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YACHT DESIGN IN THE ERA OF DIGITAL TRANSITION

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ABSTRACT

The design of ships has changed dramatically since the 1970s. We have shifted from manual drafting to digital tools and computers, mostly because computer technology has greatly improved. Now, with the growth of smart digitalization in Industry 4.0, using modern digital software and tools makes ship design more efficient and enhances its quality throughout a ship's entire lifespan. However, this shift has also made operations more complex and requires users of the software to have more specialized training. Today, technologies like automated optimization, simulation-based design, managing the entire product lifecycle, digital twins, and artificial intelligence are commonly used in the shipping industry. These technologies are applied during both the design and construction phases, as well as in preparing and inspecting ships. This paper reviews major advances in these areas and discusses how the industry can address current and future challenges.

Keywords: yacht digital design, generative design tools, collaborative platforms, virtual reality

1. Introduction

The information technology landscape has undergone notable transformations in recent years, marked by the emergence of big data, cloud computing, additive manufacturing, and industrial robotics. Consequently, the profound convergence of information technology and industrial processes has positioned intelligent manufacturing as a salient theme in global economic strategic planning, garnering considerable attention from governmental bodies internationally. Illustrative examples include the Advanced Manufacturing National Program in the United States, France's "New Industrial France" initiative, Germany's "Industry 4.0," and China's "Made in China 2025" strategy. Intelligent manufacturing represents a fundamental innovation in production organization and business models, arising from a synergistic and comprehensive integration of manufacturing technology and information technology. This constitutes a multifaceted yet systematic construct that transcends discrete technological advancements or the superficial implementation of novel production equipment [1].

This paper explores the digital technologies of Industry 4.0 to highlight their role in yacht design practices, although they do not seem to be influenced by the transformations that have occurred in digital production technologies. The impact of these new technologies on yacht design is considered more of a paradigm shift in practices, without a clear question on how the design process should change in order to drive the digital revolution [2].

In this study we ask the question: How can innovative yacht design practices, which rely on digital technologies, change the approach to yacht design?

2. Yacht digital design

The ongoing industrial revolution is causing widespread societal change. Within design, digital and interconnected technologies are enhancing not just visualization but also influencing formal inspiration and the creative process itself. This research examines how digitally enabled technologies are reshaping disciplinary approaches within yacht design, a specific area of industrial design where engineering and design methodologies intersect. Through case studies and future-oriented workshops, the study outlines a progression towards a more digitally aware and virtually collaborative setting, suggesting that traditional yacht design processes are becoming obsolete. The findings, presented in the form of three roadmaps, show how digital technologies of Industry 4.0 are changing the representation of design projects, as well as their formal tools. Consequently, this research highlights three potential changes that may occur in yacht design practices: a transition from analog to digital input data, refocusing from measurement to inference; a move in "digital doing" from drafting to logic through parametric and generative tools; and a transformation in communication media towards more collaborative strategies via digital twins. he findings presented here are the result of a three-year research project exploring the role of Industry 4.0's digital technologies in the transformation of yacht manufacturing and the resulting challenges for yacht design practices [2]. This research topic was chosen based on an anticipated need to understand and guide the digital evolution of the yacht design sector, as "Yachting 4.0" is a largely unexplored area in current literature.

Since its inception in 2011, Industry 4.0 has increasingly captured the attention of organizations, governments, and researchers. This industrial revolution is unique in its a priori prediction, allowing for proactive shaping by both academia and industry. In addition, its economic impact extends everywhere in design, which influences business models, and human behavior. However, the disruptive changes in digital production and new production models do not seem to influence this design. Current discussions on technology's impact often fail to recognize the shift to digital representation and manufacturing as a paradigm shift in practices. Beyond limited onboard applications of smart and virtual technologies, research focuses on listing technological opportunities and challenges without questioning the changes in the yacht design process that will set in motion the digital revolution. Despite the crucial role of design in yacht projects, existing literature typically examines it from an engineering viewpoint, describing the process as an iterative trial-and-error method for meeting predefined requirements – a spiral of incremental optimization from desired capabilities to final design evaluation [3].

This research aims to stimulate critical thinking about emerging yacht design practices that are being shaped by the digitally enabled technologies of Industry 4.0. The exploration of potential future directions seeks to address two key research questions: Firstly, how can these technologies be more effectively integrated into the digital product-service ecosystem surrounding yachts? Secondly, how do these future scenarios alter the fundamental disciplinary approaches to the yacht design project and its associated practices?

In the wider field of design, a series of technologies (collaborative platforms, the Internet of Things (IoT), intelligent products) reshaping not only how design projects are represented but also the sources of formal inspiration, the initial data used, the communication strategies employed, and the very process of design itself. The digitally enabled technologies driving the Industry 4.0 revolution and which include Additive Manufacturing (AM), Virtual and Augmented Reality (VR/AR), Industrial Internet of Things (IIoT), Big Data Analytics, Cloud Manufacturing, Advanced Human Machine Interfaces (AHMI), and Big Data Analytics, are widely acknowledged as the primary forces behind this ongoing transformation [3].

Starting from the main European industrial strategies, these digital technologies can be classified as follows: (IIoT and Cloud Manufacturing) - focused on connectivity; (Big Data Analysis and Simulation and System Integration) - which enable intelligence; (VR/AR and AHMI) - focused on digitalization and (AM and Co-robots) - which are related to production. Furthermore, these technologies are intrinsically linked with six core Design 4.0 principles: service orientation, decentralization, virtualization, real-time capability, self-configuration, and flexibility. These principles collectively serve to strengthen the interconnectedness between product-service systems and the underlying manufacturing processes [4].

Existing literature emphasizes two key behaviors of design principles—namely, consciousness and interoperability—alongside two distinct levels of integration within both manufacturing and design processes, as visually represented in Figure 1. As illustrated, these principles facilitate the development of Industry 4.0 considering two levels of integration (a vertical level, which is integrated through the production system, value chain and customer services and a horizontal level that is integrated into the value networks of businesses) [2].

Horizontal integration in the context of Industry 4.0 refers to the seamless connection and unification of digital systems used in various aspects of a business. This includes processes related to products, production, and overall business planning. Essentially, it's about achieving comprehensive digitization throughout the entire value chain. A key aspect of horizontal integration is the centralized management of data exchange and interconnected information systems, ensuring a smooth flow of information across different operational areas [3].

In contrast to this focus on systems and information flow across the value chain, vertical integration introduces a hierarchical dimension. This type of integration organizes different levels of the manufacturing process into a structured hierarchy. These levels include [5]:

- The field level, which directly interacts with the physical production process through sensors and actuators.
- The control level, responsible for regulating both individual machines and integrated systems.
- The process is line-level, which requires continuous monitoring and control to ensure efficient production.
- The operations level encompasses crucial functions like production planning and quality management.
- The enterprise planning level, which deals with overarching business processes such as order management, processing, and the overall production schedule.

Within this vertical integration framework, a digital execution platform plays a pivotal role. It acts as a central hub, transforming the traditional manufacturing headquarters into a dynamic center for information and connectivity across all hierarchical levels.

Based on these concepts, the authors of this research analyzed how digital technologies can connect with the six fundamental principles of Design 4.0. This analysis is based on real-world case studies, thus providing a clear understanding of how the strengths of these technologies can be integrated both vertically and horizontally into the digital framework of the yachting industry [5].

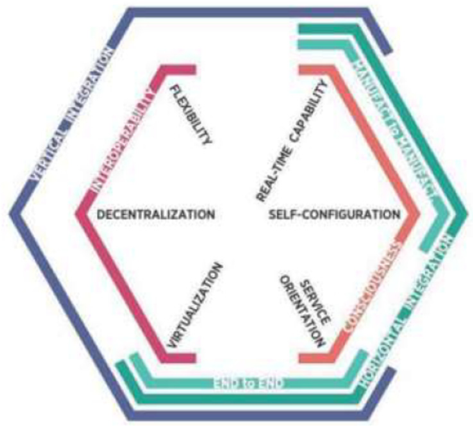

Figure 1 The design principles that make the development of Industry 4.0 possible, in graphic interpretation [2]

3. The methodological approach

The inherent uncertainty in predicting future scenarios and challenges with absolute certainty means that instead of precise predictions, the research emphasizes foresight and understanding as crucial tools to inform present actions. Given the novelty and the "unexplored complexity" of the Industry 4.0 paradigm, particularly within the yachting sector, and the limited existing academic literature on this specific intersection, the research prioritizes strategic thinking for exploring alternative futures, a methodology often referred to as Future Studies [6].

Historically, the onset of previous industrial revolutions originated within the industrial sector itself, subsequently triggering significant societal transformations. However, the current industrial revolution presents a contrasting dynamic. The impetus for this transformation process does not directly stem from the industry in isolation but is instead ignited by a hyper-connected society. This marks a significant departure from historical patterns. Notably, this is the first instance in history where an industrial revolution is being anticipated and analyzed proactively, rather than being understood only after its unfolding. This unique characteristic provides both researchers and companies with unprecedented opportunities to shape their future direction actively [5].

To systematically explore this evolving landscape, the research strategy mirrors the structured six-step process of strategic forecasting. The research activities are divided into corresponding phases to guide the study logically, starting from an initial review of existing literature and culminating in a proposed agenda for future research.

The initial phases, Framing and Scanning, were designed to establish a robust foundation for forecasting. This was achieved through a combination of desk research (analyzing existing reports, publications, etc.) and case studies. These activities aimed to identify key drivers within the digital yacht ecosystem (the factors propelling change), the significant challenges that need to be addressed, and the inherent uncertainties surrounding the future.

The selection of good practices for the case study analysis was a deliberate process, informed by consultations with various stakeholders. These included academics with expertise in relevant fields, representatives from naval and nautical shipyards, suppliers of marine technology, yacht designers, and nautical industrial associations. This multi-stakeholder input ensured a comprehensive and industry-relevant selection of cases [7].

The data sourcing for the case studies was conducted in two stages. The first involved primary source semi-structured observation during major nautical trade shows held between 2017 and 2019. This firsthand observation allowed the researchers to gather contextual information and insights directly from industry events. The second stage involved secondary data document review, which entailed analyzing online data, such as company websites, industry reports, and publicly available information related to the selected case studies [3].

Subsequently, the characteristics of each identified case study were systematically analyzed based on several key parameters:

• Technologies and sub-technologies enabling the implementation of user experience (UX): Identification of specific digital tools and their underlying components used to enhance the user experience.

• Relevant 4.0 design principles: Assessing which of the core Design 4.0 principles (virtualization, self-configuration, etc.) were evident in the case study.

• Impact on the Yacht Design (YD) process: Analyzing how the technologies and principles influenced the way yachts are designed.

• Impact on the customer journey: Evaluating how these elements affected the overall experience of the yacht customer, from initial interest to ownership and beyond [8].

Following the initial analysis, scenario-building, specifically employing the Forecasting and Visioning phases, was chosen as the primary forecasting method. This selection was based on the inherent nature of the uncertainties involved in predicting the future of the yachting industry within the Industry 4.0 context, and it aligns with the established framework of Future Studies [2].

While the analysis of the case studies was conducted with an expert-driven perspective, the subsequent forecasting phase adopted a participatory mindset, actively involving stakeholders as co-researchers. To encourage engagement and interaction among these stakeholders, a specific set of activities and tools was designed. This design followed the methodology of the Future Technology Workshop (FTW). The FTW method is particularly suitable for involving people with practical knowledge or experience. The goal was to design the interactions between current and potential technologies within a defined sectoral scenario.

The construction of the scenarios was based on the four main phases of the FTW method [2]:

•A general introduction: This phase focused on outlining the purpose of the workshop and the overall forecasting framework being used.

•A structured brainstorming session: This involved guided activities to generate a wide range of ideas and possibilities related to the future.

•A free envisioning session: This allowed participants more open-ended exploration and creative thinking about potential future scenarios.

•A scenario model-building phase: This involved collaboratively constructing models of future scenarios, specifically exploring the gap between current technological capabilities and potential future advancements.

Crucially, the fourth step of the workshop also included activities focused on listing the requirements for future technology applications and outlining critical aspects that would need to be considered for their successful implementation.

This workshop activity served as the crucial link to the subsequent research phases: Planning and Acting. In these subsequent phases, a retrospective analysis was carried out to substantiate the knowledge acquired and to understand new approaches and tools for yacht design [5].

The research results were presented in the form of roadmaps, which were conceived as a bridge linking future predictions to the current situation, the scenarios being developed through participatory research. The methodological approach here views roadmaps as the strategic plan that defines the digital scenarios. This plan integrates different dimensions of innovation strategy, identifies the significant technologies and tools that will be needed, and plots these elements along a defined timeline.

4. Digitalization of the yachting industry and the necessary technological factors

To provide a visual representation of how the different groups of case studies relate to each other, this research introduces a graphic map, illustrated in Figure 2. This map's primary function is to emphasize the interconnections and relationships observed between the clusters that emerged from the card-sorting activity.

The central organizing principle of this map is a vertical axis representing five distinct levels of consciousness in Industry 4.0 integration. These levels signify a progression in how digital technologies are adopted and utilized within the yachting sector. They are [2]:

1. Digital data gathering: The initial stage, focused on the digital acquisition of information.
2. Simulation: Creating digital models for analysis and prediction.
3. Optimization: Using data and simulations to improve performance and design.
4. System integration: Connecting disparate digital systems for enhanced functionality.
5. Generative design: Employing algorithms to automatically generate design solutions.

These five levels are then analyzed in the context of two horizontal dimensions identified early in the cluster analysis: communication and collaboration. These dimensions likely represent the extent to which the technologies in each cluster facilitate information sharing and joint work among stakeholders.

Based on this framework, the identified groups of case studies are labeled and described as follows:

1. Digital data gathering:

This category includes projects where the primary goal is monitoring the assets of yachts through the integration of the Internet of Things (IoT) and Advanced Human Machine Interfaces (AHMI). The case studies within this group commonly utilize:

• Digital gateways: To collect and transmit data from various onboard sensors and systems.
• Onboard electronic logs: To digitally record operational and maintenance information.
• Digital platforms for vessel system control and automation: To monitor and sometimes remotely control various yacht functions.

Additionally, this cluster encompasses the analysis of environmental digital data, such as weather and sea conditions. The main aim here is to collect and analyze this real-world ("field") data, with a future intention of using these insights to inform the yacht design process [9].

The data gathered from both the vessel itself and the marine environment via IoT structures in these cases is predominantly applied for maintenance purposes, enabling proactive and condition-based maintenance.

Interestingly, only one case within this "Digital data gathering" group explores the more advanced application of comparing the collected real-world operational data with the original design specifications of the yacht. This feedback loop has the potential to significantly improve future designs [10].

2. Data simulation for communication purposes:

This group comprises projects that integrate big data, simulation, Virtual Reality (VR), and AHMI, but are not informed (or only partially informed) by actual operational data collected from yachts in the field. The main objective here is communication.

Key examples include [2]:

•The use of virtual reality in marketing strategic communication, where VR experiences are created to allow potential customers to virtually explore yachts, enhancing the marketing and sales process.
•Virtual sailing testers, which are simulation tools that allow users to experience sailing a yacht in a virtual environment. These can be used for training, evaluating design aspects

from a user's perspective, or even for entertainment. These simulations often rely on general hydrodynamic principles rather than specific real-world data from particular yacht models.

3. Simulation analysis and optimization:

This category includes projects that utilize simulation analysis (using digital models to understand performance) and optimization techniques (using algorithms to find the best design or operational parameters). However, these projects operate within an ecosystem that is not yet fully integrated with other digital systems and are not informed by real-world operational data [11].

The focus here is on using computational tools to analyze and improve yacht designs based on virtual models, without direct feedback from how these designs perform in the real world or a strong connection to other stages like manufacturing or operation.

4. Optimization using systems integration:

Main focus: This refers to collaborative projects that aim to optimize both the product (the yacht itself) and the process (the way it is designed, built, and operated) across the entire value chain.

Key Characteristic: The emphasis here is on leveraging integrated digital systems to achieve this optimization through collaboration among different stakeholders involved in the yacht's lifecycle.

Examples: This group brings together all the collaboration platforms that have been developed for the maritime and yachting industry. These platforms are used to manage various aspects, such as:

•The design phases of a yacht project.

•The broader value chain, involving communication and coordination between designers, manufacturers, suppliers, and potentially owners.

•The operational aspects of yachts, including offshore activities and sailing operations, facilitate better planning, monitoring, and decision-making.

The key idea is that by integrating digital tools and fostering collaboration, it becomes possible to identify and implement optimizations that span multiple stages of the yacht's life, leading to more efficient and effective outcomes [2].

5. Optimization through generative:

Core Focus: This group involves projects that utilize generative design tools to optimize and enable self-configuring product shapes, taking into account the manufacturing process.

Key Technologies: Generative design software, which uses algorithms to explore a wide range of design possibilities based on specified goals and constraints (including manufacturing limitations), is central here.

Description Overlap: The text then provides a more specific description that seems to fall within this "Optimization through generative" category [5]:

•This cluster comprises those collaborative platforms that are used to manage the manufacturing process.

•These platforms are aided by digital-assisted tools such as additive manufacturing (3D printing) and collaborative robots (co-robots).

•The projects in this cluster, with a collaborative nature, aim to obtain self-configurable product shapes depending on the constraints and possibilities of the manufacturing process, using generative design tools.

•The text also notes that a few cases utilizing cloud manufacturing as a key technology are gathered in this group. Cloud manufacturing involves using shared manufacturing resources accessed via the internet, which can complement generative design by providing flexible production capabilities for the algorithmically generated shapes.

In essence, "Optimization through generative" focuses on using computational power and AI-driven design tools, often in conjunction with advanced manufacturing techniques, to create optimized forms that are also well-suited for how they will be produced. The collaboration aspect here likely refers to the interaction between designers, engineers, and manufacturing specialists using these digital tools [3].

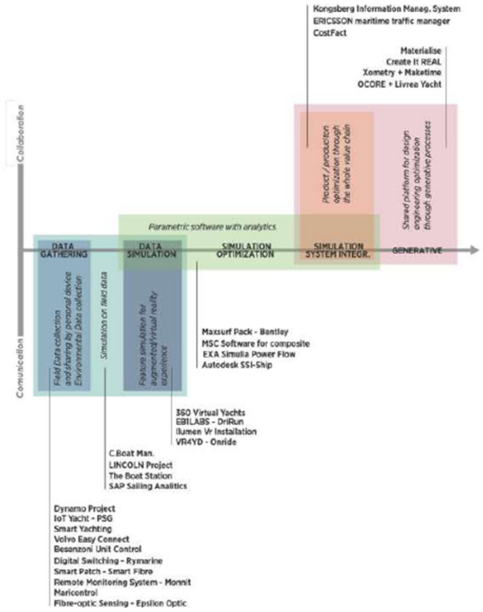

Figure 2 The five levels of consciousness in Industry 4.0 integration [2]

Based on the graphic map, a distinct separation emerges between projects focused on communication and those emphasizing collaboration. Communication-centric strategies tend to be more prevalent in projects with lower levels of Industry 4.0 integration consciousness. In contrast, collaborative strategies are more characteristic of projects that demonstrate systemic integration and deeper self-configuration processes.

Technologies associated with communication-focused clusters align with Design 4.0 principles of virtualization, service orientation, and decentralization [5].

In contrast, the analysis indicates that case studies implementing collaborative platforms for design typically do not use field data along the value chain, and this is also true for the optimization processes within these cases. The technologies employed in these more advanced, often generative design-oriented, projects directly contribute to design principles such as flexibility, self-configuration, and real-time capability, bridging the horizontal integration aspects of both manufacturing and design [3].

Specifically, the research observes the emergence of novel communication media in the relationships between companies and the end-users of yachts. These new environments aim to facilitate faster and easier access to information using digital platforms and personal devices.

5. Yacht Forecast 4.0

To build the forecasting framework for the scenario development phase, the results of the case study analysis are examined through the perspective of an ecosystem approach adapted for Industry 4.0 scenarios. This framework outlines a four-stage evolution from a product-centric model to a platform-focused one [2]:

Core Product: This represents the foundational, traditional offering, which can be "digitized" by incorporating supplementary digital layers. (ii) Digital Augmentation: Here, digital customer interfaces, visualization tools, touchpoints, and channels are introduced to enhance the user experience and enable diverse interaction modalities.

Digital Service: At this stage, digital services and the physical product are integrated to provide a complete solution that responds to a broader spectrum of customer needs. (iv) Digital

Ecosystem: This final stage involves embedding the product within a wider ecosystem that includes interfaces for suppliers, partners, and customers, fostering co-creation and the capture of additional value.

In the context of this research, the standard Industry 4.0 scenario framework is expanded to incorporate the manufacturing process within the systemic approach, as well as the "after launch" stage of the yacht's lifecycle. As illustrated in Figure 3, this extended frame features four concentric circles that are divided into four quadrants by the two axes [2].

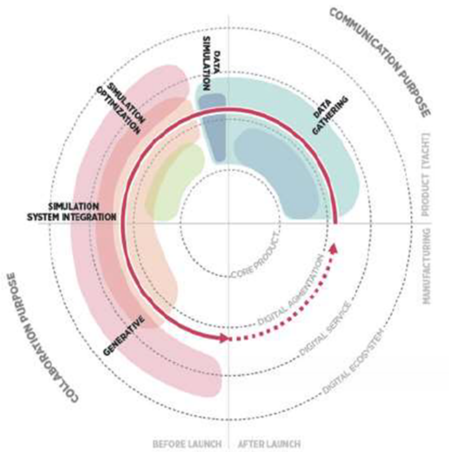

Figure 3 Yachting 4.0 manufacturing process in the systemic approach [2]

The horizontal axis of the frame differentiates between the focus on product and production, and the vertical axis delimits the two parts, distinguishing between the "before launch" and "after launch" phases of the yacht's life cycle. This division of the concentric circles into four sectors yields: design (product-focused, before launch), manufacturing (production-focused, before launch), sailing (product-focused, after launch), and maintenance (production-focused, after launch).

The Yachting 4.0 forecasting framework is constructed by superimposing the clusters identified in the Case Studies map onto this scenario framework. This overlay aims to provide a foundation for addressing the first research question: How can these technologies be implemented more effectively for yachts, considering the digital product-service ecosystem scenario? [5]

Between the "before launch" and "after launch" sections, there is a barrier that reflects the previously observed separation between communication and collaboration. Specifically, digital data from real-world usage ("field") and user engagement are not consistently used in the two phases of design and maintenance. This leads to a disconnect between the two phases, potentially limiting the quality and quantity of input data for design and maintenance.

Within design and manufacturing, horizontal integration of digital data takes place for optimization, simulation, and self-configuration processes.

Collaboration strategies are associated with projects that exhibit a higher level of Industry 4.0 awareness and more advanced horizontal systemic integration, while communication strategies are more often implemented in projects characterized by interoperability. However, even in these latter cases, the implementation of collaborative platforms for optimization and generative design processes often does not fully leverage field data along the value chain [3].

A visual representation of the Yachting 4.0 forecast framework reveals a relative lack of experience in the outermost circle, which represents the digital ecosystem, and insufficient connectivity between the four sectors of the graph. This, in fact, confirms the immaturity of the yachting sector regarding Industry 4.0 and underscores the need for more systemic and holistic visions [2] [5].

6. Scenarios for the yacht digital design

The research pursued three primary objectives: (i) to discuss and validate the proposed scenario framework; (ii) to explore and develop alternative scenarios for Yacht Design 4.0, identifying key drivers and critical issues;

and (iii) to engage and inform the relevant industrial community about the opportunities presented by digital technologies.

To achieve these objectives, the research involved a diverse group of experts from the yacht design field (designers, draftsmen, project and production managers from shipyards, managers from yacht industry associations, as well as digital transformation experts and policy makers). The Future Technology Workshop (FTW) framework served as a guiding framework, aiming to reach a common understanding within a matrix of four categories: digital augmentation - everyday activities enhanced by new technologies; technology and everyday activities; digital ecosystem - new activities that capitalize on new technologies; digital services - new activities facilitated by current technology.

Given the focus on yacht design practices, a holistic perspective on the entire yachting sector was encouraged. Consequently, while the overall scenario-building process followed the four main phases outlined in the methodology, parallel and cyclical activities were conducted, fostering an iterative dialogue between challenges and opportunities, particularly during the free envisioning and scenario exploration phases. This process ultimately led to the creation of three visions, each symbolized by a distinct Roadmap.

The definition of these Yacht Design 4.0 Roadmaps was approached as a design problem, representing a synthesis of activities to understand new processes and tools for yacht design based on the Yachting 4.0 forecasting framework.

A series of generated scenarios were grouped based on the identification of common points, taking into account: (i) the four stages of digitalization within the Yachting 4.0 forecasting framework; (ii) the insights emerging from the scenario exploration phase, shared by the participants; and (iii) three clusters related to yacht product and production: top-of-the-line, and model-based.

Conclusions

In this era of digitalization, all those digital tools and systems that have been recently implemented have a positive impact on increasing the efficiency and quality of the ship design process. Today, the maritime industry widely uses simulation-based design, artificial intelligence, digital twins, etc., in all stages of ship design, operation, and production, which allows the implementation of classic and new design concepts in versatile and integrated platforms. This provides users with a variety of options for developing alternative ship designs, using various tools for analysis, parametric optimization, and virtual prototyping. For example, there is design software (HOLISHIP) that allows for continuous adaptation to current design needs by configuring synthesis models for multiple application cases.

Design teams are increasingly using simulation-based ship design and artificial intelligence to tackle complex design tasks with greater efficiency.

The authors believe that the ambitious goals of building zero-emission ships are a target that requires special attention and can be achieved through the use of new digital technologies, with an emphasis on research and the use of MBSE (Methods of Economy, Environment, Economy and Safety) applications for detonator-based (DT) ship designs, with a view to increasing energy efficiency and improving ship performance. Given these issues and due to an insufficient regulatory framework, innovative measures are proving to be extremely necessary. Developing models and tools for change based on a holistic view of the ship's life cycle is a real challenge for design systems. Currently, there are no standardized DT-based design methods.

Therefore, this paper considers how [12] and [13] define DT systems, as well as how a standardized DT-based framework can be applied to new constructions and ship modernization.

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