and more standardised production processes. These shipyards typically manage low-volume or mass assembly products, yet the market is increasingly demanding greater flexibility and opportunities for personalisation. The challenge of moving from mass production to mass customisation has been central to industrial debate since the 1990s (Gilmore & Pine, 1997; Piller, 2004; Piller & Euchner, 2024). With the emergence of Industry 4.0 technologies, however, this tension between economies of scale and scope can now be mitigated through digitally enabled solutions (Brettel *et al.*, 2014).

In this context, the roadmap envisions a transition towards a co-modular digital ecosystem, where yachts are conceived as modular configurations integrated into a flexible digital platform. Here, design, production, and user experience are linked by subsystems that can be combined in multiple ways, optimised by real-time data, and adapted to customer requirements.

Current (digital augmentation)
As in the previous roadmaps, the first step involves the digital augmentation of both design and production processes. Parametric 3D modelling is directly connected to virtual configurators, enabling designers (and increasingly customers) to manipulate parameters and visualise outcomes in real time. Through smart devices and AHMI,

clients can personalise elements such as furniture finishes and component features, initiating collaborative design processes. Meanwhile, onboard IoT systems begin generating data through sensors and gateways, which are stored within knowledge management platforms. These early stages of digitalisation lay the foundation for integrating customer inputs and operational data into future design and production processes.

Near future (digital services)
The second stage introduces a yacht digital twin optimised by data from onboard IoT systems. This digital replica links production sites with customer-facing virtual configurators, creating a dynamic feedback loop. The yacht itself is conceived as a flexible assembly of subsystems regulated by interdependencies within a virtual logic structure.

This vision of modularity is not speculative: it has already been explored in commercial projects and academic research (McCartan *et al*., 2011; Vallicelli *et al*., 2018). Customers engage with digital configurators as co-creators, defining personalised solutions within predefined design variables and limits. Immersive technologies (VR/AR) allow them to test design outcomes virtually, while production teams interact directly with the twin for assembly guidance. In parallel, production data are fed back into the knowledge management platform, creating continuous opportunities for optimisation.

Future (digital ecosystem)
In the long-term scenario, a fully integrated modular platform becomes the backbone of yacht design, production, and lifecycle management. Design and production are both divided into interconnected subsystems, each optimised through field data and advanced manufacturing technologies such as additive manufacturing and collaborative robotics.

Here, the modular approach extends beyond product design to encompass production planning, supply chain management, and after-launch maintenance. Subsystems are continuously refined by analysing digital data from connected vessels and production processes. In this way, the ecosystem integrates design, manufacturing, and operation into a seamless loop, offering not only flexibility and personalisation but also lifecycle sustainability.

Implications for yacht design

The design process within this roadmap can be articulated into four steps:

1. defining general conditions and parameters: establishing interdependencies and constraints for modular configurations;
2. generating subsystem variants: creating design options informed by market and trend analysis;
3. optimising variants through data: using knowledge management platforms to refine performance, production, and supply chain factors;
4. selecting and evaluating variants with customers: employing immersive technologies to support collaborative decision-making.

In this process, the design and production engineering phases are managed by a common and integrated platform for both Modular Coordination and production information modelling (e.g. architectural BIM). The integrated platform enables asset-centric organizations to converge their engineering technologies, operational technologies, and information technologies into a unique portal. In this scenario, the design process is supported by a parametric tool involving the generation and management of digital representations of physical, functional, and production properties of subsystems and their logic/construction links.

Critical aspects

Despite its potential, the co-modular digital ecosystem faces significant barriers. The yacht industry still shows a relatively low level of digital expertise, and many supply chains are composed of small, often family-run enterprises with limited resources for integration. These structural constraints could slow the adoption of modular digital platforms. Bridging the gap will require investments in training and the diffusion of parametric and integrated design competencies across the entire value chain.

As previously mentioned, these roadmaps were primarily developed in 2020. In the last five years, the research activity has focused on monitoring their evolution. This continuous observation confirmed that the trajectories outlined were not static predictions, but dynamic tools able to lighten the way of industrial professionals.

The pandemic years played a decisive role in accelerating the early steps of digital augmentation. Virtual communication platforms, parametric modelling, and immersive tools became more common and, sometimes, essential to maintain both design operations and client engagement.

At the same time, recent debates surrounding Industry 5.0 have redefined the context in which these roadmaps must be interpreted. The shift from purely efficiency-driven digitalisation towards a more human-centric, resilient, and sustainable paradigm has reinforced the need to couple technological innovation with systemic responsibility. In this light, the future stages of the roadmaps are not only about enhancing personalisation or efficiency but also about ensuring that the digital transformation contributes directly to decarbonisation, circular design, and long-term sustainability of the yachting industry.
These themes will be explored in the next section. Here, the focus will shift to how computational strategies, additive manufacturing, digital twins, and AI-driven tools can support not only flexible personalisation but also the urgent ecological transition facing the nautical sector.

7.2 Computational strategies in the yacht design process

> **The digital revolution is changing each side of our society. In the world of Industrial design, the deep transformation improves not only the representation but also the formal references, and, eventually, the design itself. [...] As every turning point, the change regarded not only the (object) shape, which means formal features, but also the concept and the approach to design, namely design process. (Rossi and Buratti, 2018).**

Computational strategies in the yacht design process are built upon the research results illustrated in the roadmaps, putting them in a broader conversation with the recent debate on parametric morphologies, computational design engineering, and digital design thinking. As shown by the roadmaps, the journey toward a computational morphology system affects not only the design practice with the use of novel design tools but also the input data, the design process, and the communication media between designers and customers and designers and the manufacturing site.

As also suggested in the case study analysis (Chapter 5), the integration of digital enabling technologies is pushing yacht design toward a more digitally conscious and virtually collaborative environment. The evidence collected in this research highlights three central shifts that are reshaping design practices and will likely continue to do so in the near future:

- input data are moving from analogue to digital, reframing the focus of the designer's practice from measured data to inferred data.
- The use of parametric and generative tools is shifting the essence of *digital doing* from digital drafting to digital logic.
- The introduction of the digital twin is transforming communication media into more collaborative, multi-actor platforms.

Digital data from connected vessels have become the *new oil* of design, revealing fresh demands. Yet, without qualitative context, they cannot serve as design input alone. For this reason, data are always managed within shared knowledge platforms and connected to a living DT.

The DT – an evolving model that integrates information and real-time data – acts as the bridge between virtual projects and physical assets. It replaces drawings and renders with a dynamic co-design medium involving designers, engineers, customers, and supply chains. The progression from direct modelling to parametric and generative design reframes the relationship between creativity and digital work. While parametric systems improved interoperability, they still rely on manual variation of parameters. Generative design, instead, shifts the digital focus to the creative process itself, asking algorithms to explore design space semi-autonomously. A parallel path is modular optimisation, where logic governs the relations between subsystems and junction constraints.

This emphasis on the reasoning level of design has been described as meta-design of systems (Menichinelli & Valsecchi, 2016; Menichinelli, 2020). Computational design, in this sense, is a digital structure linking inputs, processing, and outputs to create responsive objects that adapt while preserving morphogenetic logic (Rossi & Buratti, 2018). In such a process, the designer defines structures and grammars, sets requirements, and evaluates outcomes.

7.2.1 Digital data input

The expansion of IoT is enabling access to a volume of data unprecedented in yacht design. Alongside analogue sources, such as marketing insights, design and engineering expertise, and onboard experience, designers now have at their disposal vast quantities of direct data measured by sensors and smart devices. Within the sphere of digital augmentation, not only can IoT-generated design data be accessed ubiquitously, but information from multiple devices can be combined into large, complex datasets.

The case study analysis already highlighted numerous opportunities for data gathering, ranging from embedded sensors in composite materials to infrared, temperature, humidity, and proximity detectors. These systems have often been conceived as isolated elements, rather than as part of a connected network. The possibility of integrating and networking distributed datasets shifts the focus of data input from simple measurement toward inference through big data analysis.

As indicated in the roadmaps, relevant data can be gathered both before launch (during production, informing component design and assembly procedures) and after launch, where operational data complement user experience insights to describe onboard dynamics between humans, objects, and systems. The categories of data potentially captured by smart devices and stored in digital gateways include:

- environmental information (e.g., meteorological and forecasting data);
- asset data (e.g., status of systems, tanks, engines, energy consumption, production tools);

- biometric data (e.g., physical characteristics and conditions of users);
- behavioural data (e.g., sailing routes, crew and user movements, time and mode of interaction with onboard equipment).

Since the roadmaps emphasise the centrality of data interpretation, a Knowledge Management (KM) platform is positioned as the link between data collection and the yacht design process. KM systems analyse large and varied datasets to identify patterns and formalise them as rules interpretable by design tools, thereby supporting knowledge creation, representation, and application. Although widely studied in business and organisational contexts, their implementation in design, and particularly in yacht design, remains underdeveloped.

One major challenge is interoperability: datasets are often heterogeneous, unstructured, or stored in incompatible formats. Poor interoperability may restrict access and limit meaningful use. The development of digital experience platforms, as proposed in the roadmaps, aims precisely at overcoming such barriers by providing coherent interpretative frameworks.

Two questions arise at this stage: How can data be made meaningful for users? How can design knowledge be created from data?

In the context of yacht design, these challenges are acute. A yacht is never truly static, even at anchor, and therefore static data cannot be reliably isolated. Digital insights must therefore be contextualised through existing analogue knowledge. As Rowland *et al.* (2015) observe, static datasets typically provide conceptual frameworks or interpretative contexts for dynamic data. Similarly, Davenport and Cronin (2000) argue that analogue and digital data can be embedded in a single KM platform only when knowledge is characterised as a flow. Within such a model, dynamic data become a fluid mix of quantitative information, contextual references, and user insights, bounded by the analogue framework of designer expertise.

7.2.2 Yacht Design process and tools

The roadmaps indicate that yacht design processes are progressively evolving through three main stages: from simulation, to optimisation, and finally to generative design. This trajectory reflects a growing degree of computational awareness in design practice, and each step introduces a distinct relationship between digital tools, design knowledge, and the role of the designer.

At the stage of simulation, the design process retains the iterative nature of the traditional yacht design spiral, but it is now increasingly powered by real-time data. Parametric modelling allows designers to embed engineering constraints from the beginning, and knowledge management platforms support cycles of analysis and visualisation. These tools improve interoperability between design and engineering teams and enable integration with DTs, which serve as shared references across the project. Yet, despite these advances, data analysis and design remain largely separate domains. Optimisation depends on the designer's ability to interpret requirements, material constraints, and simulation outputs, and to adjust parameters manually within 3D models. The process is still incremental, step by step, and its logic is not far removed from the traditional approach, even though it is more flexible and digitally enhanced.

The second stage, optimisation, introduces a more collaborative and systemic use of digital platforms. Here, the design process is not carried out exclusively by the design team but becomes the result of co-creation with customers and other stakeholders. Subsystems of the yacht are defined, varied, and fine-tuned through successive loops that combine data analysis with user interaction: parameters are set, alternatives are generated, results are optimised through field data, and final selections are made with customer input. In this environment, digital tools no longer serve primarily as drafting instruments but as logical frameworks managing the relations between modules and their constraints. The process moves from shaping the overall yacht in successive refinements to configuring and optimising subsystems within a modular structure. This shift does not remove boundaries or open the process to unlimited variations, but it does enable a wider space for customer involvement and data-driven adjustment within defined parameters.

The third stage, generative design, represents a more radical departure. Rather than manually exploring variations or optimising predefined modules, designers set rules, constraints, and grammars of form, while algorithms explore the design space semi-autonomously. Artificial intelligence is not employed simply to simulate or optimise but to propose multiple alternative solutions. Designers interact with this generative structure by defining inputs and limits, and later by evaluating and selecting from the outcomes produced. Among the different generative approaches, grammar-based methods are particularly relevant to yacht design: algorithms are tasked with creating new forms according to established rules, and computational techniques such as finite-element analysis guide the structural and performance validation of these alternatives. In this stage, computational design tools move beyond support functions to act as co-creators, expanding the range of possibilities far beyond what could be achieved manually.

This progression – from simulation, through optimisation, to generative design – marks a fundamental shift in yacht design practice. The process moves away from drafting and incremental refinement toward logic-based and computationally driven exploration. At each step, the role of the designer is redefined: first as an interpreter of data, then as a co-ordinator of collaborative logic, and finally as a curator of algorithmically generated results. Such transformations underline the need for new skills and design mindsets, as well as for deeper theoretical and applied research to guide their implementation within the still-emerging digital culture of the yacht sector.

7.2.3 Communication media

In parallel with the availability of field data and the shifting focus of digital processes, enabling digital technologies are opening the way to new forms of communication, and therefore collaboration, within yacht design and engineering. To frame the discussion, it is useful to clarify terminology. The communication medium is conceived here as the overall strategy through which information is conveyed, encompassing tools, channels, and interfaces. The channel refers to the flow of information from sender to receiver, in this case, digital, while the interface connects the tool and the channel, storing and processing the communication (e.g., personal devices, augmented reality headsets) (Lim & Benbasat, 1991).

Nowadays, yacht design communication is still dominated by analogue media. Whether at the concept stage with customers or at the production stage in shipyards, the most common tools remained 3D renders, 2D drawings, and written instructions. Some experiments with digital channels, such as virtual reality is emerging, but the potential of digital technologies was not being addressed from a systemic perspective.

In the roadmaps, the DT emerges as the enabler of integration, supported by IoT networks for data gathering, and as the core communication medium of the cyber-physical system. As Schroeder et al. (2016) argue, the DT operates at multiple levels of the living model to exchange data between digital and physical systems. For this reason, it is not only a communication tool but also a medium for collaboration in the journey toward a computational morphology system. Coupled with augmented/virtual reality and advanced human–machine interfaces, Digital Twin could facilitate communication and collaboration across three primary levels.

- Within design teams. Functioning as an assembly of different subsystems, the Digital Twin allows multiple analyses to be carried out simultaneously, supporting collaboration among design and engineering teams. It provides simulations and evaluative tools that span the entire yacht life cycle, from production and sailing to maintenance activities.
- Between designers and customers. As a digital replica of the yacht, the DT enables future owners to experience the vessel from the earliest design stages. Depending on the roadmap, the twin may be manipulated by designers to present options (as in the generative-integrated ecosystem) or co-designed directly by customers, who select, aggregate, or move subsystems within a parametric structure (as in the co-modular ecosystem). In both cases, the DT scales up experiences already noted in case studies by linking the virtual image to the logical framework of parametric tools. Beyond design, it also becomes a resource during the operational and maintenance stages, where virtual logs of specifications, assembly procedures, and real feedback from sailing can guide service and refit operations.
- Between design and production. Here, the DT embeds the logic of construction and material properties, connecting directly

to production tools ranging from CNC machines to 3D printers and collaborative robots. It also facilitates communication with suppliers and, in the future, cloud manufacturing networks. During production, the twin can be explored through AHMI and augmented reality devices, replacing printed drawings and written instructions. Moreover, it creates space for feedback loops, allowing work teams to record modifications or suggestions directly into the design model.

Regarding interfaces, the research findings suggest that AHMI and personal devices equipped with augmented and virtual reality should be further developed not only to provide immersive experiences of the yacht but also to record new field data. In this way, even the interaction between humans and virtual assets could generate data for analysis, extending the design process into a collaborative, data-driven, and multi-actor environment.

PART 4

Acting

8. Emerging approaches in Designing for Sustainability and Customisation

8.1 State of the art and pioneers' projects

The past chapters have shown how digitalisation, new design processes, and industry frameworks could reshape the practice of yacht design. However, in recent years, the debate around yacht design has increasingly converged on two pressing and interconnected themes: the pursuit of sustainability and the demand for flexible customisation. Both challenges call for a rethinking of established practices, shifting from incremental improvements on isolated components to systemic innovation that redefines processes, materials, and the relationship between yachts, their users, and the environment.

This chapter introduces a selection of emerging approaches that are beginning to transform the sector. These include the integration of artificial intelligence in yacht drafting and rendering, the application of additive manufacturing to overcome the limits of mould-based production, the use of digital tools to manage the entire life cycle of a yacht, and the exploration of new materialities through smart, bio-based, and living materials. Together, these developments illustrate how advanced technologies and new design paradigms can expand both the cultural and technical boundaries of yacht design.

At the same time, the chapter also presents ongoing research activities conducted at the Politecnico di Milano by the author's research group. These projects, embedded in wider academic and industrial collaborations, explore the practical potential of emerging technologies in real design contexts. Each of the following sections is therefore built around a dual perspective: a critical account of the international state of the art and an introduction to current research pathways that aim to foster innovation in yacht sustainability and flexible customisation.

Artificial intelligence has rapidly moved from a hidden technology to a design tool in many creative industries. In yacht design, AI is beginning to play a role in concept generation, sketching, and rendering, accelerating workflows and opening new opportunities for collaboration between designers and clients.

3D printing is increasingly recognised as a disruptive technology with the potential to overcome the limitations of mould-based production. By combining computational design and AM, the yacht sector can experiment with new levels of flexibility, reducing waste and enabling high degrees of customisation. On the other hand, sustainability in yachting cannot be achieved by focusing on isolated components alone, or on a single production technology. Instead, it requires a life cycle approach that considers design, production, use, maintenance, and end-of-life. Digital tools such as parametric modelling, digital twins, knowledge management platforms, IoT, offer a new way to connect these phases.

Finally, the chapter turns to materials, which have always been central to yacht innovation. Today, the focus is shifting towards bio-based, smart, and living materials that combine sustainability with new forms of user experience. From interactive, connected, and smart (ICS) materials to biophilic design and speculative experiments on living matter, the last section explores how a new material culture could transform yacht design.

8.2 AI in yacht drafting and fast-rendering environments

As already introduced, generative design, commonly known as AI, has the potential to transform the way we conceive and produce design radically, and the world of yachting is no exception.

With the boom made by the image-generating tool and the ChatGPT autonomous chatbot at the last years, AI rapidly popped up on everyone's lips, starting to hint at where things are going. Together with the increase in interest, people are assuming contrasting positions in response to integrate such tools. Some view AI as a threat to autonomy, resisting and fearing its implementation; others see AI as an out-of-control competitor in the creative sphere. At last, many professionals are embracing AI as a collaborative tool for innovation, recognising its ability to not only simplify daily and repetitive activities but also to optimise processes and expand design possibilities.

To navigate the complexities of epistemological and ontological dimensions of AI, this study defines AI as computer systems or intelligent agents capable of collecting, analysing, and representing data and information to achieve complex goals (Romero *et al*., 2024). These intelligent capabilities may manifest in various forms, such as the ability to memorise and recall information (Chase *et al*., 2019), optimisation and autonomy of procedures and parameters, and comprehension of human natural language (Kaplan & Haenlein, 2019). Its history is both long and fascinating.

From ancient myths of mechanical beings to Fritz Lang's Metropolis (1927) and Kubrick's 2001: A Space Odyssey (1968), artificial intelligence has long been a topic of cultural fascination. Since then, AI has evolved from symbolic reasoning to advanced neural networks and deep learning, which today power many applications so integrated into our lives that we hardly identify them as AI: search engines, digital assistants such as Siri and Alexa, recommendation systems on platforms like Amazon or Netflix, autonomous driving, and even advanced gaming environments. These examples highlight that the journey of AI is far from complete, and that the technologies we consider ordinary today were once at the frontier of innovation.

Within this landscape, the maritime and yachting sectors are beginning to experience the impact of AI. Yacht design and management, traditionally grounded in human skill and tacit knowledge, are now integrating machine intelligence to analyse vast datasets, simulate complex scenarios, and generate innovative solutions. One of the most immediate areas of application is routing, as already described in the case studies Podium Platform and Sea.AI, for example. In an environment where speed, fuel efficiency, and safety are crucial, AI-powered navigation systems promise to revolutionise voyage planning. These projects already demonstrate how data from hull stress, engine performance, energy consumption, and onboard monitoring systems can be combined with advanced weather routing to improve efficiency. These AI-driven systems provide predictive analyses and intelligent routing decisions that enable owners, captains, and managers to reduce costs, lower emissions, and enhance safety.

It is, however, in yacht design that AI is proving most disruptive. Naval architecture has long employed powerful computational tools for optimising stability and performance, but the integration of AI into concept generation represents a significant step. Algorithms are now able to analyse past design data, market trends, and user preferences, producing insights and imagery that stimulate creativity and guide new concepts. Leading studios, including Olesinski, Luca Dini, ThirtyC, Hotlab, and Winch Design, have openly expressed interest in these tools, seeing them as a new source of inspiration (Merl, 2023). The challenge lies in determining how far current AI-generated visuals can be transformed into viable and technically sound yacht designs.

This tension between conformity and creativity is central to the debate. While AI excels in pattern recognition, human creativity thrives on originality, often breaking rules to innovate (Anantrasirichai & Bull, 2022). In recent years, design software powered by AI has begun to inspire new forms of ideation across the creative industries, with leaders such as Adobe and OpenAI developing tools that are now being adopted by designers worldwide (Gok, 2023). Yacht design, with its blend of engineering rigour and creative expression, is particularly susceptible to the opportunities and risks of these developments.

Educational initiatives are beginning to acknowledge this transformation. Since 2023, the Politecnico di Milano has introduced a course on AI sketching for interior yacht design (Bionda & Incitti, 2024). These platforms enable students, even those with limited modelling or rendering skills, to produce conceptual designs rapidly, iterate ideas, and communicate visions with clarity. The results are impressive. The majority of students encounter AI for the first time, particularly at a fundamental level for generating rendered images. The obtained results do not highlight these blanks, with surprisingly good results for a few hours of course. The quality of the obtained images was highly professional, comparable to the field state of the art. Such tools not only accelerate the learning process but also prepare future professionals for a market in which AI will be deeply embedded in creative practice.

Figure 16.
AI generated render from the course AI sketching for interior yacht design.

In professional contexts, the proliferation of AI-generated yacht concepts on social media demonstrates the rapid adoption of these tools, but also raises questions about their impact on client relations and the role of the designer. Text-to-image systems such as DALL·E and MidJourney can generate striking yacht visuals from simple textual prompts within seconds. An input such as «modern explorer yacht in a Norwegian fjord» or «luxury superyacht master cabin overlooking Sardinia, marble and wood interiors» can produce compelling images, serving both as inspiration and as tools for engaging client preferences. Beyond static images, sketch-to-render and 3D-to-render platforms such as LookX are enabling architects and designers to upload basic 3D models and transform them into detailed renderings with customised styles and lighting. Research is also advancing in image-to-3D and text-to-video applications, which are currently being tested in animation and gaming, but hold clear potential for yacht design. These advances point toward a near future in which designers move directly from AI-generated concepts to AI-assisted 3D models and even into structural and performance simulations, bridging creativity and engineering in a continuous workflow.

The convergence of AI-driven concept generation and AI-powered performance analysis opens up unprecedented possibilities. Designers could soon create imaginative exteriors and interiors and immediately test them for feasibility, efficiency, and structural coherence, radically reducing the distance between vision and execution. In this sense, AI is not only a tool for inspiration but also a potential bridge between creativity and technical validation.

Nevertheless, such opportunities come with challenges. Intellectual property, authorship, and ethical considerations remain unresolved. The balance between human expertise and machine-generated outputs is delicate, and the risk of over-reliance on AI must not be ignored. For this reason, some shipyards and studios are exploring the development of in-house AI systems designed to support concept generation and scenario analysis while ensuring privacy and protecting trademarks. This approach suggests that AI will not necessarily replace the human role but will be adapted into professional practice in ways that preserve creative autonomy and brand identity.

Whether welcomed with enthusiasm or approached with caution, the integration of AI into yacht design is no longer a future scenario – it is already taking place. From drafting to rendering, from education to professional studios, AI tools are reshaping how ideas are generated, visualised, and communicated. The challenge for the industry will be to harness these tools responsibly, ensuring that they enhance rather than undermine the collaborative and creative essence of yacht design.

8.3 Additive manufacturing for flexible customization

Prior to the mid-twentieth century, yacht construction was predominantly a craft-based practice. Boats were built almost entirely by hand, shaped from wood and metal with extraordinary artisanal skill. Each vessel was unique but also costly, slow to produce, and accessible only to a limited clientele. The introduction of fibre-reinforced plastic composites marked a profound turning point, especially for yachts under 40 metres (Musio-Sale *et al.*, 2020; Peterson, 2022), enabling serial production through mould-based methods. It effectively industrialised yacht building and had significant socio-economic consequences, democratising access to recreational boating and fuelling the post-war expansion of the marine leisure sector. However, while mould-based composite construction laid the foundations for the modern industry, it also locked production into a rigid scheme that today reveals pressing limitations.

Two challenges stand out. The first is sustainability. Moulds for yacht production are generally produced in composite materials that are extremely difficult to recycle. After a limited production run, they become large-scale waste destined for landfill, contributing to one of the sector's most severe environmental burdens. The second is flexibility. Moulds impose geometrical constraints and restrict formal freedom. For highly customised yachts, this creates a contradiction in principles. Too often, meeting customisation demands requires reverting to labour-intensive artisanal methods, thereby reintroducing high costs and inefficiencies.

The solution lies in rethinking not only the yacht as a product, but the production process itself. The challenge is to move towards zero-tooling, data-driven paradigms that unite the efficiency of industrial production with the freedom and responsiveness of craft. The NEMO – Design 4 Yacht Flexible Customisation project, initiated by the Design Department of the Politecnico di Milano within the PNRR MICS (Made in Italy Circolare e Sostenibile) partnership, was conceived precisely within this perspective. Its objective is to explore how additive manufacturing, coupled with computational design, could enable radical new forms of flexible customisation in the yacht sector.

The approach has been tested through an experimental case study on a yacht component, benchmarked against traditional composite production methods.

As already seen, additive manufacturing offers inherent advantages for mass customisation. Free from the need for moulds, it enables the production of components tailored to specific functional or aesthetic requirements. Furthermore, AM reduces waste (by depositing material only where needed) and enables the creation of lightweight, structurally optimised components. On the other hand, computational design offers the opportunity to code processes and rules that generate shapes specifically for AM. Through parametric and algorithmic logic, design optimisation becomes dynamic, repeatable, and open to continuous variation (Caetano & Leitão, 2020; Manavis *et al*., 2023; Ramage, 2022). The combination of these two approaches enhances both flexibility and sustainability and has already shown transformative potential in fields such as automotive, aerospace, and construction (Vasco, 2021; Chatterjee *et al*., 2022). In the nautical industry, however, documented examples remain rare.

The NEMO project expanded this exploration through a case study on a major yacht component: a three-metre-long, L-shaped multifunctional unit located in the aft of the Wallywhy100 yacht, serving simultaneously as a seating area and kitchen cabinet (Piccioni *et al*., 2024). Its size, aehestetic role, complexity, and hybrid function made it a suitable candidate to test the advantages of AM. A comparative analysis was carried out against the traditional hand lay-up composite method.

The results were striking. The AM prototype achieved a 45% weight reduction (from 209 kg to 114 kg) through a hollow rib-stiff-

Figure 17.
NEMO project case study and detail of additive manufacturing process.

ened structure that balanced material efficiency with structural integrity. Costs fell by approximately 27%, largely due to the absence of tooling. Preparation time was also streamlined: computational software reduced pre-production work, removing the manual labour required to build moulds. Although total process hours were higher than traditional methods (142 vs. 80), the comparison is misleading. Most of the AM time (72 hours) was autonomous machine printing, requiring minimal human supervision. Continuous 24/7 operation therefore allowed for shorter lead times in practice, while drastically reducing active labour hours. This shift reframes efficiency from human work-time to automation potential.

Beyond these quantitative results, the case study underscored the paradigm shift required by Design for Additive Manufacturing (DfAM). The prototype was originally conceived for mould-based production and then re-engineered for AM. In a true DfAM scenario, however, design constraints would be defined from the outset around the freedoms and opportunities of additive processes. Draft angles and tooling restrictions would no longer dictate forms; instead, designers would focus on optimising geometry, performance, and functionality directly for printing. This would elevate design from being a downstream adaptation to becoming the driver of process innovation. AI generative design was also tested, revealing an interesting aesthetic path, although not yet suitable for real-world engineering.

The implications are considerable. From a workplace perspective, AM significantly reduces operator exposure to the volatile organic compounds released during composite lamination, improving health and safety (Piccioni & Ratti, 2024). From a market perspective, it enables unprecedented degrees of personalisation, strengthening the emotional bond between user and product. Customisation, in this sense, is no longer only a luxury but also a sustainability strategy: by increasing perceived value, it reduces the tendency towards premature replacement. From a systemic perspective, eliminating moulds directly addresses one of the most problematic waste streams in yacht production. Furthermore, the choice of using thermoplastic material in AM components enables reprocessing, supporting circular economy principles and a cradle-to-cradle lifecycle for components.

The scalability of such an approach extends beyond yachting.

The innovations tested in this project could be applied to recreational vehicles, hospitality, and furniture, where space optimisation and flexible customisation are equally critical. At the same time, limitations must be acknowledged.

The current NEMO research is based on a limited set of pilot cases, and further studies are required to validate the methodology across a wider range of nautical components with different scales and structural demands. Future developments within the NEMO project will therefore focus on assembly and finishing, exploring integrated features such as snap-fits, reversible upholstery, and design-for-disassembly strategies. Such advancements would not only enhance flexibility and customisation but also strengthen the sustainability of the entire lifecycle, aligning the sector with broader goals of decarbonisation and circularity. The integration of additive manufacturing and computational design opens a new frontier for the nautical industry. It challenges the rigidity of the mould-based paradigm, responds to the dual pressures of sustainability and customisation, and positions design at the centre of production innovation.

8.4 Tools and perspective in yacht life cycle

The yachting sector has experienced steady growth in recent decades, driven by technological innovation, evolving customer expectations, and the growing culture of luxury experiences. However, yacht design and production remain resource-intensive processes; operations continue to be closely tied to fossil fuel consumption, and end-of-life management is still underdeveloped. Even if the sector is looking toward sustainability, current efforts are often limited to incremental improvements, such as substituting materials, experimenting with biocomposites, or testing hybrid propulsion systems. These actions represent important advances, yet they frequently remain isolated, improving specific components rather than addressing the yacht as a whole system (Ceschin & Gaziulusoy, 2019).

This situation has created an ambiguous position for many manufacturers. On the one hand, the majority of shipyards are increasingly communicating their environmental commitments, investing in low-impact materials, certified resources, or alternative fuels. On the other hand, such strategies rarely extend to a systemic level. By focusing narrowly on single attributes, there is the risk of burden shifting, reducing impacts at one stage of the life cycle while increasing them elsewhere (Hauschild *et al.*, 2018). A common example is the adoption of bio-based composites or recycled plastics, which reduce raw material demand but often rely on chemical additives that challenge recyclability. This gap between environmental promises and systemic outcomes is what the literature frequently refers to as greenwashing (de Freitas Netto *et al.*, 2020).

To address these challenges, a Life Cycle Design (LCD) approach has gained ground. Unlike Green Design, which focuses on targeted interventions, LCD integrates environmental requirements across the entire product development process. Literature in the field distinguishes between three levels of integration: macro (strategic), meso (tactical), and micro (operational) (Brones & de Carvalho, 2015; McAloone & Pigosso, 2018; Schöggl *et al.*, 2023). The macro level concerns long-term commitments and corporate strategy; the meso level embeds environmental criteria in design and engineering routines; while the micro level is concerned with the tools that designers and engineers use on a daily basis.

As previously mentioned, in the yachting sector, this systemic integration is still in its infancy. Research has tended to focus on specific aspects (such as propulsion, materials, or compliance with regulations) without consolidating these into a comprehensive framework that spans the entire life cycle. To overcome this gap, the doctoral project Effectively Integrating Life Cycle Design in Yachting (Ruggiero, supervised by Bionda, in collaboration with Sanlorenzo and the Water Revolution Foundation) is one of the first to propose such a framework, while the MILDS project (2021-2023, Politecnico di Milano Alta Scuola Politecnica with Sanlorenzo) has laid foundations by exploring the use of digital twins for life cycle management.

The environmental urgency is evident in the limited but public shared life cycle assessment (LCA) studies available on yachts. These confirm that the use phase is the most impactful, accounting for more than 85% of CO_2-equivalent emissions (GWP100), primarily through fuel consumption, which depends on engine power, operational hours, and navigation patterns (Favi *et al.*, 2017, 2018). However, other phases cannot be ignored. The production phase carries a high burden due to energy-intensive processing of composites, aluminium, and steel, as well as significant scrap generation. The maintenance phase introduces environmental risks through the use of antifouling paints, lubricants, and component replacements, thereby contributing to marine contamination. Finally, the disposal phase reveals a striking asymmetry: metals are readily recyclable, but composites usually end up in landfill or incineration, compounded by coatings, adhesives, and insulation (Favi *et al.*, 2018).

It is precisely here that digital tools can provide systemic solutions, connecting the fragmented phases of a yacht's life into a coherent and data-rich cycle. Tools such as parametric modelling, KBE, DT, and IoT networks can serve as bridges between design, production, operation, maintenance, and end-of-life.

At the design stage, parametric modelling has already begun to change practice. Instead of treating design as a series of static drawings, it allows designers to work with relationships, rules, and constraints. Performance targets, regulatory conditions, and even preliminary sustainability criteria can be embedded at the earliest stage. When this is coupled with knowledge management systems, operational data from previous yachts can be integrated into new projects, ensuring a progressive accumulation of know-how. The DT represent the place where data analysis and digital model design could come in place simultaneously.

During the production and use phase, the integration of IoT networks and sensors extends the digital model into a living DT. This evolving representation of the yacht records operational data in real time – structural stress, energy consumption, or user behaviour – and becomes a shared platform for designers, shipyards, owners, and crews. The MILDS project has shown how such a system can reduce unplanned maintenance costs by applying predictive algorithms based on mean-time-to-failure. Similarly, digital twins can manage energy efficiency, linking propulsion optimisation with onboard systems such as HVAC or lighting, thus reducing consumption without compromising comfort.

At the end-of-life stage, in maintenance and refit, these tools transform practices that were once reactive into proactive and collaborative processes. A digital twin can act as an interactive logbook, combining technical specifications with operational history. When visualised through augmented or virtual reality, it allows crews, engineers, and clients to *walk through* the yacht's systems, plan interventions, and test modifications before physical implementation. This not only increases efficiency but also extends the vessel's usable life, aligning sustainability with economic value. Such an approach supports circular economy strategies, shifting the yacht industry away from linear models of production and disposal.

Taken together, these technologies indicate a paradigm shift. Rather than seeing yacht design as a linear chain of distinct stages, digitalisation enables a continuous cycle of data and knowledge. Information no longer disappears between phases but is shared, updated, and reapplied across the vessel's life. This creates new opportunities: strategic sustainability goals can be translated into operational practices; design and production can anticipate future maintenance or disposal; and clients can be engaged in new forms of co-creation.

Challenges remain, expecially in cultural acceptance among designers and shipyards, but the yachting sector can move beyond incremental sustainability efforts towards systemic LCD. This is not merely a technical upgrade but a cultural transformation, repositioning design as the driver of a more circular, data-driven, and sustainable future for yacht building.

8.5 A new materiality: smart and bio materials for yachts

Material innovation has always played a central role in the evolution of yachts. The history of yachting has already shown how radical these transitions can be: from wood and steel to composites, each material shift has reshaped design practice, manufacturing, and the very idea of luxury on the sea. Today, we are at the beginning of another transformation. What researchers are calling a *new materiality* brings together bio-based composites, smart materials, and living matter, opening scenarios that go well beyond performance or durability. It is not simply a matter of finding alternatives to traditional FRPs but of rethinking the meaning of materials themselves in yacht design.

One important strand of this work comes from the study of so-called ICS materials (Interactive, Connected, Smart). In this context, Parisi *et al.* (2018) suggest a useful classification: inactive, reactive, and proactive. Inactive are the conventional materials with no interaction. Reactive are the better-known *smart* materials that respond to light, temperature, or pressure, often in combination with traditional substrates. Proactive materials, instead, embed electronics, sensors, or computational components, making them programmable and networked. As Rognoli (2020) has argued, this marks a hybridisation of the physical world: even what was once considered inert matter can now become interactive, connected, and intelligent.

This shift intersects with sustainability. The concept of smartainability, coined by Girardi and Temporelli (2016), highlights how *smartness* can be measured against its contribution to energy efficiency, environmental benefits, and quality of living. In other words, intelligent materials should not only create comfort or surprise but also actively reduce impacts. In the maritime sector, this logic is beginning to take shape. Cruise ships and superyachts are experimenting with biomimetic and smart features that merge technical efficiency with new forms of user experience.

Alongside this, designers are increasingly influenced by biophilic approaches. Biophilic design, as defined by Kellert *et al.* (2008), stresses the integration of natural light, airflow, patterns, and textures that recall nature, with measurable benefits for wellbeing. Recent experiments such as Oceanco's NXT project or the Biophilic Superyacht by 3deluxe take these principles into the nautical field. In the first case, interiors are re-imagined through organic forms, soft lighting, and materials inspired by natural surfaces. In the second, the yacht becomes a floating greenhouse, a *garden of Eden* where food cultivation, communal lounges, and open layouts replace the closed, compartmentalised model of the traditional superyacht.

What is interesting here is how personalisation and materiality converge. Living materials – those able to regenerate, purify, or react – offer a chance to move beyond static luxury finishes. Imagine interior panels that glow softly through bioluminescence, upholstery that purifies air, or modular partitions that change according to privacy needs. In such cases, the material does not simply serve a function or an aesthetic but becomes part of a personalised experience. Owners increasingly value time, privacy, and uniqueness; materials capable of responding and adapting can embody these values in physical form.

Research projects have begun to explore this speculative horizon. At Politecnico di Milano, two initiatives – ICS-Materials (2017-2019) and the ongoing Re.Live (2023-2025) – have investigated the potential of responsive and bio-integrated materials. Workshops have tested concepts ranging from bio-integrated wellness spaces to surfaces that engage with air or light (Parisi *et al.*, 2019; Guarino *et al.*, 2025). Though largely speculative, these studies underline the high potential of smart and living materials for the nautical field.

Ultimately, what emerges is not just a new selection of materials but a redefinition of the onboard experience. The sensorial aspect of materials becomes a trigger for emotions, while responsiveness introduces an additional layer of exclusivity. In this perspective *new materiality* for yachts is not only about environmental responsibility but also about reinforcing the cultural link between luxury, customisation, and the sea.

9. Concluding Reflections

The reflections presented in this book represent the outcome of an explorative journey into the digitalisation of yacht design. Rather than providing definitive answers, the work has sought to open questions, to map a field that is still in rapid transformation, and to connect different layers of knowledge. Literature reviews, empirical evidence from case studies, and speculative research actions have been interwoven in order to capture the many dimensions of a sector that is now facing one of the most significant shifts in its history. The ambition was not to propose a linear narrative but to acknowledge the complexity and fluidity of a transformation that touches culture, processes, tools, and materiality at the same time.

In this sense, what emerges is less a closed framework than a field of possibilities. Digitalisation has already entered the everyday practices of yacht design and production, but its potential is far from exhausted. Each of the technologies discussed represents not only a tool but also a new language for design. To adopt these technologies requires not simply learning how to operate them but also rethinking the role of the designer, the relationship between creativity and engineering, and the meaning of luxury in the contemporary world. The exploratory character of this research is therefore crucial: only by experimenting, testing, and speculating can the sector move from isolated innovations to systemic transformation.

Among the different directions investigated, the use of artificial intelligence for yacht design opens some of the most intriguing but also challenging questions. At the time of writing, AI tools for drafting, fast rendering, and early-stage concept generation are being tested in academic and professional contexts. Yet these remain preliminary explorations. The creative industries at large have shown that AI can act as a powerful accelerator of ideation, but its full impact on design languages, authorship, and customer relationships is only beginning to unfold. For yacht design, which is inherently multidisciplinary and deeply linked to identity and personalisation, the task ahead is to understand how AI can contribute to a new expressive vocabulary without undermining the cultural and artisanal values that define the sector. This will require not only technical experimentation but also critical reflection on ethics, intellectual property, and the balance between human imagination and machine-driven processes.

Closely connected to this is the question of skills. The digital transformation is not simply about equipping studios and shipyards with new software or machines. It demands a reconfiguration of competences at all levels. Designers must acquire abilities in computational thinking, algorithmic modelling, and data interpretation, complementing but not replacing traditional expertise in naval architecture, ergonomics, and aesthetics. Engineers must be prepared to work with generative processes, parametric twins, and data-driven optimisation. Managers must learn to interpret the flows of information that digital platforms generate, making decisions based not only on intuition but also on predictive and real-time analytics. The success of digitalisation in yacht design will depend as much on education and professional training as on technological readiness. Without this parallel investment in people, even the most advanced tools risk remaining underutilised or misapplied.

Another aspect that emerges from this research is geographical. The work has been conducted with an international outlook, but with a particular focus on the European context, which continues to represent the centre of yacht design and shipbuilding. Italy, the Netherlands, Germany, and the United Kingdom hold established leadership, not only in terms of production capacity but also in cultural influence and design excellence. The *Made in Italy* brand, for instance, has been instrumental in shaping the global imagination of yachting as a field of luxury, craft, and innovation. Yet, at the same time, new regions are rapidly entering the scene, bringing different values, expectations, and levels of technological maturity.

The Far East, particularly China, is showing remarkable acceleration in the fields of electrification, digitalisation, and advanced manufacturing. The development of smart cities and integrated digital infrastructures creates a fertile environment where new forms of yacht design and use may emerge. The Middle East, with its strong investment in luxury sectors and its vision of diversification beyond oil, is also positioning itself as a future hub for sustainable yachting innovation. These regions do not only represent new markets; they may introduce disruptive approaches to how digital technologies are perceived and applied on board. The cultural codes of luxury, the pace of technological adoption, and the regulatory frameworks may differ significantly from European traditions, reshaping global balances in unexpected ways.

This global diversification reinforces the need for systemic thinking. Sustainability, personalisation, and digitalisation cannot be tackled as isolated objectives. They intersect and overlap, requiring strategies that combine environmental responsibility, cultural sensitivity, and technological innovation. The future of yacht design will be shaped by how effectively the sector can integrate these dimensions. This is where the role of research becomes indispensable.

Universities and research centres, such as the Politecnico di Milano, provide spaces where speculative visions can be tested, prototypes developed, and collaborative frameworks established with industry partners. Such collaborations not only advance technical solutions but also foster the conceptual and ethical reflection needed to navigate change responsibly.

Ultimately, the picture that emerges from this book is one of transition. The digital era is not a fixed destination but a process in motion, characterised by experimentation, negotiation, and adaptation. Yacht design stands at the confluence of tradition and innovation: it must honour its artisanal heritage while embracing computational methods; it must preserve exclusivity while moving towards sustainability; it must maintain cultural continuity while opening to new global players. The challenges are significant, but so too are the opportunities.

The journey ahead will require courage to invest in shared platforms, willingness to redefine roles and skills, and openness to new cultural influences. If the sector succeeds in aligning technological innovation with sustainability imperatives and the evolving values of luxury, yacht design can once again reinvent itself, as it has done in past centuries. What is at stake is not only the future of an industry but also the possibility of creating meaningful experiences where technology, culture, and the sea come together in new and responsible ways.

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MICS
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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. MICS is a national research programm dedicated to advancing the transformation of the Italian manufacturing system through circularity, digital innovation, and sustainability. It promotes collaboration between universities, research institutions, and industry to foster new models of design, production, and consumption that combine technological excellence with environmental and social responsibility.
https://www.mics.tech/en/home/.

Designing Yachts in the Digital Era examines the transformation of yacht design within the context of the digital and industrial transitions characterising contemporary design practice.
Drawing on over ten years of research, and enriched by the results of NEMO and CYClaDES projects (PNRR – MICS programme), the volume investigates how computational technologies, advanced manufacturing, and data-driven systems are redefining processes, roles, and disciplinary boundaries in the yachting industry. Through a structured methodology of framing, scanning, forecasting, and acting, the research connects theoretical reflection with empirical studies, industrial mapping, and co-design experimentation. It explores how digital frameworksare reshaping the relationship between design, production, and user experience, and how yacht design can evolve from object-centred practice toward a systemic approach. By integrating foresight methods with design research, it outlines new models for digital integration, sustainability, and customization, positioning design as a form of strategic intelligence capable of navigating complexity and guiding transformation.
Addressed to scholars, designers, and professionals engaged in advanced design and maritime innovation, this work offers both theoretical foundations and methodological tools for rethinking yacht design in the age of digital transformation.

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