Chapter

Yacht Digital Design: Technologies toward a Computational Morphology System

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Abstract

The huge transformation fostered by the current industrial revolution is changing each side of our society. In the design field, the use of digital and connected technologies improves not only the representation but also the formal references and the creative process itself. The research investigates the role of the digitally enabled technologies in modifying the disciplinary approaches to yacht design, a particular field of industrial design in which engineering and design approaches are mixed and overlapped. Through case studies and forecasting workshops, the research proposes a journey toward a more digitally conscious and virtually collaborative environment, highlighting as the traditional process of the yacht design discipline is no more valid. The research results, presented in the form of three roadmaps, show as 4.0 digital technologies are deeply transforming not only the representation of a design project but also its formal references and tools. For this reason, the three possible shifts in the yacht design practices are highlighted—input data are moving from analogic to digital reframing the focus from the measuring to inferring, the use of parametric and generative tools is shifting the "digital doing" from drafting to logic, digital twins are modifying the approach to communication media toward more collaborative strategies.

Keywords: digital technologies, forecasting framework, yacht design, design practices, digital design

1. Introduction

The present paper presents the final results of a three years research process that explores the topic of the digitally enabled technologies of Industry 4.0 with the purpose of understanding its role in yacht manufacturing transformation and then introducing its challenges into the field of yacht design practices. The choice of focusing on this research topic does not derive from a recognized field of study—the Yachting 4.0 topic is almost absent in the literature review—but rather from an intuition about the need to foresight the role of the new digital technologies and new manufacturing models in the transformation of the yacht design sector to understand and guide the undergoing digital transformation.

Since 2011, when it was first conceptualized, Industry 4.0 has been at the center of increasing attention from organizations, governments, and the scientific community [1][1]. As described by Herman et al. [2], the fascination for Industry 4.0 is two-fold. First, for the first time, an industrial revolution is predicted a-priori, not observed ex-post providing opportunities for both researchers and companies to shape the future actively. Second, the economic impact of this industrial revolution encompasses the entire design system, on new business models, product-service systems, and human behaviors [3].

The yacht design sector seems not aware and influenced by the disrupting transformations of digital production technologies and the new manufacturing models. The discussion on new technology impacts on the yacht design discipline struggles in considering the transition to a digital representation and digital manufacturing as a paradigmatic change of practices. Besides the few applications of smart materials and virtual technologies on board, the research is often limited to listing opportunities and challenges and in terms of technological availability, without really asking the question of whether and how the yacht design process itself will have to change to drive the digital (r)evolution. 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[2]. The yacht design process is overall described as an iterative trial-and-error procedure aiming at satisfying predefined requirements; a sequence of operation represented as a spiral involving incremental optimization from the yacht's requested capability to the final design evaluation [5].

In this research, a reflection on novel yacht design practices driven by the digitally enabled technologies of Industry 4.0 is fostered. The explorations of future alternatives pointed at answering the two main research questions: *How could these technologies be better implemented in the yacht digital product-service ecosystem scenario? How do these scenarios modify the disciplinary approaches to the yacht design project and its practices?*

In the field of design, the Internet of Things, robotics, collaborative technologies, 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. Digitally enabled technologies of Industry 4.0 revolutions—Industrial Internet of things (IIOT), Cloud Manufacturing, Additive Manufacturing (AM), Co-robots, Big Data Analytics, Simulation and system integration, Virtual and Augmented reality (VR/AR), and Advanced Human Machine Interfaces (AHMI)—are broadly considered the main drivers of the ongoing transformation. According to the main European Industrial plan,[3] the digital technologies could be divided into four families—connecting (IIoT and Cloud Manufacturing), manufacturing (AM and Co-robots), intelligence (Big Data Analysis and Simulation and System Integration), and digitalizing (VR/AR and AHMI). Furthermore, they come together with the six 4.0 Design principles [2, 6]—virtualization, self-configuration, real-time capability, service

[1] A bibliometric study identified an exponential growth in the number of publications per year on the topic, from only three papers in 2012 to more than 500 in 2015, and roughly 5,800 articles in 2018 [1].

[2] The large quantity of scientific articles is focused on naval architecture (the study of resistance to the movement of the hull), aero-dynamics (efficiency of the appendages and sails), structural engineering, construction, and material technology [4].

[3] Industrie 4.0 (Germany), Piano Nazionale Impresa 4.0 (Italy), Danish MADE, Made in Sweden 2030, Industrie du Future (France), Digital revolution in Industry (The Netherlands).

orientation, decentralization, and flexibility—to strengthen the relationship between product-service systems and the manufacturing process.

The literature highlights two behaves of design principles (consciousness and interoperability) and two different levels of integration in the manufacturing and design processes as schematized here in a graphical representation. As shown in **Figure 1**, the 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 levels 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 into a hub of information and connectivity [4].

Trying to connect the digitally enabled technologies of Industry 4.0 and the six 4.0 Design principles, the authors presented in 2020 a radar diagram analysis, based on case studies, that resulted in a clear understanding of the technology strategic strengths in relation to their vertical and horizontal integration in the yachting industry digital framework (for methodological approach see Bionda [7]).

As shown in **Figure 2** "4.0 Design principles—digital technologies radar diagrams", AM and co-robot are employed in the horizontal integration in

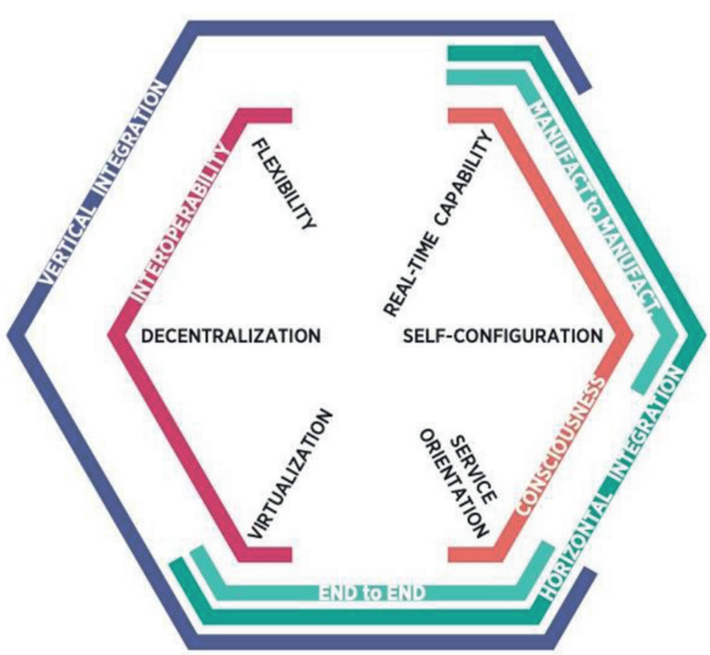

Figure 1.
Graphical interpretation of the design principles according to the different dimensions of digital integration.

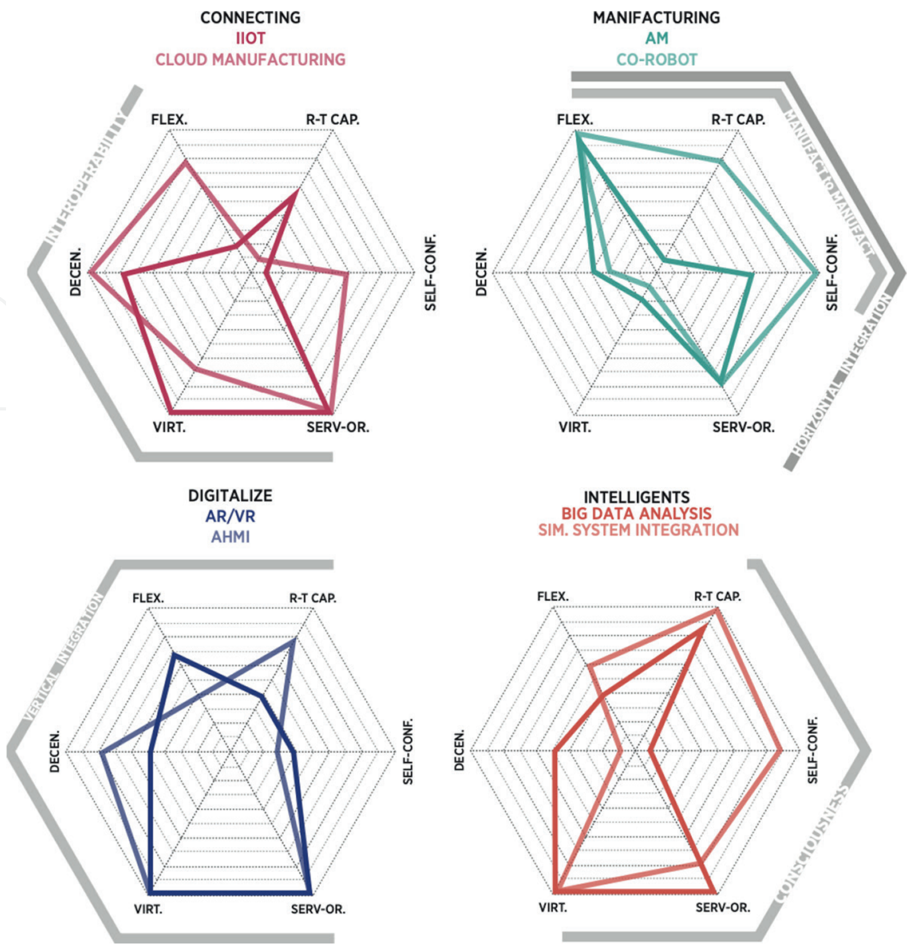

Figure 2.
4.0 Design principles—digital technologies radar diagrams.

manufacturing processes (manufacturing to manufacturing or design studio to manufacturing) with the main characteristics of enabling a more flexible production and, therefore, higher customization. The 4.0 technologies of the connecting family allow interoperability, the ability of a system to exchange and make use of information [6], and are applied in vertical integration processes. Close to the manufacturing family are the technologies big data and simulation and system integration allowing awareness of and responsive actions. These technologies share with IoT a high level in virtualization and service orientation and are able to respond in real-time for horizontal integration of manufacturing and design processes. Looking at the radar chart, the two families connecting and intelligence have complementary behaviors. At last, as the technologies of the digitalize group are mostly digital and virtual communication media, they could be implemented in vertical integration processes, not only at the two extremity of costumer journey sections—communication user-company and communication product-company—but also in each phase of design and manufacturing processes. The digitalized family technologies rely, furthermore, on the design principles of flexibility (i.e., higher customization) and real-time capability, collecting data, analyzing it, and making decisions straight away according to the new findings.

The enabling technologies of the fourth industrial revolution have overlapping areas of application and their implementation is based on digital design and simulation, highly automated manufacturing processes, production data management, and networking. The two main characteristics that describe the evolving system of digital manufacturing-plus-design are "information-driven"—referring to the consciousness principles—and "cyber-physical" with the connection of digital and real word and the ability of a system to exchange and make use of information through and across the value chain (interoperability).

The information-driven system is triggered by IoT and the idea of tagging and tracking "things" with low-cost sensor technologies. In this context, some authors also refer to the Internet of Services, which is based on the idea that services are becoming easily available through web technologies, allowing companies and private users to combine, create, and offer new kinds of value-added services [8]. On the other hand, cyber-physical systems can be defined as "a new generation of systems that integrate physical assets and computational capabilities and are able to interact with humans" [9]. In general, it consists of two main functional components—(1) the advanced connectivity that ensures real-time data acquisition from the physical world and information feedback from cyberspace; and (2) intelligent data management, analytics, and computational capability that constructs cyberspace [10].

Connecting the information-driven capacity with the cyber-physical system, the Industry 4.0 scenario will result in an increased capability of self-organization of manufacturing and other systems, which requires their digital modeling (i.e., virtual factory) and the use of advanced artificial intelligence for process control. As argued by Rodič [11], in this panorama, the product-manufacturing-service system has a unique digital representation, called Digital Twin, consisting of a digital shadow of the real product or manufacturing that alters its properties, condition, and behavior by means of models, information, and data.

It is clear as, in the contemporary panorama, a designer needs to face up design requirements strongly influenced by these advanced technological systems characterized by connected, computational, and open-sourced digital manufacturing. However, the discussion on Industry 4.0 impacts on design discipline is still immature, with few papers discussing the arguments since 2016, only [12].

In the next paragraph, the research methodological approach is presented together with methods and tools adopted. Then, the findings of the analysis of case studies are depicted and discussed as key drivers in the Yachting 4.0 forecasting framework. At last, the research results are collected in three scenarios and three roadmaps toward a yachting computational morphology system. The implications on yacht design processes of these roadmaps were then analyzed in the final paragraph of the chapter, showing the possible future shifting in the design practices on data input, design process and tools, and communication media.

2. The methodological approach: design for the future

If future scenarios and challenges cannot be predicted with an unquestionable level of uncertainty, they can be foresighted and understood to inform present acting. Due to the freshness and the "unexplored complexity" [13] of the Industry 4.0 topic and the lack of reference in literature, strategic thinking to explore alternative futures—Future Studies [14]—is prioritized. The beginning of all industrial revolutions took place in the industry and caused a massive change in society. The current industrial revolution is the opposite. The beginning of the transformation process is not driven directly by the industry itself [15] but is triggered by a hyper-connected society. For the first time in history, the industrial revolution is predicted, providing opportunities to shape the future actively.

For this reason, the methodological framework of the research is placed in the broader area between the Discipline of Anticipation [16] and Design, aiming to push the boundaries of yacht design practices. Furthermore, this context of investigation compels the research to continuously shift from field exploration and interpretation (surveys and case studies) and forecasting activity (participatory scenario-building workshop), opening up to several tangents or critical matters that position the study at a conceptual level to be verified with on-site practices.

Even though there are no data about the future, companies, designers, and policymakers currently use many strategies, methods, and tools to gather data for future investigation. Among them, the present study refers to the six-ing steps of activities depicted by Hines and Bishop in the book *Thinking About the Future, Guidelines for Strategic Foresight* [17] to answer the research questions. These steps were identified by the Association of Professional Futurists' Development Team as fundamental for a comprehensive foresight strategy. The six activities—Framing, Scanning, Forecasting, Visioning, Planning, and Acting—aimed at getting a systemic understanding of expected, alternative, and preferable changes in introducing the digitally enabled technologies of industry 4.0 in yacht design and construction practices. The concept of "system" implies that drivers of changes affect the behaviors in a network of interaction and feedback loops between input and outcomes. With this perspective, the present study, while aiming at investigating the changes in yacht design processes and tools, includes the broader sector of the yacht industry at the core of strategic forecasting research. The whole system embraces the design and production process as well as the user interaction, that is, sailing and maintenance stages.

The research strategy mirrors the six -ing steps of strategic forecasting, dividing the activities into likewise steps to drive the study from the initial literature review to the future study agenda, as following described.

The phases *Framing* and *Scanning* aimed at building a robust forecasting framework through desk research and case studies highlighting drivers in the digital yacht ecosystem, challenges, and uncertainties. The identification of the good 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—while the case studies data sourcing was performed in two steps—primary source semi-structured observation (during the main nautical trades 2017–2019) and second data document review (online data). Then, the features of each case study were analyzed on the following four parameters—enabling technologies and sub-technologies for UX implementation, relevant 4.0 design principles, impact on YD process, and impact on the customer journey. The collective and parallel analysis of the multiple cases was executed, thanks to a card-sorting activity where the cases were gathered in overlapping clusters. This activity results in the Yachting 4.0 forecasting framework, described in detail in the next chapter.

Then, scenario-building workshop (*Forecasting* and *Visioning* phases) was selected as a forecasting method based on the nature of the uncertainty involved in the activity and referring to the Future Studies framework proposed by Courtney [18]. While case studies analysis was conducted with an expert mindset, the forecasting phase had a participatory mindset, involving stakeholders as co-researchers. To foster the participation and the interaction among stakeholders a proper set of activities and tools were designed following the Future Technology workshop method (FTW) [19], a method specifically suited to involve people with everyday knowledge or experience in a specific industrial process in an envisioning activity to design the interactions between current and future technology in a specific sector. The scenario-building workshop was divided into the four main FTW phases—a general introduction on purpose and forecasting framework, a structured brainstorming, a free envisioning session, and a scenario model building exploring the gap between current and future technology. The fourth step of the workshop involved, also, listing requirements and outlining critic aspects for future technology applications. This activity was the link with the next -ing phases—*Planning* and *Acting*—where a retrospective analysis to ground the workshop results in an understanding of novel yacht design approaches, processes, and tools driven by the Yachting 4.0 forecasting framework takes place.

The research results were then presented in the form of roadmaps, as the bridge between the forecast and the present situation [20], taking the scenarios developed in the participatory research at the destination. The method here adopted comes from Phaal et al. [21], where the roadmaps are conceived as the strategic plan that defines the digital scenarios connecting the different dimensions of the innovation strategy, the significant technologies and tools needed, and the plotted timeline.

3. Technology drivers for the digitalization of the yachting industry

As previously shown in the 4.0 design principles-technologies diagrams (**Figure 2**), the enabling technologies of the fourth industrial revolution have common behaviors and overlapping areas of applications that set the conditions on which to build a forecasting framework for the 4.0 development in the yachting sector. With the aim of further investigating that relation and revealing opportunities and trends for the scenario-building phase, a Case Studies analysis on digitally enabled technologies applied in the yachting industry was carried out. A card-sorting activity with an expert mindset was performed to grouped cases with the same behaviors without clustering them merely according to technologies adopted. After desk research, case studies were divided into three macro areas—design, manufacturing, and sailing. Some samples were placed across two groups representing a link between them. Looking at these links, two different groups were identified—the cases in which 4.0 technologies allow collaboration within multiple actors and the cases in which the virtualization and decentralization of communication media are predominate. The second stage of clustering involved the parallel investigation of the already labeled cluster to identify common grounds. The cases were, then, sub gathered according to the levels of consciousness in Industry 4.0 integration and to the influence on the disciplinary approach on the yacht design project in its processes and tools.

A graphic map to collect all the card-sorting clusters is here proposed to highlight the respecting relation between them (**Figure 3**). The map shows, at the central line, the depicted five levels of consciousness in Industry 4.0 integration—digital data gathering, simulation, optimization, system integration, and generative design. These five levels are put in relation to the two dimensions of communication and collaboration identified in the first step of cluster analysis. The resulting case studies groups are following labeled and described.

Digital data gathering: Projects integrating IoT and AHMI with the primary purpose of monitoring yacht assets. This group collects all the cases based on digital gateways, onboard electronic logs, and digital platforms for vessel system control and automation. Plus, it includes the environmental digital data analysis with the main purpose of gathering and analyzing field data to (in perspective) inform the design

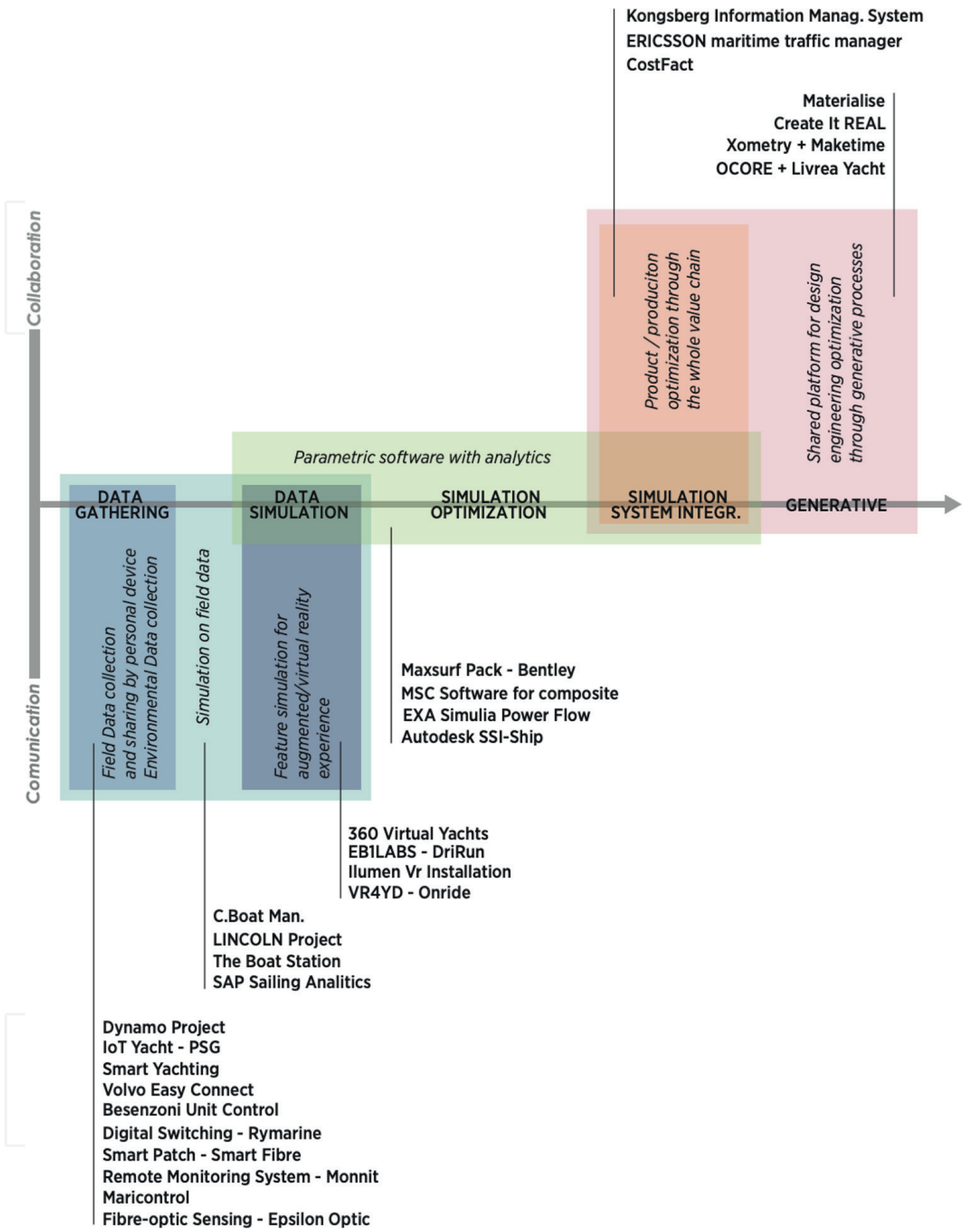

Figure 3.
Case studies map.

process. Vessel and marine environmental data gathering from IoT structures are mainly used in this cluster for maintenance purposes. Only one case experiments the possibility of confronting field data with design data.

Data simulation for communication purposes: Projects not informed (or partially informed) by field data integrating big data, simulation, VR, and AHMI. The main examples are a virtual reality in marketing strategic communication and virtual sailing testers.

Simulation analysis and optimization: Projects not informed by field data in a not-integrated ecosystem. This group encompasses simulation software to predict real-world performance and tools for manufacturing process optimization.

Optimization through system integration: Projects with a collaborative nature aiming at the optimization of both product and process through the whole value chain. This group collects all the collaborative platforms developed for the marine and yachting industry to manage the design phases, the value chain, or the offshore and sailing operation.

Optimization through generative: Projects involving generative design tools to optimize and self-configuring product shape according to the manufacturing process. This cluster encompasses the collaborative platforms currently used for managing the manufacturing process with the aid of digital assisted tools as additive manufacturing and collaborative robots. These case studies have a collaborative nature aiming at self-configuring product shapes according to the manufacturing process by the use of generative design tools. A few cases, including cloud manufacturing as the key technology, are gathered in this group.

We can observe in the map, a clear separation between the two categories, which are communication and collaboration. Communication strategies are more implemented with low consciousness projects, while collaborative strategies lead projects with a higher level of systemic integration and self-configuring processes. The technologies adopted on the left side of the map refer to the design principles virtualization, service orientation, and decentralization. On the other hand, cases that implement the use of collaborative platforms for generative design do not make use of field data through the entire value chain, as well as the optimization processes. We can observe that the technology adopted here leads directly to flexibility, self-configuration, and real-time capability as design principles crossing the two areas of horizontal integration in manufacturing and design. In particular, new media of communication are emerging in the relation within companies and the yacht final user to allow (i) a more immersive experience, and (ii) faster and easier access to information through digital platforms and self-devices.

4. The Yachting 4.0 forecasting framework

To build the forecasting framework for the scenario-building phase, the results of case studies analysis are observed through the lens of the ecosystem approach for Industry 4.0 scenarios by PWC [22]. The PWC Industry 4.0 scenario framework identifies four steps in moving from a product-oriented to a platform-focused approach—(i) Core Product, the traditional base offering, which can be "digitized" by adding digital layers around it; (ii) Digital Augmentation, digital customer interfaces, visualization, touchpoints, and channels augment the experience and allow a variety of interaction models; (iii) Digital Service in which digitally enabled services are added to the physical core product providing an end-to-end solution to a broader customer need; and (iv) Digital ecosystem with interfaces to suppliers, partners, and customers, the product is embedded in an ecosystem for co-creation and additional value capture.

In the present study, the PWC Industry 4.0 scenario is expanded to include the manufacturing process in the systemic approach and the "after launch" stage. As we can observe in **Figure 4**, the scheme becomes a group of four concentric circles divided into four sectors by the vertical and the horizontal axes.

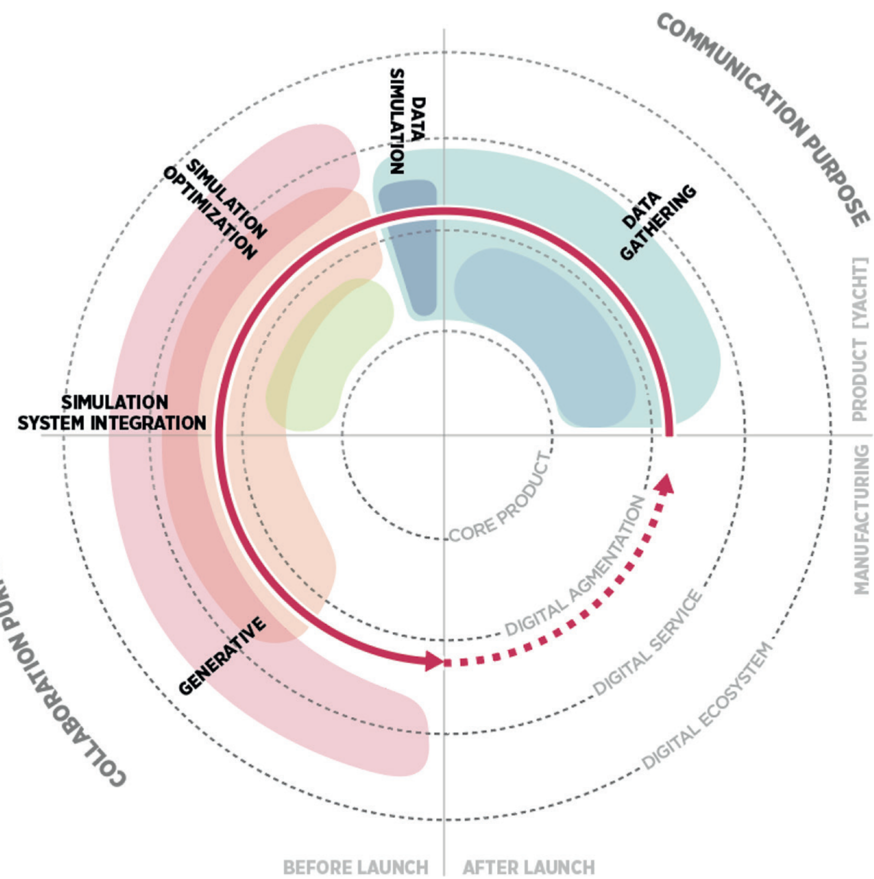

Figure 4.
Yachting 4.0 forecasting framework.

The horizontal axis separates the focus on product from the focus on production, while the vertical axis marks the temporal division between before launch and after launch phases. The four sectors of the circles result in design (focus on the product before launch), manufacturing (focus on production before launch), sailing (focus on the product before launch), and maintenance (focus on production after launch). The Yachting 4.0 forecasting framework is built by overlapping the groups of the Case studies map to the scenario framework scheme with the purpose of giving fundament in answering the first research question—How could these technologies be better implemented in the yacht digital product-service ecosystem scenario?

A clear barrier between the "before launch" and the "after launch" sections is observed. This evidence refers to the previously depicted separation between collaboration and communication. The digital data coming from field and user engagement are not yet employed in the design phase and maintenance stage. This results in a disconnection between the after launch and before launch phases at the expense of input data design quality and quantity.

On the design and manufacturing side, horizontal integration of digital data for simulation, optimization, and self-configuration (generative) process is arising. While communication strategies are more implemented with interoperability projects, collaborative strategies lead projects with a higher level of consciousness and of systemic horizontal integration. In these cases, the implementation in the use of collaborative platforms for optimization and generative design process does not make use of field data through the entire value chain. At last, the visual representation of the Yachting 4.0 forecasting framework shows a lack of experiences in the last circle, the digital ecosystem, and an insufficient connection between the four sectors of the graph. This fact is a further confirmation of the general immaturity of the yachting sector on the theme of Industry 4.0 and a need for systemic visions, leading the research activity into the scenario-building workshop.

5. Three scenarios for the yacht digital design

The workshop activity, conceived as a co-research phase, had three objectives—(i) discuss and validate the scenario framework; (ii) explore and build alternative scenarios on Yacht Design 4.0, outlining drivers and criticalities; and (iii) involving and making aware of the specific industrial community on digital technologies opportunities. To achieve the intended research objectives, the workshop involved experts in the yacht design field—yacht designers and draftsmen in the yard, shipyards project and production managers, yacht industrial association managers, and experts in digital transformation and policymakers. The workshop took the FTW scheme as a reference aiming at reaching an informed understanding of a grid of four boxes—everyday technology and activities (core product), an everyday activity supported by new technology (digital augmentation), a new activity supported by current technology (digital services), and new activities with new technologies (digital ecosystem). Moving inside the grid, the workshop partakers are guided in the scenario visioning activity.

The workshop was focused on yacht design practices, but a systemic view on the whole yachting sector was fostered. For this reason, even if the whole scenario-building workshop was divided into the four main phases described in the methodology, parallel and circular activities were performed in an iterative conversation among challenges and opportunities, especially in the free envisioning and scenario exploration phases. As a workshop result, three visions symbolized by the three Roadmaps were created.

The definition of the Yacht Design 4.0 Roadmaps was, in itself, a design matter. Sustained by all the qualitative data and knowledge, collected by case studies and by the co-design visioning activity, the roadmaps represent the synthesis of the collaborative activities, and the grounding of the workshop results in an understanding of novel yacht design approaches, processes, and tools driven by the Yachting 4.0 forecasting framework.

The multiple scenarios developed in the workshop were grouped up based on common ground identification looking at (i) the four steps of digitalization of the Yachting 4.0 forecasting framework; (ii) the insight coming from the workshop scenario exploration phase and shared by the workshop partakers; and (iii) the three cluster of yacht product and production, which are [23] top of the line, model-based, and semi-custom. The timeline for a roadmap toward a computational morphology system was defined according to the workshop results discussed with the partakers:

- current: digital augmentation, within five years;
- near future: digital services, within 10 years;
- and futures: digital ecosystem, from 10 to 20 years.

In the next sub-paragraphs, the three roadmaps are presented and depicted together with their implications on designer work and their critic aspects, as discussed with the scenario-building workshop partakers. The implications on yacht design processes were then analyzed on the primary levels already set in the previous research activity (case studies)—data input, design process and tools, and communication media.

5.1 Top of the line roadmap to digital product-service ecosystem

The top of the line cluster encompasses companies dealing with a high level of product customization and looking toward the larger segment of super- and megayachts. This type of boat is part of what is called luxury design, where the project is highly influenced by the specific culture and personality of the client [24], where the request for a craftmanship tailor-made product is continuously increasing, and the focus of the market is shifting on rare and personalized experiences [25]. The roadmap takes the peculiarity of this cluster into account, proposing a journey toward a digital product-service ecosystem in which personalized service and yacht components are designed on real data gathered in a digital experience platform.

Current: The first step is the digital augmentation of both the design project, that is, 3D model of the yacht, and the product, that is, the yacht itself. The yacht design modeling becomes parametric. The designer interacts with a digital structure that was generated by a mechanism according to a set of predefined relations between shapes and components. In this way, the first phase of preliminary concept design embeds the design engineering steps allowing rapid change of design dimension and structure in the project representation. On the other hand, sensors and remote-control networks are placed on-board, transforming the vessel into a connected object. The first level of services proposed is (i) the electronic log for sailing automated data recording, (ii) the gateway of the universal system, and (iii) the social media integration. The user experience data are recorded in a knowledge management platform.

Near future: The second step is the connection of the knowledge management platform, featured with big data real-time analysis, to the design project. Knowledge management platform examines large and varied field data sets to unveil hidden patterns represented by formal, computer-interpretable rules. The design project makes use of the data resulting from the iterative process of data analysis and simulation to verify the yacht premises. Furthermore, the yacht 3D model becomes a non-living digital twin—a digital replica of all the physical and IoT assets of the vessel, allowing direct communication with both the production site and the whole supply chain. Virtual/augmented reality and AHMI tools could be used as communication media for a preliminary customer immersive experience. For what concern novel digital services, the use of big data analysis allows the development of on-board personalized service including optimized and automated routing according to sailing analytics, to environmental and forecast data, maintenance and marina service feed by real-time field data, and legal insurance services.

Future: The digital product-service ecosystem encompasses the physical and the virtual world, and data are transmitted seamlessly (and in two ways) between the yacht and the living digital twin. The knowledge management platform examines not only the field data sets but also the design project information, allowing interoperability and vertical system integration between yacht components. At the same time, the parametric digital twin is conceived as a living project providing insight on both the elements and the dynamics of how digital devices operate and live throughout the yacht life cycle. The yearly maintenance or refitting stage benefits from the field data gathering and analysis of the digital experience platform, allowing a yacht optimization on real customer needs.

Implication on yacht design process and tools: In this scenario, the yacht design processes maintain its character of an iterative cycle of refinement steps. Due to the use of a parametric design tool,[4] the sequence of steps of simulation and optimization are integrated into a unique analytical process on geometrical models.

In this contest, the living digital twin is managed by parametric design technologies and optimized by the result of the digital experience platform analysis. Moreover, the design platform could allow multiple evaluative analyses and support the collaboration among the different design and engineering teams involved in the yacht design process. At last, the living digital twin embedded in the digital experience platform could be visualized through virtual reality digital devices both for augmented customer experience and manufacturing/maintenance purposes. The representation highlights not only the yacht feature and the control gateways but also the information on how the yacht, the systems, and the components operate throughout the whole life cycle.

Critic aspects: The scenario shares with the broader Industry 4.0 development the challenge in data and privacy protection. Even if the ethical challenges created by mass data gathering through online interactions are scientifically reported [27], there is not a clear policy ethical framework on digital technologies due to the rapid and disruptive changes in the information technology environment. On the other hand, maritime sector suffers from cybersecurity as well. According to the EU report on cyber security challenges in the maritime sector [28] and the findings of the collaborative scenario-building workshop, maritime cybersecurity awareness is currently low to nonexistent.

5.2 Semi-custom model-based roadmap to generative-integrated ecosystem

The second group represents the companies with a model-based production with a high level of flexibility and customization of the core product, of digital integration in design and production processes, and experience in 4.0 enabling technologies. The roadmap to a generative-integrated ecosystem takes the current advancement of the cluster into account, proposing a journey in which the virtual data coming from user experience and field measurements could inform the design phase in generative processes for higher optimization and personalization in project development. The roadmap from optimization to generative consists of three steps, which are as follows:

Current: To support the present design process (from concept to design engineering), a knowledge management platform is placed across the sailing and the production stages. Data coming from the digital augmentation of the yacht and the vessel production tools are recorded and analyzed. The process data outputs are formal, computer-interpretable rules that are considered in the parametric yacht design modeling. Knowledge-based methods have been intensively studied and applied in other transportation industrial sectors, such as maritime; however, it has not been studied or adopted in the yachting industry, dominated by low volume production and small or medium-sized companies, so far. Despite that, the large amount of already formalized engineering knowledge in codes and regulations could be implemented in the yacht design as well.

[4] The relations between the project dimensions are no more directly drafted on a digital continuum space (as in a cad direct modeling tool) but are dependent upon various parameters. This process is generally described as predictive models, as opposed to direct modeling, in which the descriptive modeling process brings together with manufacturing logic and material proprieties [26].

Near future: The second phase represents the knowledge integration into the yacht digital twin. The refinement optimization steps are directly managed by the digital replica of all the physical and IoT assets of the yacht. The integration in a unified platform allows direct communication with both the production site and the whole supply chain. The communication media becomes a digital interface on personal devices, and production work teams could interact with the digital replica sending feedback to the knowledge management tool. Virtual reality and augmented reality could be used to verify the features and the assembly operation of onboard optimized components.

Future: A generative design tool is integrated into the knowledge management platform to transform the data coming from user experience and field measurements into alternative shapes. This process allows the generation of different solutions by changing the parameters of design constraints (from knowledge management platform) and design requirements (from direct design modeling). Consequently, the quantitative analysis of computational techniques based on the finite-element method is translated into qualitative alternatives of complexity. The use of parametric and generative design tools is driven by the possibility of applying advanced manufacturing processes to yacht production. In particular, additive manufacturing and cloud manufacturing could represent a turning point in the customizability of yacht components.

Implication on yacht design process and tools: In the generative-integrated ecosystem, the current parametric design process is shifting toward a computational process model of digital design under the impact of a new generation of associative algorithms. The linked and iterative cycles of design, analysis, simulation, and optimization of the yacht design spiral are no more valid in describing the new paradigm of the yacht design process. The two platforms of knowledge-generative design and integrated management have unified the process of simulation, evaluation, and fabrication within designer-scripted morphogenesis processes. Furthermore, the integration of the 4.0 enabling technology of additive manufacturing and collaborative robotics in the roadmap led to including the “making level” in the design process.

Critic aspects: Besides the previously mentioned ethical issues on data confidence and privacy and cybersecurity, a discussion on the shifting role of designers emerged. Although the parametric approach has increased the interoperability of systems and the flexibility among geometry relations, the exploration of yacht design alternatives is still limited by the manual operation of designers in varying individual parameters. Whereas, what a generative approach does is asking artificial intelligence to explore the design space semi-autonomously, revealing options that would otherwise be hidden. The designer role is shifting at the beginning and final stage of the process interacting with the generative structures of the yacht model, defining the project requirements and the grammar of shapes, and finally evaluating the generative results. New digital skills are requested for designers and a new way of thinking. These challenges are also arising in academic research around the concept of digital design thinking [26].

5.3 Model-based roadmap to co-modular digital ecosystem

The third cluster encompasses the companies that have a lower value in customization and an engineered production process. The cluster is mainly represented by shipyards dealing with low series and mass assembly core products even if a request for higher personalization is rising in the market, which are claiming for more flexible and integrated process in both the design and the production of yachts. Moving from mass production to mass personalization is challenging the worldwide industry from the early 90s and is extensively discussed in theory and applications [29, 30]. However, the integrated use of the enabling technologies of Industry 4.0 seems to offer a solution to the dilemma between the economies of scale and scope triggered by the concept of mass customization [31]. In this context, the model-based roadmap envisions a journey toward an integrated-modular digital ecosystem, where the yacht product, design, and production processes consist of integrated (design-production-product) subsystems with little interdependencies serving as modules links.

Current: As for the previous roadmaps, the first step in digitalization is the digital augmentation of the yacht design project and the model-based yacht. The parametric design tool for yacht 3D modeling is directly connected to a virtual configurator, able to manipulate the set of parameters according to the designer's work. In this phase, the customers interact through a personal smart device (AHMI) with a digital structure generated to link furniture finishing and components features. A knowledge management platform received and store the data coming from the onboard IoT system as component sensors and universal system gateways. The service offered to the final user is the ones described in the roadmap to the digital product-service ecosystem.

Near future: A yacht digital twin is optimized with the data coming from the onboard IoT systems. This digital replica of all the physical and IoT assets of the vessel represents the link between the production site and the customer virtual configurator. The yacht project is conceived as a flexible assembly of different modules regulated by interdependences in a virtual logic structure. In this vision, the boat could be highly customizable. The effectiveness of the modular yacht concept is already proven by several commercial proposals and academic research [32, 33]. The customer virtual configurator is conceived as a co-creation guiding tool to build customized solutions based on predefined design variables and limits. The opportunity offered by VR/AR on smart devices and AHMI allows to virtual test the finished product and provide end-user with product support.

Future: An integrated and modular digital platform is placed at the core of the design process involving not only the yacht conceptualization and engineering through digital twin modeling tools but also the production and supply chain assets managing. Both the design and the production process are divided into interconnected and integrated subsystems. An interdependence logic structure manages the modules relation based on configuration variables and yacht design constraints. Furthermore, the subsystems are optimized by the analysis of the digital field data coming from the connected vessel (i.e., connected subsystems of different vessels) and the digital-based production tools, such as co-robots and additive manufacturing. Although introduced on modular yacht design products, the concept of modularity is now applied to many different areas of the production system, production planning, and optimization processes.

Implication on yacht design process and tools: A sequence of four steps divides the design process of the co-modular digital ecosystem scenario. (i) Definition of a preset of general condition and parameters mirroring the first cycle of the yacht design spiral aiming at setting the interdependence logic structure of yacht based on the configuration variables and the yacht design principle and constraints; (ii) Variants generation of subsystems according to market and trend research. This step involves, furthermore, the module links definition and the logic correlation between subsystems; (iii) Variant optimization by field data from product performances (sailing and user experience), from the production process, and supply chain management;

and (iv) Variant selection, final product visualization, and evaluation by customers through virtual reality. The collaborative design process here involves the customers in flexible customization. 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.

Critic aspects: In addition to the previous scenario criticalities that remain constant even in this third vision, a generally low level of digital experiences in the yachting sector could represent a crucial aspect in the development of the roadmap. Furthermore, the small and (sometimes) family dimension of the nautical supply chain could be a barrier to digital integration. To bridge this gap, specific design competencies in parametric and integrated design are needed across the whole value chain at different hierarchical levels.

6. Computational strategies in digital yacht design

At last, this paragraph discusses the research results presented through 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-customers and designers-manufacturing. The roadmaps highlight that the yacht design process is progressively moving away from the linked and iterative cycles of design, analysis, simulation, and optimization of the yacht design spiral. The novel approach seems reflecting the level of 4.0 consciousness previously described in the framework—simulation, optimization, and generative design (**Figure 5**). The Yachting 4.0 forecasting framework also suggests that the digitally enabled technologies are driving the yacht design process toward a more digitally conscious and virtually collaborative environment. Three different approaches to the yacht design process driven by digital and computational modeling tools are depicted and named—digital yacht design spiral, digital yacht module optimization cycle, and generative yacht design tangle.

At first, in the roadmap toward a digital product-service ecosystem, the yacht design process maintains its characteristic of an iterative cycle of refinement steps feed by real-time data. The Digital yacht design spiral (**Figure 6a**) represents the first level of the 4.0 consciousness: simulation. The data analysis and the design process are still being separated, and the manual operation of designers drives the optimization process in varying individual parameters. In this process, the use of parametric design tools allows interoperability between different design and engineering teams as well as a direct connection with the digital twin (conceived as the communication medium between stakeholders and digital assets). However, the exploration of yacht design alternatives is still directly connected with the capability of designers in interpreting customer requirements, setting production and material constraints, and understanding simulation results to appropriately vary the individual parameters of 3D models.

The second level of 4.0 consciousness in yacht design processes—optimization—is represented by the roadmaps to the co-modular digital ecosystem and the process “Digital yacht module optimization cycle” (**Figure 6b**). In this roadmap, the yacht

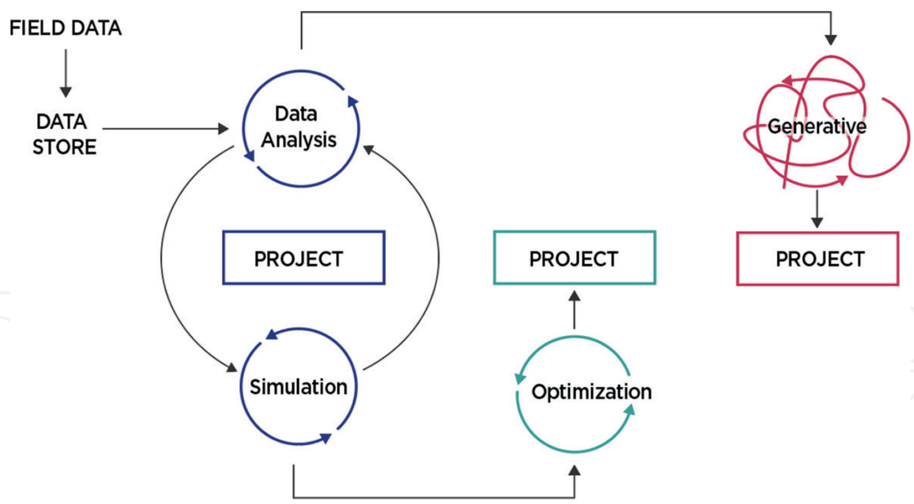

Figure 5.
Computational strategies in the Yacht design process.

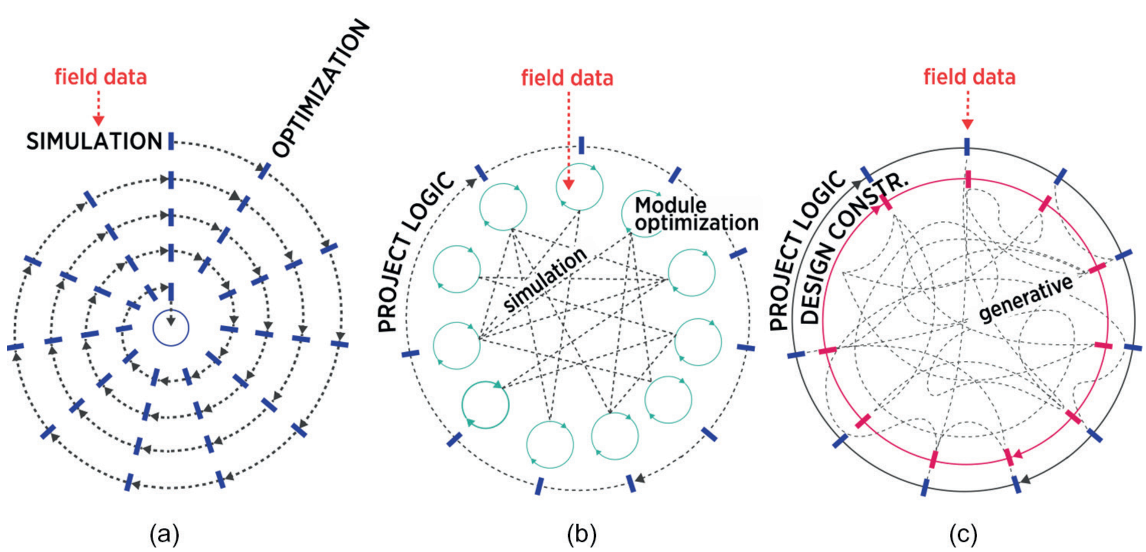

Figure 6.
Approaches to the yacht design process driven by digital and computational modeling tools: (a) Digital yacht design spiral; (b) Digital yacht module optimization cycle; and (c) Generative yacht design tangle.

design process is not entirely managed by the designer/team itself but is the result of a collaborative process of co-creation with customers. The sequence of refinement steps characteristic of the yacht design process is here moving from the entire product conceptualization to the design of the single subsystem. The exploration of yacht alternatives is directly managed by customers and mediated by a digital platform that embedded the logic of the project and the self-assembly optimization parameters. Working on the logic of vessel design, structure, and modules interconnection, the yacht design process is not opened to disrupting co-design results, even if novel assembly systems and unexpected results could be created by co-design interaction.

In the generative-integrated ecosystem, the current parametric design process is shifting toward a computational process model driven by associative algorithms, driving the reflection toward the Generative yacht design tangle (**Figure 6c**). Already experimented in a few yacht design cases and intensely explored in the literature review in the industrial design and architectural field, generative processes are disrupting the dichotomy between creative thinking and digital drafting. In the generative processes, the focus of artificial intelligence is not analyzing and simulating data but exploring alternatives and creating a solution. Within the different types of generative processes, a grammar-based approach emerged as the more suitable in the yacht design field. In this process, the designer interacts with the generative structures, their limits, and input, defining the grammar of shapes, and finally evaluates the generative results [34].

Contrarily from the previous two processes, here, the design results are multiple and interchangeable. The selection criteria of the proper design solution is still an open issue, not discussed in the present study, and weakly tackled in the literature review on the design engineering field. The research highlights three possible (future) shifts in yacht design practices.

Input data: Data are moving from analogic to digital and the opportunity to networking information distributed across many different sources shifts the focus of data input from measuring to inferred (i.e., big data analysis). Parallel to analogic data—marketing and customer insight, specific designer and engineering knowledge, and onboard experience—yacht designers could make use of a large quantity of direct data measured by sensors and smart devices. In the digital augmentation sphere, not only IoT design data are accessible everywhere, but information from many different devices can be combined in datasets. It is important to underline that digital data coming from production processes and intelligent vessels become the new oil for design empowering and customer involvement only if they can be fully understood within a qualitative context framework of previous analogic yacht design knowledge.

Design processes and tools: The use of parametric and generative design tools is shifting the "digital doing" from digital drafting to digital logic in which the digital focus is the creative process itself. In focusing on the design process, moving from direct modeling to parametric design and then, to generative yacht design, could fragment the dichotomy between the creative thinking and the digitally drafting of the vessel shapes. Here, artificial intelligence is asked to explore the design space semi-autonomously to disclose options based on predefined generative rules, relations, and principles. An alternative way is presented through the roadmaps and identifies the journey toward a modularized system of optimization. Even in this process, the digital focus is moved to the logic structure. While in the generative design process the "logic" refers mainly to the design principles and the grammars of shapes, in modular-computational processes, it has to do with the relation between elements and junction constraints. This focus on the reasoning level of the design process is highlighted in the purposes of generative and computational design processes [35]: "creating responsive objects able to react to external stimuli by modifying the formal shapes while conserving the morphogenesis logic."

Communication media: The digital twin is modifying the approach to communication media toward a more collaborative media strategy. Parallel to the availability of field data and the shifting of digital focus in yacht design processes, the 4.0 enabling technologies and new manufacturing paradigms of Industry 4.0 could enable a novel approach to the communication, and therefore collaboration, tools for yacht design and engineering. In the journey depicted in the roadmaps, it acts as a medium virtually replacing the paper draft and drawing and project render. As a shadow of the projects embedding all the physical and digital assets, the digital twin could be furthermore used as a co-design tool between yacht designers and engineers as well to involve customers or manufacturing teams and supply chain in the project definition. Furthermore, the Digital Twin supports the visualization and management of the vessel throughout the whole life cycle, becoming a valuable tool in the maintenance stages.

7. Conclusion and further steps

The paper presents an explorative study of the topic of Industry 4.0 in the yachting field. The research focus raised from an intuition about the need to foresight the role of the new digital technologies and new manufacturing models in the transformation of the yacht design sector to understand and guide the undergoing digital transformation, filling the literature gap where no scientific publications consider the impact of Industry 4.0 in the yacht fields on its entirety.

Due to the freshness and the unexplored complexity of the Industry 4.0 topic in the yacht design practices, strategic thinking and collaborative research activities to explore alternative futures were prioritized, using case studies analysis and scenario-building participatory workshop as main research methods. With the purpose of building a robust forecasting framework, a card-sorting analysis on 4.0 enabling technologies applied in the yachting industry was carried out to ground the knowledge on relations between industry 4.0 design principles and digital technologies. This activity led to the discussion on opportunities and trends for the Yachting 4.0 forecasting framework. This first research result was used in the scenario-building participatory workshop as a guiding backdrop.

Then, three scenarios and three roadmaps toward a computational morphology system are presented. The definition of the Yacht Design 4.0 Roadmaps was, in itself, a design matter. Sustained by all the qualitative data and knowledge collected by case studies and by the co-design visioning activity of a scenario-building workshop, the roadmaps represent an unavoidable subjective synthesis of the research results, conceived as a guide in bridging the gap between the current situation and the visions developed. Furthermore, they contain a reflection on novel yacht design practices affected by the new manufacturing models and digital technologies of Industry 4.0 as the main contribution of the study in the yacht design field.

The research evidence highlights three central possible (future) shifts in the yacht design practices, which are as follows:

- the input data are moving from analogic to digital, reframing the focus of the designer practice from the measured data to the inferred data;
- the use of parametric and generative design tools is shifting the "digital doing" from digital drafting to digital logic driving the process toward a more digitally conscious and virtually collaborative environment;
- the digital twin is modifying the approach to communication media toward a more collaborative media strategy.

The research achievements resulted positioned on a conceptual level. The founding has numerous links and overlapping with the research on Computational design and morphogenesis logic design [35]. For this theoretical nature of the research, the results still need to be pragmatically tested and verified by applied research projects both the shipyards and in design studios. Plus, the workshop discussions point out numerous criticalities at different levels that should be considered for future study in the field—(i) the emerging role of digital yacht designers and the new skills necessary to face the digital transformation, (ii) the design of specific tools for yacht design co-creation, (iii) the issue of data using and data protection, and (iii) the challenges on cybersecurity in the maritime sectors.

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