Journal of
Marine Science and Engineering

MDPI

Article

Holistic Approach to Ship Design

Apostolos D. Papanikolaou

Ship Design Laboratory, National Technical University of Athens, 15773 Athens, Greece; papa@deslab.ntua.gr

Abstract: The recently completed Horizon 2020 European Research project—HOLISHIP—Holistic Optimization of Ship Design and Operation for Life Cycle (2016–2020) has developed suitable tools and software platforms which are necessary for the creation of innovative design solutions meeting the set low-emission strategic objectives. The present paper introduces an innovative, holistic approach to ship design and the development of integrated design software platforms and tools, which are used in practical applications. In the era of the 4th industrial revolution, this project sets out to substantially advance ship design via the introduction of a fully computerized, multi-disciplinary optimization approach to ship design and life-cycle operation. The approach enables the exploration of a huge design space in a relatively short time, as well as the distributed/multi-site working and the virtual reality testing; thus, it is a strong asset for the development of innovative maritime concepts in response to the needs of the 21st century.

Keywords: holistic ship design; multi-criteria optimization; digital siblings; innovative designs; life-cycle assessment; design software platform

Citation: Papanikolaou, A.D. Holistic Approach to Ship Design. *J. Mar. Sci. Eng.* **2022**, *10*, 1717. https://doi.org/10.3390/jmse10111717

Academic Editor: Spyros Hirdaris

Received: 13 October 2022
Accepted: 7 November 2022
Published: 10 November 2022

1. Introduction

The concept of a holistic approach to ship design was introduced more than 10 years ago by the author [1]. It is based on the philosophical notion of holism introduced by Aristoteles in his treatise Metaphysics (384 B.C.–322 B.C.). *Holism* originates from the Greek notion *ὅλος*, *holos*, meaning "*all included, whole, entire*" and it simply postulates that *the whole is more than the sum of parts*; thus, systems of different type (physical, biological, chemical, social, economic, mental, etc.) and their properties should be viewed as *wholes*, *not just as a collection of parts*. This is trivial in mathematical nonlinear systems and obvious in systems theory.

The wide implementation of a holistic approach to ship design was achieved in the EU funded project HOLISHIP (2016–2020) [2], which is a HORIZON 2020 Large Scale RTD project. HOLISHIP stands for the "Holistic Optimization of Ship Design and Operation for Life Cycle", and represents the joint effort of 40 European maritime RTD stakeholders: HSVA (coordinator)—Germany; ALS Marine—Greece; AVEVA—United Kingdom; BALance—Germany; Bureau Veritas—France; Cetena—Italy; Center of Maritime Technologies—Germany; CNR—Italy; Damen—Netherlands; Danaos—Cyprus; DCNS-Naval Group—France; DLR—Germany; DNV-GL—Norway/Greece; Elomatic—Finland; Epsilon—Malta; Fraunhofer-AGP—Germany; Fincantieri—Italy; Friendship Systems—Germany; Hochschule Bremen—Germany; IRT SystemX—Germany; Institute of Shipping and Logistics—Germany; Kongsberg Maritime—Norway; Lloyd's Register—United Kingdom; MARIN—Netherlands; SINTEF—Norway; Meyer Werft—Germany, Navantia—Spain; National Technical University of Athens—Greece; Sirehna—France; SMILE FEM—Germany; Starbulk—Greece; TNO—Netherlands; TRITEC—United Kingdom; Uljanik—Croatia; Univ. Genoa—Italy; Univ. Liege—Belgium; Univ. Strathclyde—United Kingdom; van der Velden—Netherlands.

In the era of the 4th industrial revolution [3], this project sets out to substantially advance ship design by the introduction of a fully computerized, multi-disciplinary optimization approach to ship design and life-cycle operation. The approach enables the exploration of a huge design space in relatively short time, as well as investigations into the distributed/multi-site working and the virtual reality testing. Thus, it is a strong asset for the development of innovative maritime concepts in response to the needs of the 21st century. Moreover, the HOLISHIP, multi-objective optimization approach to green shipping, has been recently presented with a subset of its functionality, namely the design of two green design RoPAX case studies [4].

2. HOLISHIP Design Approach

We interpret the holistic approach to ship design, as implemented in the HOLISHIP project, as the *parametric, multi-objective and multi-disciplinary optimization of maritime products for life cycle*. The HOLISHIP approach includes. virtual reality (VR) product modelling and VR prototyping. The HOLISHIP project has also enabled and demonstrated multi-disciplinary collaboration through multi-site cloud working of the integrated HOLISHIP design platforms CAESES® and RCE®, in which a large number of design and performance simulation tools have been integrated [5].

Ship design was in the past more an *art* discipline than a *science*, highly dependent on experienced naval architects, with good background in various fundamental and specialized scientific and engineering subjects. Inherently coupled with the design process is design optimization, namely the selection of the best solution out of many feasible ones. In traditional naval architecture, optimization means taking the best out of 2–3 feasible solutions, and it is up to the designer to make decisions about the assessment procedure and applicable decision criterion (or criteria) on the basis of his experience. Of course, the space of feasible design solutions is huge, the relevant assessment criteria are plenty and complex, as are the many feasible design constraints; after all, the assessment procedure must be *rational and not intuitive*, thus according with the contemporary state of the art. All this calls for a step change in the design process in naval architecture, something which has been the main objective of the HOLISHIP project.

Modern, *systemic approaches* to ship design consider a ship's overall system in a *modular way*, namely as the assembly of a series of modules. These may be replaced by others over a ship's life cycle either when serving a different transport/operational scenario, or when undergoing retrofitting for improved and/or safer transport services. The decomposition of the system into parts is a *top-down* approach and may be trivial in ship design. However, when talking of a software system supporting the entire ship design and all its components, the top-down approach becomes very complex, and the use of such software systems requires special training. Such systems are known in the CAD market and are used as advanced design tools by designers for solving problems in the maritime industry (e.g., NAPA®, FORAN®, AVEVA®, etc.).

The evolution of the HOLISHIP approach to ship design has been rather[1] a *bottom-up* systemic approach, operating by piecing together of sub-systems to give rise to a more complex software platform. The approach was initiated by various researchers in the 80s and its use continues to this day. It first referred to ship design optimization with respect to specific *prime* objectives, e.g., minimizing a ship's structural weight, maximizing ship's hydrodynamic performance (hydrodynamic hull form design), maximizing ship's safety (Design for Safety and Risk-based Design), optimizing ship's operation (Design for Operation), optimizing performance/efficiency (Design for Efficiency) and environmental protection (Design for Zero Emissions or Zero Pollution). This type of study later came to include more complex and multiple objectives, e.g., the life-cycle economic and environmental performance (Design for Life-Cycle) (Figure 1).

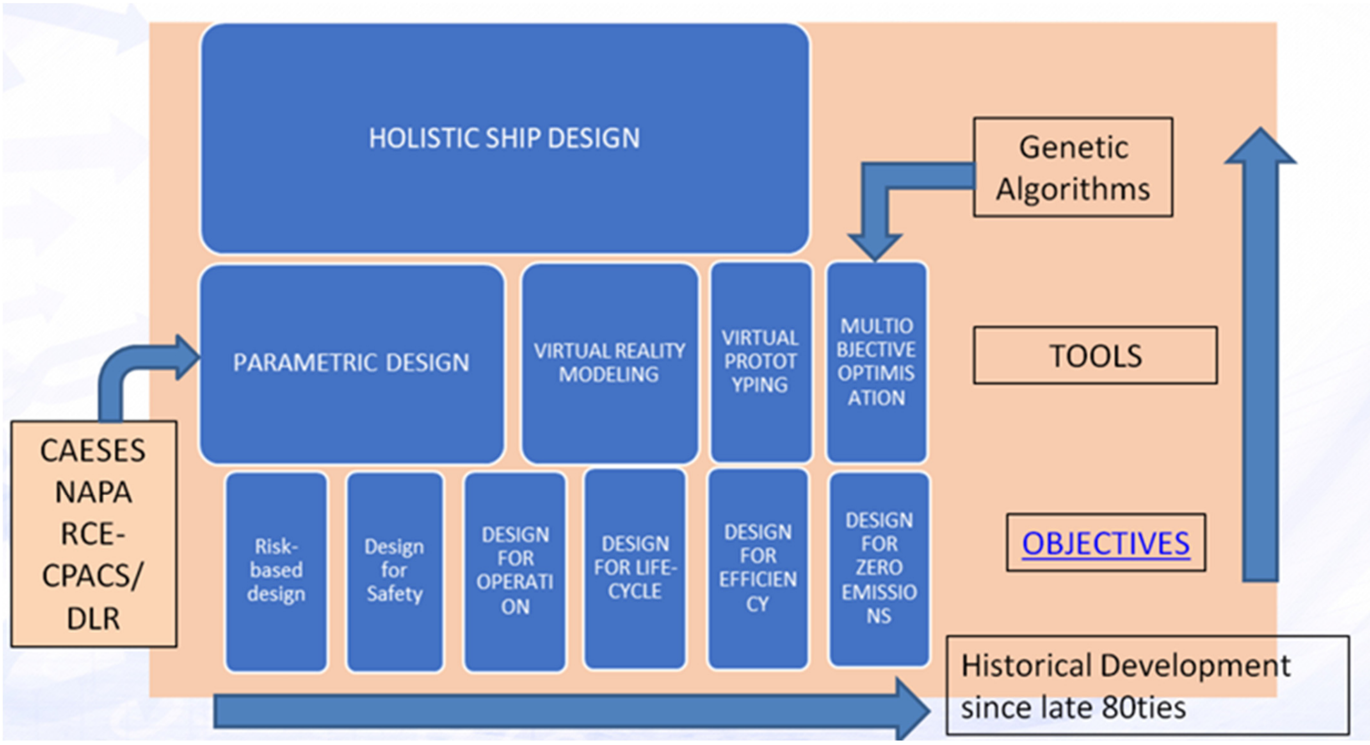


Figure 1. Evolution of Holistic Approach to Ship Design: Bottom-Up Systemic Approach.

Several applications of the multi-objective ship design optimization approach were accomplished by the Ship Design Laboratory of NTUA under the direction of the author of this paper. They integrated well-established naval architectural and optimization software packages (e.g., NAPA®, modeFRONTIER®, CAESES®) with various application methods and software tools (Shipflow®, STAR-CCM+®, in house s/w tools), such as are necessary for the evaluation of stability, resistance, seakeeping, structural integrity, etc., as listed below. Below national and EU funded projects cover the period 1988–2022.

- Hull form optimization of high-speed mono- and twin hulls for least resistance, wave wash and best seakeeping (AEGEAN QUEEN SWATH, EU VRSHIP-ROPAX2000, EU FLOWMART, EU TrAM).
- Optimization of the compartmentation of RoPax and cruise vessels for increased damage stability and survivability, minimum potential loss of lives (PLL) (EU SAFER-EURORO, EU ROROPROB, EU NEREUS, EU GOALDS, EMSA).
- Optimization of arrangements of containerships for the maximum number of deck-containers, least overstowage and minimum ballast (GL-CONTIOPT).
- Optimization of naval ships for increased survivability in case of damage in seaways and least structural weight (NAVAL OPT).
- Optimization of an LNG floating terminal (FSRU) for reduced motions and wave attenuation on terminal's lee side (EU GIFT).
- Logistics-based optimization of ship design (EU LOGBASED).
- Risk-based design optimization of tankers for increased cargo capacity, least environmental impact, minimum ballast (EU SAFEDOR, GL-BEST).

This evolution was enabled by the parallel development of IT technology and software tools, encompassing the parametric modelling and design, virtual reality modelling and prototyping, along with multi-objective optimization tools on the basis of genetic algorithms. Several of these types of software tools are nowadays inegrated intoto advanced design software platforms, e.g., in the frame of HOLISHIP:

- the CAESES® platform of Friendship Systems (https://www.friendshipsystems.com/products/caeses/, accessed on 6 November 2022),

- the NAPA® platform of NAPA Oy (https://www.napa.fi, accessed on 6 November 2022)
- the RCE®/CPACS® platform of DLR (Deutsche Luft- und Raumfahrt, https://www.dlr.de/sc/desktopdefault.aspx/tabid-5625/9170_read-17513/, accessed on 6 November 2022)
- the CADMATIC® platform of Elomatic (https://www.cadmatic.com/en/, accessed on 6 November 2022)
- the SAR® platform of Naval Group [6].

The above design platforms are all integrated into the HOLISHIP design framework, enabling their communication, the interchange in data and the use of tools/design procedures, as necessary for the address of a specific design tasks related to a ship or a maritime product in general. As an example, the interchange in data with the powerful naval architectural software package NAPA® is herein particularly highlighted. This is enabled by the development of dedicated macros (coded design procedures) for specific design tasks. These macros enable researchers to conduct of complex naval architectural calculation and design procedures, like the evaluation of the intact/damage ship stability and the preliminary structural design by NAPA®. Consequently, results are transferred to CAESES® for design synthesis, processing/optimization and final assessment (Figure 2).

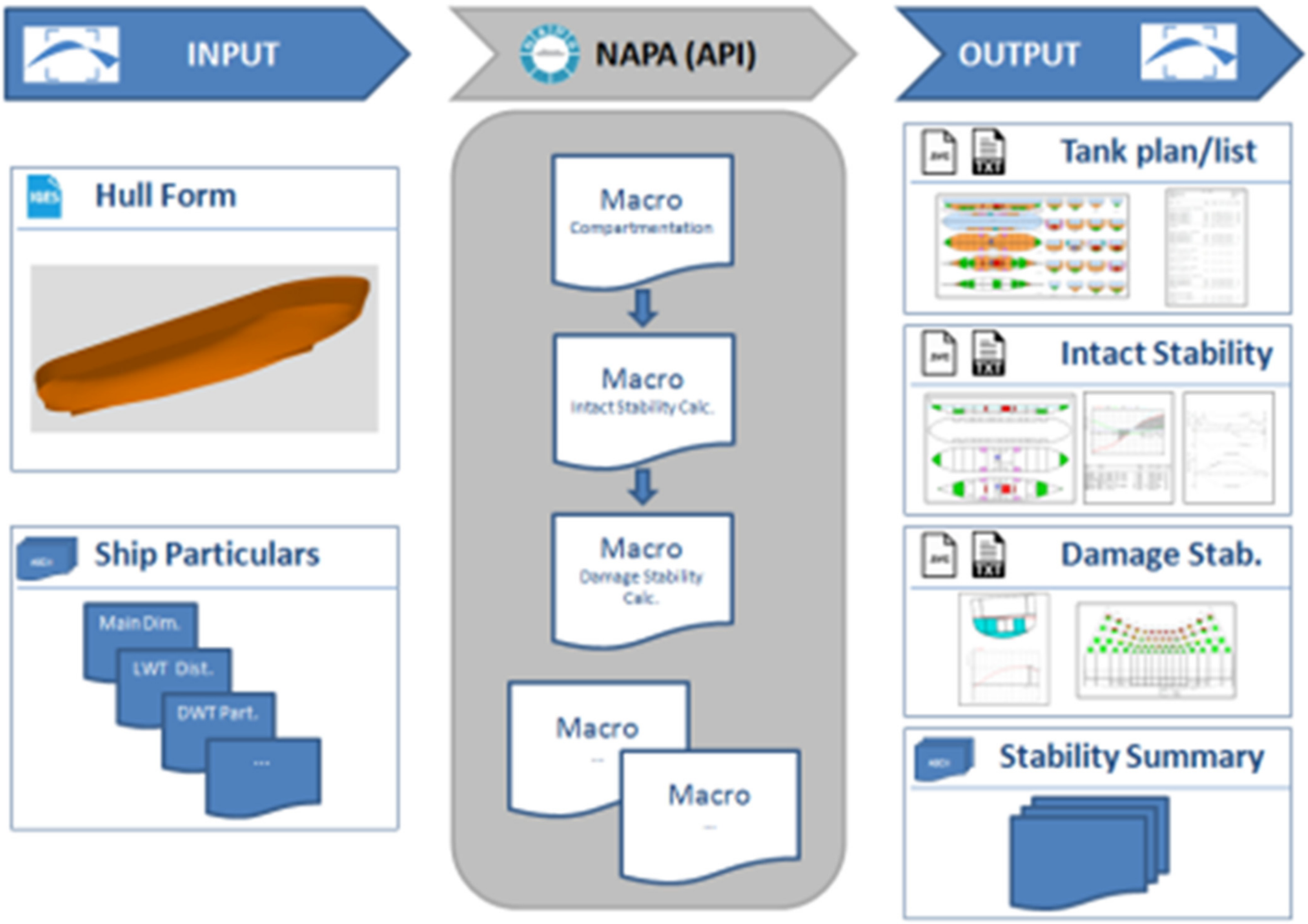


Figure 2. HOLISHIP Collaborating platforms CAESES and NAPA. Intact and damage stability determined by NAPA; pre- and postprocessing conducted by CAESES, NTUA & Hochschule Bremen (HSB) [7].

For the simulation of ship's energy management, the software tool Bureau Veritas SEECAT® may be used. In Figure 3, the simulation of the energy management of a hybrid diesel-engine/battery driven double-ended ferry is schematically shown. It enables the comparison of alternative propulsion plants (conventional diesel engines, hybrid diesel/battery system and full electrical/battery system) with respect to the overall energy management efficiency, CAPEX/OPEX and environmental impact (greenhouse gas emissions) [8].

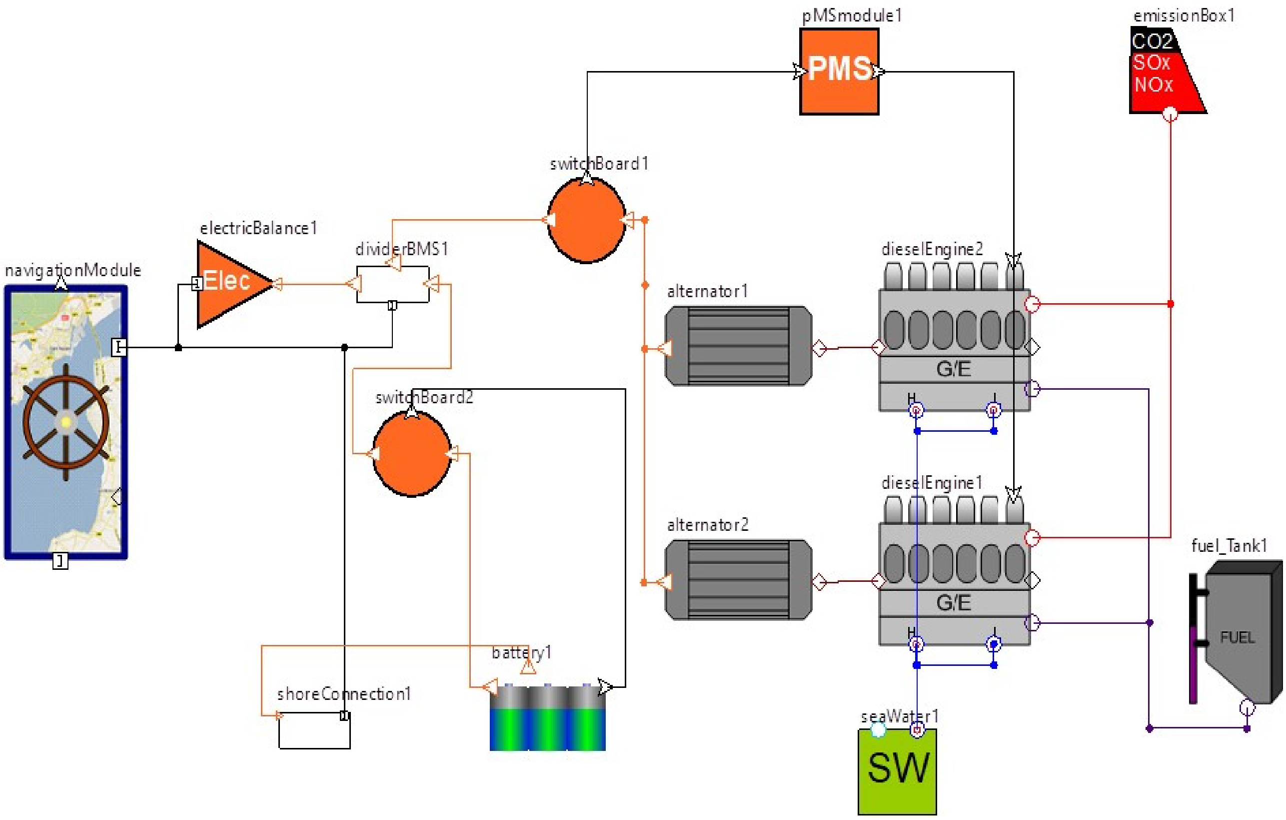


Figure 3. SEECAT®—Simulation of Energy Management of Hybrid DE Ferry (BV-Elomatic).

The COSMOS® tool of Det Norske Veritas (DNV) (https://www.dnv.com/news/dnv-gl-introduces-next-generation-energy-efficiency-methodology-6607, accessed on 6 November 2022) has been also integrated into the CAESES® platform and has been used in other application cases.

A synthesis of tools for the simulation of ship maneuvering and virtual prototyping of two alternative rudders has been realized with the Bridge Simulator of MARIN (Figure 4). Thereby, the following tools have been integrated into the RCE (Remote Component Environment of DLR) platform:

- CPACS®: Common Parametric Aircraft Configuration Schema of DLR
- HOLISPEC®: Marine Version of CPACS developed in HOLISHIP
- GES®: the initial design software tool of TNO
- CFD ReFresco and other maneuvering simulation tools of MARIN
- Rudder design tools of Damen MC

The Life-Cycle Cost and Environmental Impact Assessment of HOLISHIP is being conducted by the developed LCPA tool, a joint development of BALANCE, EPSILON and CETENA (Figure 5).

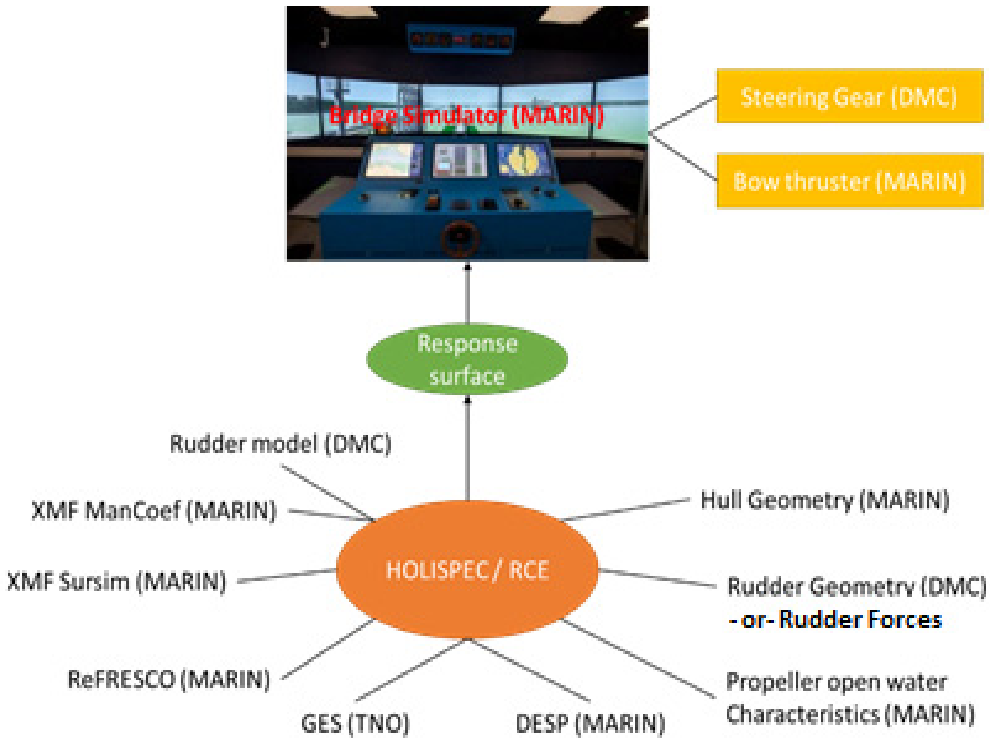


Figure 4. Simulation of Ship Maneuvering and Virtual Prototyping of Rudders (MARIN) [9].

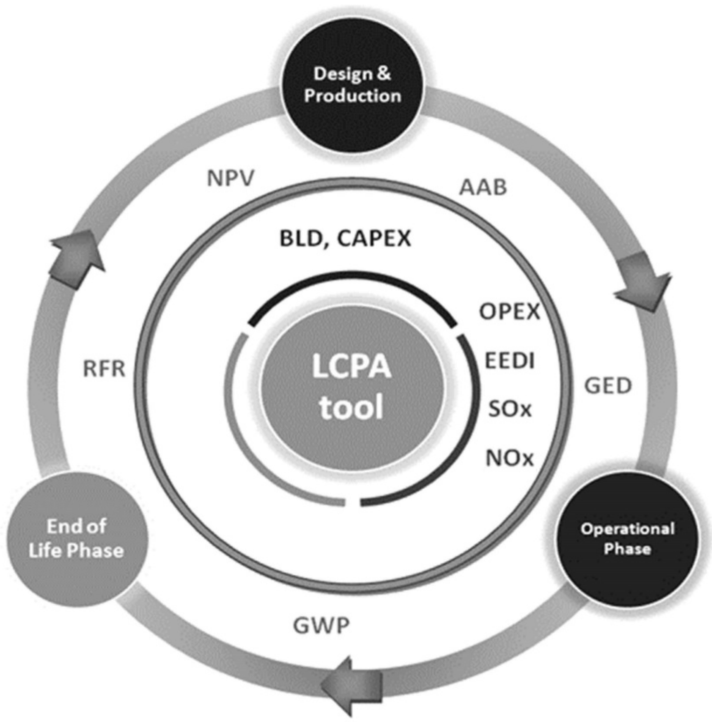


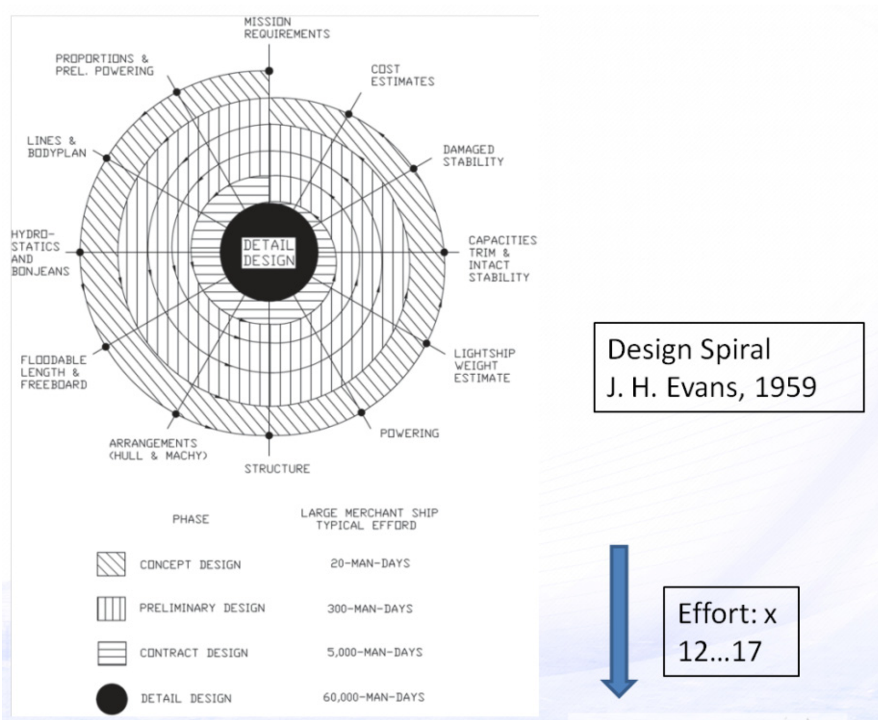
Figure 5. Stages of a vessel life cycle and HOLISHIP LCPA tool [10].

3. Ship Design Optimization

Optimization is an inherent attribute of ship design, even though in practice we often may encounter feasible, but not optimal (or only partly optimal), design solutions. When considering ship design over a ship's life cycle, we split the design procedure into various stages that are traditionally composed of the concept/preliminary design, the contractual and detailed design, the ship construction/fabrication process, and the ship's operation with possible retrofitting and finally scrapping/recycling ("*from cradle to grave or back to cradle*"). It is evident that the optimal ship, with respect to her whole life cycle is the outcome of a holistic optimization of the entire, above-defined ship system over its life cycle. It is noted that mathematically, every constituent of the above defined life-cycle ship system evidently itself forms a complex nonlinear optimization problem for the ensuing design variables, with a variety of constraints and criteria/objective functions to be jointly optimized.

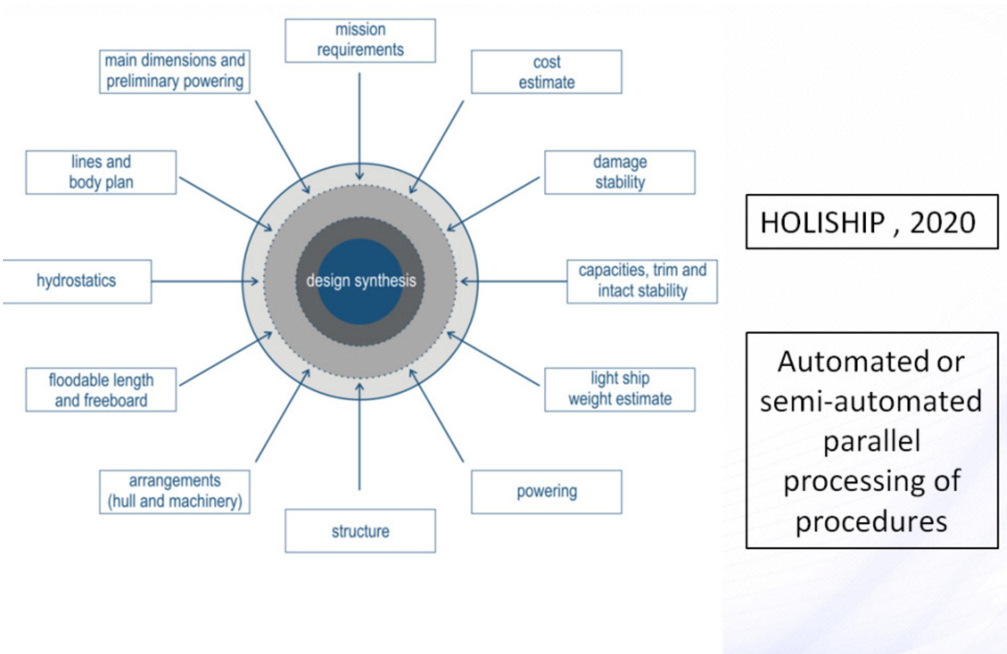
The traditional approach to ship design may be represented by the design spiral of J.H. Evans [11], even if outdated by today's state of the art [12]. It is an iterative, serial and gradually effort-increasing process that moves from the concept design, to the preliminary, contract and detailed designs (Figure 6a, [13,14]). Characteristically, when moving to the next stage, the effort in manpower increases by a factor between 12 to 17. Even if the cited manpower/days data refer to the *manual* design of ship in the late 50s and they are nowadays reduced by a factor in the range 15–20 in view of modern CAD systems, the relationships with respect to the comparable effort in the different design stages remain unchanged.

In contrast to the serial processing of the design spiral, the HOLISHIP approach adopts the parallel processing and synthesis of design tools, as elaborated in Figure 6b [15,16]. Characteristically, the processing of the various design steps is conducted in parallel with fully automated or semi-automated procedures calling a core ship database embedded in the used design platform. The depth of the assessment of a specific ship design attribute, e.g., ship's hydrodynamic performance, can be adjusted to high accuracy at early design stage.



(**a**)

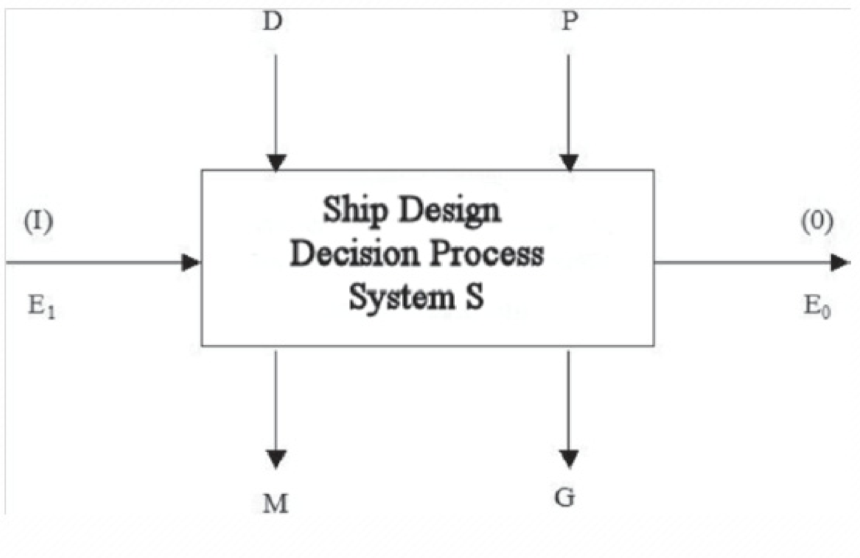
Figure 6. *Cont.*



(**b**)

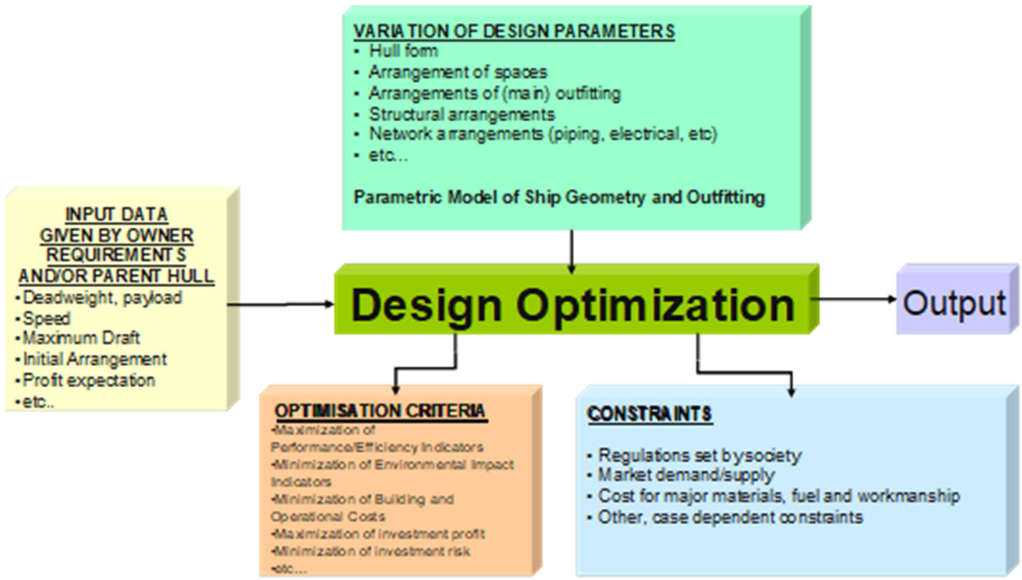
Figure 6. (**a**) Design Spiral/Serial Processing [13]. (**b**) Design Synthesis/Parallel Processing [16].

The progress of ship design optimization in the last 5 decades has been revolutionary and in line with developments in the IT hardware and software knowledge, moving from single-objective optimization for the required freight rate (RFR) of a tanker [17] to multi-objective ship design optimization of various types of ships for a variety of criteria (Figure 7a,b).



(**a**)

Figure 7. *Cont.*



(**b**)

Figure 7. (**a**) Ship Design from Single- to Multi-Objective Optimization [16]. (**b**) Ship Design from Single- to Multi-Objective Optimization [1].

An important feature of the multi-objective optimization procedure presented in Figure 7b is the *Parametric Ship Modelling*, namely the variation of design parameters for the generation of digital "siblings" (Figure 8). This refers to the variation in the ship's geometry, in space and main outfitting arrangements, in main structural elements, etc. by the use of selected design parameters that are optimized in the frame of a defined optimization procedure. Digital "*siblings*" are higher-level digital "*twins*", with enough modelling accuracy to allow for the exploration of the huge design space in the frame of a global optimization procedure.

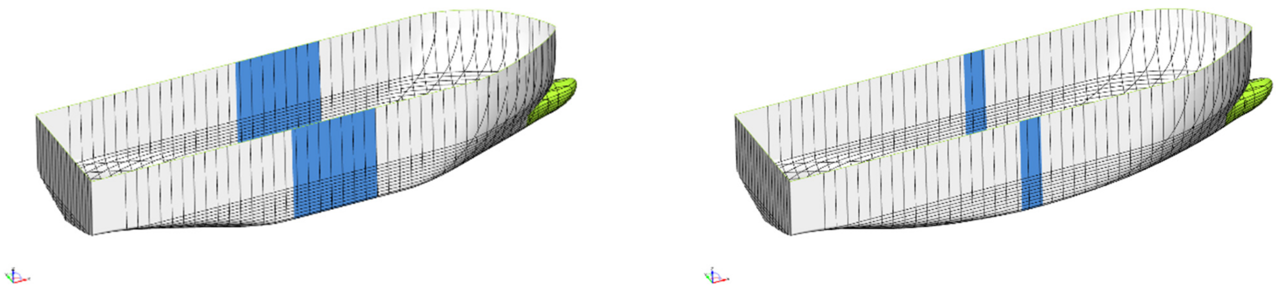


Figure 8. Digital Siblings: Two hull forms with lengthened and shortened parallel mid-body (shown in blue), but with identical displacement and longitudinal centers of buoyancy [18].

For the synthesis of software tools, the PIDO environment (Process Integration and Design Optimization) of CAESES® (www.caeses.com, accessed on 6 November 2022) was used in HOLISHIP and in the studies presented herein (Figure 9).

CAESES® is a versatile CAD system for the parametric modeling of geometry, particularly hull forms, propulsion systems and appendages. Complementary, it is a flexible integration platform, allowing the execution of tools across operating systems and replacing expensive simulations with fast surrogates (i.e., metamodels). The key components needed for running and combining many different design tools and simulation codes are:

- Parametric modeling and robust variation of geometry in order to run design studies (variable geometry);

- Conversion and preparation of data for simulations to provide geometry and information to and between various tools and codes (preprocessing);
- Flexible and easy coupling of any external tools and codes, using task-specific input and output files as templates (software connection);
- Data extraction and aggregation from tools and codes (postprocessing);
- Variant generation by means of design-of-experiments (DoE) (exploration) and optimization strategies (exploitation) along with variant management and design assessment.

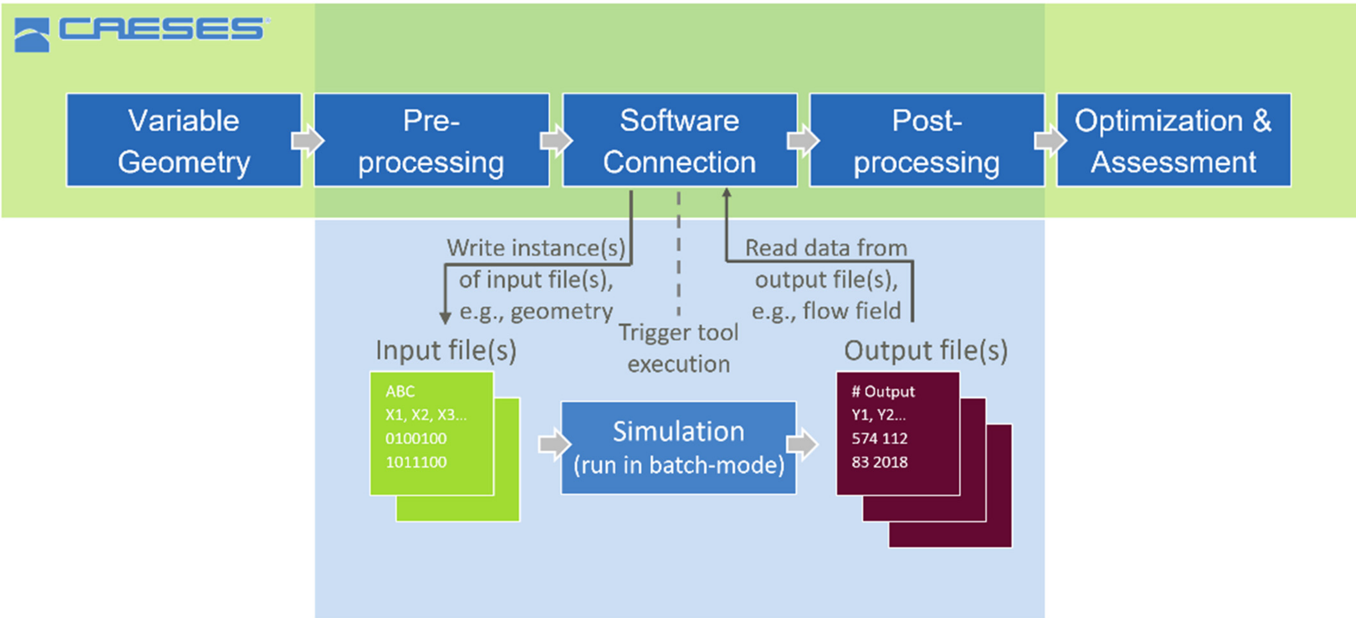


Figure 9. Overview of CAESES® main functionalities with a selection of integrated software systems & providers from the HOLISHIP consortium.

The integration of tools is rather straightforward and allows for the extending of synthesis models as needed and as design processes advance. Within HOLISHIP, about two dozen different simulation codes were coupled [17], ranging from simple spreadsheet calculations, notably using Excel (Microsoft), via potential flow-codes like NEWDRIFT+ (NTUA) and high-fidelity RANSE codes like FreSco+ (HSVA), to computer-aided engineering platforms like NAPA (NAPA Oy) and CADMATIC (Elomatic), as well as ship energy efficiency modeling tools like SEECAT (BV) and COSMOS (DnV).

Several simulation codes (CFD, FEA) typically need quite a lot of execution time, dedicated licenses, special hardware (e.g., an HPC) and, very importantly, expert knowledge of how to establish and run them properly. In general, for a design team facing a multi-disciplinary and multi-objective design task, it is far from trivial to dispose of all the software, hardware and expertise. Furthermore, a RANS simulation may take several hours per variant, while a single probabilistic damage stability analysis might still require some ten to fifteen minutes on a standard PC. Thus, if interactive study-design options are required, quickly and efficiently, the direct calculation procedure becomes prohibitive. Besides, for a formal optimization process that is executed automatically, the logistics of many tools having to run concurrently are burdensome and prone to failure. Consequently, within HOLISHIP a new approach was investigated and successfully applied, namely the encapsulation of simulation results by means of surrogates. To this end, large sets of design variants were generated and independently assessed to determine key performance indicators, such as the attained index of damage stability, the resistance in calm water, the added resistance in waves, the structural weight, life-cycle costs, etc. Designs of experiments, such as a SOBOL or a Latin hypercube sampling technique, were utilized to generate variants for pre-selected free variables, the superset of all free variables representing the design space for the design task when subsequently combining surrogates. For the surrogates modeling, different techniques were made available via CAESES®, such as kriging, artificial neural networks analysis and polynomial regression.

A typical surrogate model for the resistance of a double-ended ferry studied in project HOLISHIP is shown in Figure 10. There, the change in calm water resistance has been calculated upfront via the use of a computing power- and time-intensive RANSE code with respect to a variation in length and beam (other parameters may be added) of design variants; point results are expressed by a surrogate model function, enabling fast postprocessing when searching for the design variants with lowest resistance.

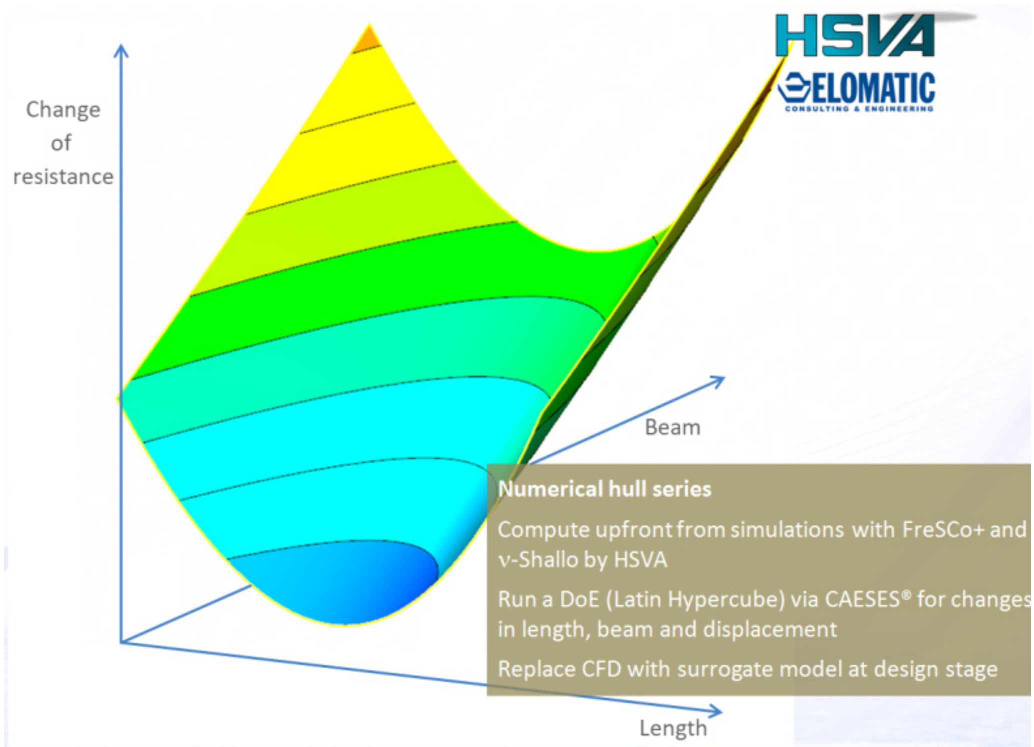


Figure 10. Surrogate model for DE-ferry [8].

A synthesis of tools for the parametric design optimization of a RoPax by the CAESES® platform is shown in Figure 11. Hull forms of digital siblings, parametrically generated by use of the CAESES model (step 1), are hydrodynamically evaluated for their calm water resistance by use of the potential theory panel code ν-Shallo (step 2) and RANSE code FreSco+ of HSVA (step 3), as well with respect to seakeeping and added resistance in waves by use of the code NEWDRIFT+ of NTUA (step 4). An assessment of the intact and damage stability of the variants by use of NAPA follows in step 5, assuming a conceptual ship arrangement and internal subdivision. The preliminary structural design of the variants by the use of Mars/BV, or alternatively NAPA steel, follows in step 6. The life-cycle economic and environmental impact assessment of the parametrically generated designs is conducted by a CAESES feature, or the more advanced LCPA tool of HOLISHIP, in step 7. Final space and outfitting arrangements are developed in step 8, but only for the identified optimal design(s), via a proper CAD drawing tool (NAPA or AUTOCAD). It is noted that the above-outlined step procedures 1–7 may be conducted in parallel, as they are independent from each other, except for the basic information about the hull form and conceptual space arrangements that are defined in step 1. Obtained results for the various properties of the generated design variants/siblings (resistance, propulsion power, stability metrics, structural weight, displacement, etc.) are postprocessed by the use of *surrogate* models that enable the fast identification of the best design variants by the application of multi-objective genetic algorithms (MOGA), available on the CAESES platform (Dakota toolkit, https://dakota.sandia.gov/, accessed on 6 November 2022).

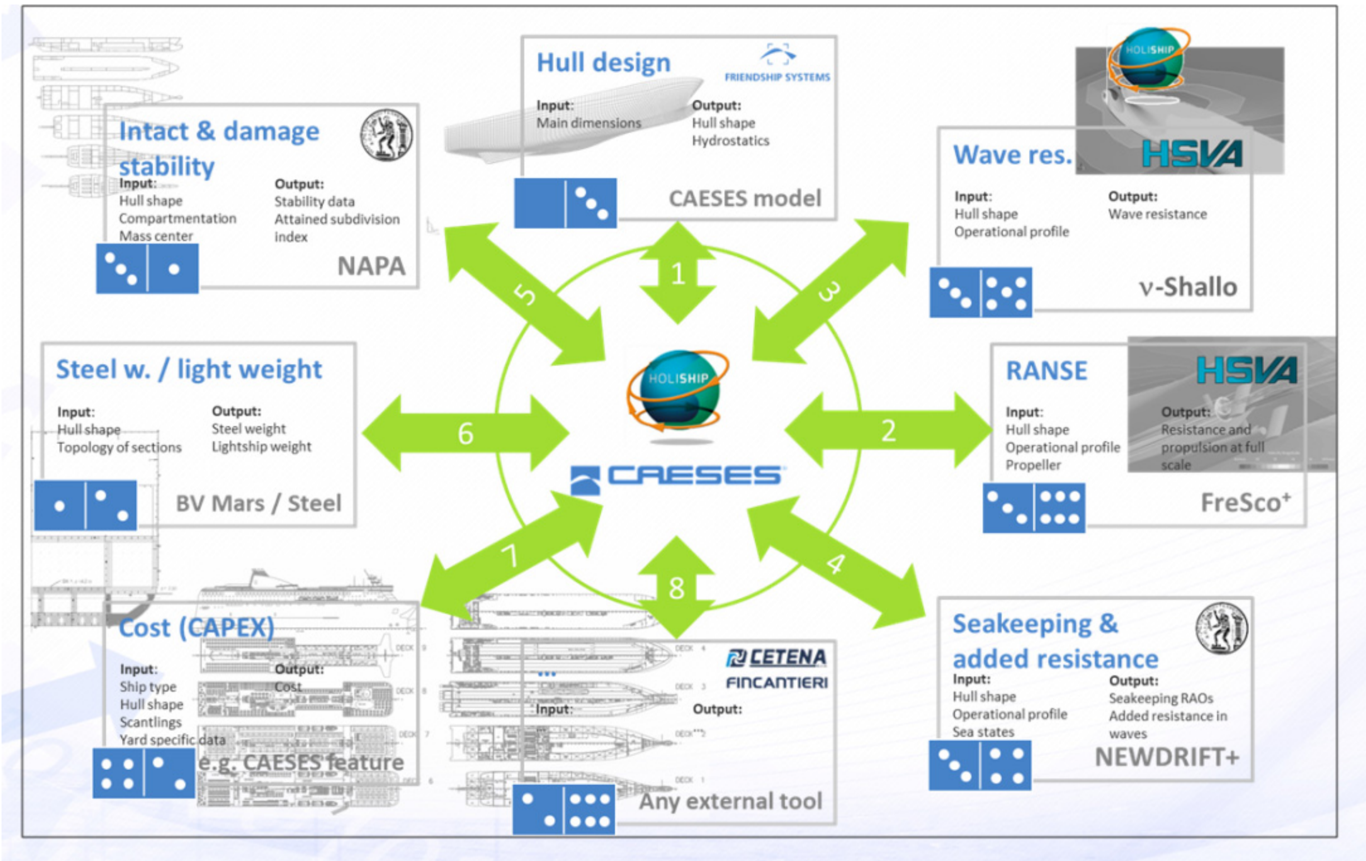


Figure 11. CAESES®/Friendship Systems Synthesis of Tools for RoPax Parametric Design Optimization.

In the frame of a RoPax optimization study, in Figure 12 (upper part) we see the results of the exploration of the design space of some hundreds of automatically generated RoPax ships in terms of the margin of the attained subdivision index (positive means: attained subdivision index is larger than the required one) in the indicated range of beam and length. Note that points in orange color indicate non-feasible designs due to the violation of some set design criterion (here: mostly damage stability). In Figure 12 (lower part) we see the net present value (NPV) of the generated RoPax design vs. the attained subdivision index margin and a clear *Pareto Frontier* of the feasible designs. Details of these studies and an elaboration of the RoPax design can be found in [19].

Beyond the *global optimization of main ship dimensions/parameters*, *a local optimization* generally follows for the most promising deign variants. In Figure 13, the transom stern of a fast catamaran has been parametrically modelled by the use of 10 design parameters, and detailed flow CFD calculation was conducted for the optimal transom stern geometry, while considering the interaction with the fitted propeller, the propeller shaft, brackets and rudder (project TrAM, [20]). This local optimization process led to a remarkable overall propulsive efficiency of about 80%, proving the feasibility of the battery driven high-speed design concept [21,22].

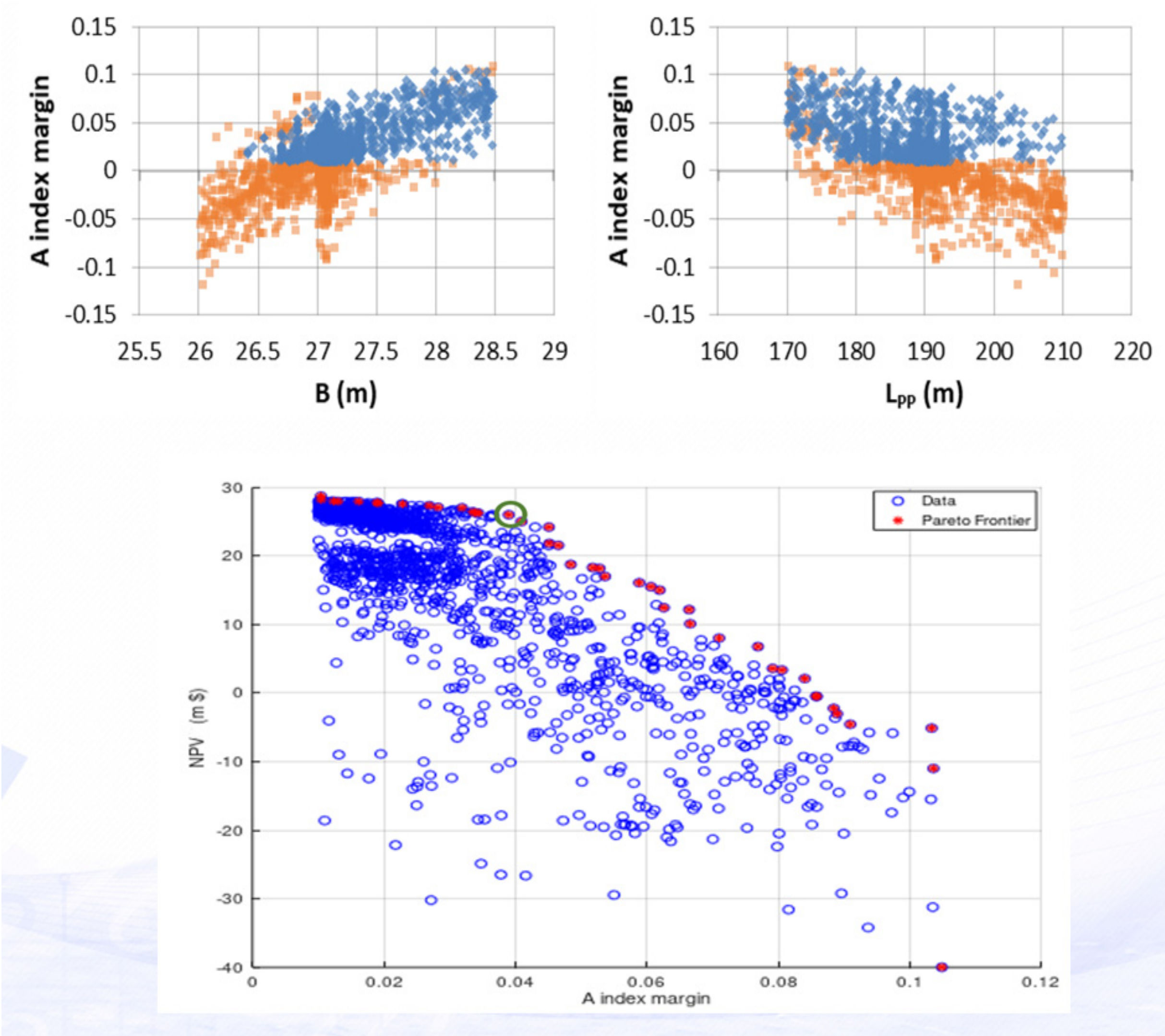


Figure 12. HOLISHIP Optimization RoPax [19].

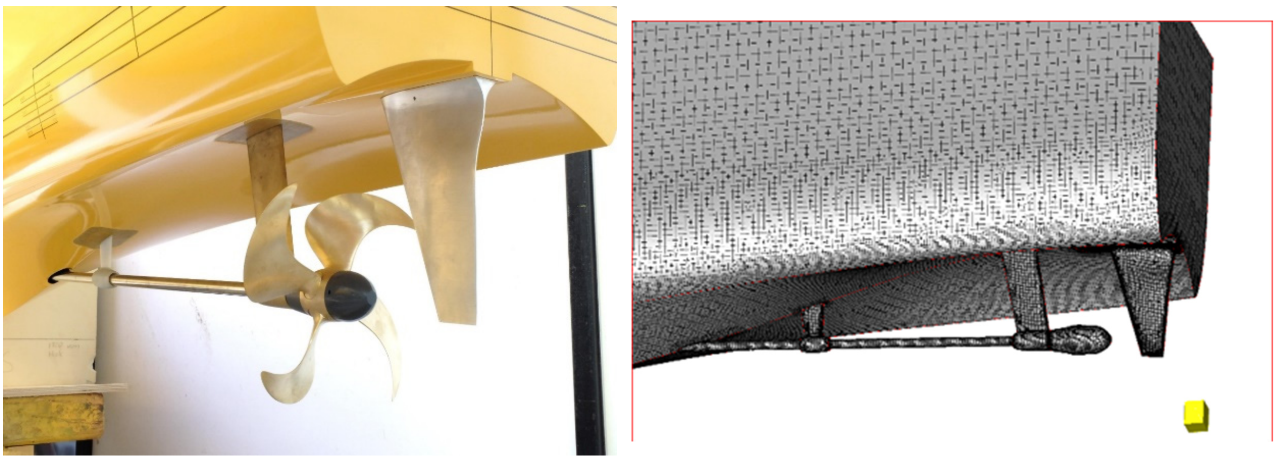


Figure 13. Numerical mesh around the stern tunnel area for the local optimization by FreSCo+ of the Stavanger Demonstrator (5.7M)—H2020 TrAM Project Battery driven fast Catamaran Local Optimization of Transom Stern [21].

4. Conventional vs. HOLISHIP Design Approach: What Is the Difference?!

The holistic approach to ship design implemented in the HOLISHIP project is not simply a new verbal notion, without substance. We claim that it is a step change in ship design, as elaborated in the following tabular comparison with the conventional approach on the basis of defined assessment criteria (Figure 14).

Criterion	Conventional	HOLISHIP
Concept design	Empirical approach; supported by available computer-added calculation and graphics processing procedures, manual generation of 1…3 variants of baseline design and intuitive selection of the most promising variant	Automated parametric generation of hundreds of variants (*digital siblings*; "cloning", Figure 8) and comparison to baseline design, including their documentation; *global optimization* of main ship dimensions and main characteristics; rational (mathematical) identification of most promising variants on the basis of set criteria.
Preliminary /Contract design	Sequential processing of design steps (design spiral, Figure 6a); individual optimization of design properties (hydrodynamics, structures, machinery, economics) of just a few design variants	Parallel processing of design steps and design synthesis (Figure 6b); multi-objective and multi-disciplinary optimization of several/hundreds of design variants (Figure 12); local hull form optimization (Figure 13).
Accuracy of calculation methods	Low at concept design level (mostly empirical modeling); high at contract design level	High at any design level, depending on the capability of the employed s/w tools; use of surrogate models for intensive calculation tasks (Figure 10).
Design lead time and person months effort	*Assuming the availability of a baseline design*: <u>Concept design</u>: some person days, depending on the experience of the design team (Figure 6a) <u>Contract design</u>: several person months, depending on the experience of the design team *If no baseline is available*: <u>Concept design</u>: many person days of collecting information, identifying and analyzing similar ships already built from public data	*Assuming the availability of suitable parametric models*, e.g., from a previous design campaign: <u>Concept and contract design</u>: lead times are significantly reduced by a factor > 5 (est.); smaller design team with less need for experience of all team members *If no parametric models are at hand*: Several days to weeks for building up robust and meaningful parametric models, depends on modeler's experience
Costs	The effect of design variants on cost is done at early design stage intuitively by designer's experience or at best by checking the costs of only a few design variants	Early assessment of the effect of hundreds of design variants on cost leads to significant cost reductions in the production cost (CAPEX) and operational cost (OPEX) or maximization of the Net Present Value (NPV) (Figure 12, lower part)
Quality of design (concept and contract)	Highly depend on the designer's and yards' experience	Superior quality thanks to systematic optimization and selection of the best out of hundreds of variants; consolidated standard design documentation; Quality assurance via consistency in the assessment of variants
Safety of ship & the marine environme nt	Rule-based design with undefined safety level	Risk-based design with quantifiable risk consequences and safety level

Figure 14. *Cont.*

Energy efficiency	Studies on energy efficiency are commonly done at contract design stage and mostly refer to the hull-propeller interaction; individual studies on overall energy consumption are nowadays common for high energy consumers (passenger ships, high-powered, special type of ships)	Improved energy efficiency in view of the integration of s/w tools for the simulation of energy consumption, including the machinery-propeller-hull interaction at early design stage (Figure 3)
Life-cycle Performance and Assessment	Mostly restricted to the economics of an investment (shipowner's side); environmental impact is only considered by enforced regulations (considering the set IMO targets as constraints)	Life-cycle assessment and optimization of economics and environmental impact at an early design stage (Figure 5)
Innovations in ship design	Limited, due to the lack of baseline designs to build upon	Enabled in view of the simulation-based (first principles) ship design approach; main design problem issue: definition of parametric model (transfer of innovation idea to a mathematical model)
Software platforms	Professional naval architectural software platforms with limited or no collaboration with external software tools; strict communication protocols	Flexible s/w platforms with simple communication protocols; long list of integrated external s/w tools, including communication with professional naval architectural platforms (CAESES); interchange in data with NAPA® through macros (Figure 2)
Design workflow procedures	In general, manual planning of design workflow, which depends on designer's experience; limited coded design workflow procedures	Enables coding of design workflow procedures by macros; HOLISHIP demonstrated more than ten (9 + 3) coded design procedures for several ship types and marine assets
Distributed working/cloud communication	Not known in ship design	Enabled through cloud communication (IoT) and demonstrated through the RCE/CAESES HOLISHIP platforms
Virtual prototyping	Not known/limited in ship design	Demonstrated by simulation of the maneuverability of a ship with alternative rudders on MARIN's bridge simulator and feedback by the captain (man-machine interaction) (Figure 4)
Acceptance by industry	Trivial, as conventional	At present the acceptance is limited to the HOLISHIP partners and knowledgeable academia; growing acceptance; education of future naval architects is essential; HOLISHIP book and dissemination through partnership

Figure 14. Conventional vs. HOLISHIP Approach to Ship Design.

5. Overview of Application Cases of HOLISHIP

In the HOLISHIP project, nine (9) basic and three (3) variant demonstrators were developed by the participating European industrial partners of HOLISHIP, supported by research institutes, societies and university laboratories. The development of these demonstrators, which are all innovative with respect to the adopted design procedures and the demonstrated performance, presumes the familiarization of the design teams with the HOLISHIP concept and its software platforms and tools, prior to application in practice. Elaborated application cases refer to concept and contract design stage, while in two cases, virtual testing by digital mock-ups was demonstrated. The following basic application cases were elaborated the by use of the developed HOLISHIP software infrastructure (Figure 15):

- The optimization of the design and operation of an Offshore Support Vessel (OSV), coordinated by Kongsberg Maritime;
- Light weight design issues of cruise vessels, coordinated by Meyer Werft;
- The design for maintainability of the engine system of a research vessel, coordinated by Fincantieri Shipyard;
- The concept and contract design of a multi-purpose ocean vessel, coordinated by the Naval Group;
- The virtual vessel mockup for the simulation of the maneuvering of a cargo ship, coordinated by MARIN;
- The hydrodynamic optimization of a containership and a bulk carrier, as well as the presentation of a weather routing system, coordinated by NTUA on behalf of DANAOS;
- The concept design of a gravity base foundation for an offshore platform operating in icy shallow waters, coordinated by Elomatic;
- The optimization of a conventional and an advanced engine/propulsion technology RoPax, coordinated by Tritec Marine;
- The design of a double ended ferry, coordinated by Elomatic.

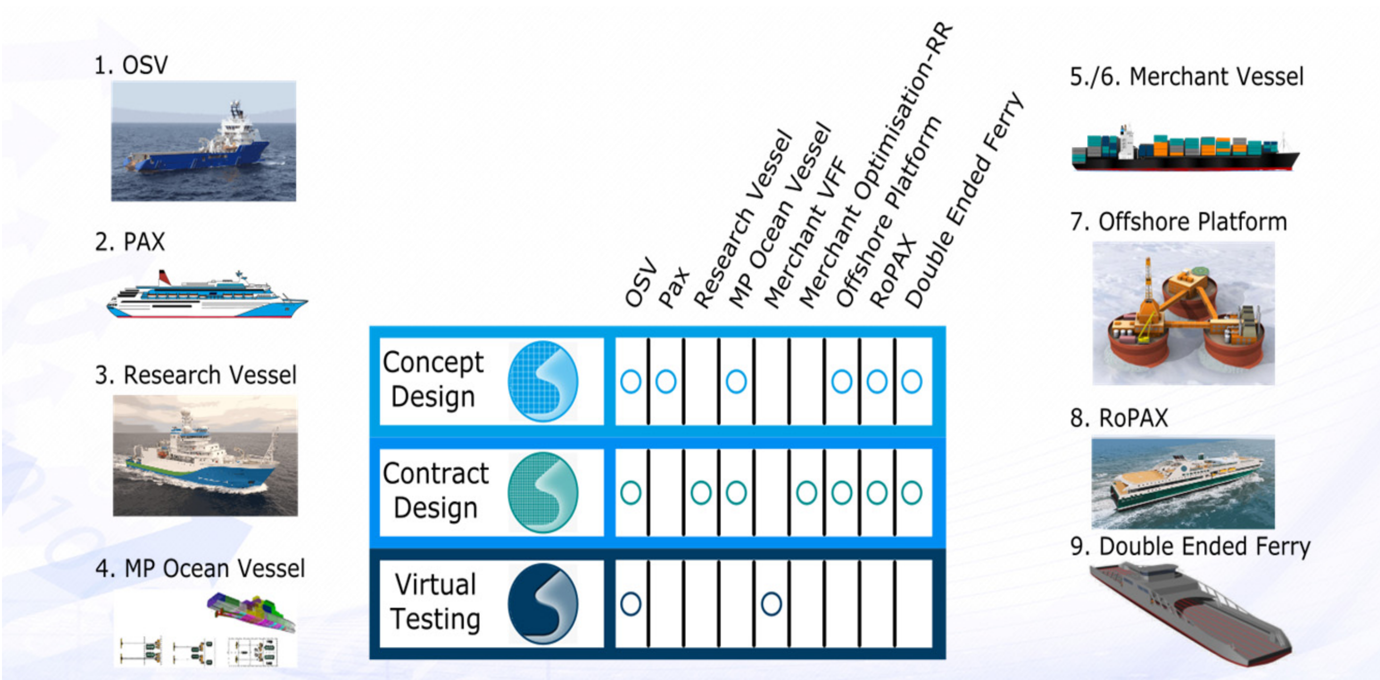


Figure 15. HOLISHIP Demonstrators.

All above application case studies were conducted by use of methods and tools described in volume I of the book "A Holistic Approach to Ship Design" [23], whereas details of the application case studies are elaborated in volume II [24]. In addition, two more application studies referring to green shipping were recently presented [4], namely:

- The design of an LNG fueled RoPax vessel for operation between Italy and Greece
- The design of a battery driven double ended ferry for operation in Finish coastal waters.

6. Summary and Concluding Remarks

A holistic approach to ship design, which was introduced earlier as a novel ship design concept, was widely applied in the HOLISHIP project, proving its viability. The concept was implemented in versatile, integrated design platforms, offering the user a vast variety of options for the efficient development of alternative ship designs by the use of tools for their analysis and multi-objective optimization with respect to all relevant (ship) design disciplines, as well as virtual prototyping. An open architecture allows for continuous adaptation to current and emerging design and simulation needs, flexibly setting up dedicated synthesis models for different application cases. The exploration of the huge design space is enabled by the use of automated parametric models of significant depth, which are processed with reduced lead time.

The achievements and introduced innovations of the HOLISHIP project are summarized below:

- Design synthesis and integration of software tools realized via a combined bottom-up and top-down approach;
- Parametric, multi-objective design optimization enabled via CAESES® platform;
- Flexible combination of tools as needed for specific design tasks;
- Continuous growth of syntheses models with more application cases;
- Replacement of resource-intensive simulations with surrogate models;
- VR modeling via RCE platform known from German aviation industry (DLR);
- Distributed Working enabled via RCE cloud computing;
- Holistic approach to ship design proven in a series of application studies;
    - Effective exploration of huge design space in short time;
    - Seamless consideration of important design aspects at early stage;
    - Rationally optimized designs by state-of-the-art tools;
    - Consideration of human factors in ship design by virtual modeling and VR testing.

In the future, further dedicated tools and applications addressing requirements arising from contemporary emission reduction policies will be integrated into the HOLISHIP Platforms and thus provide the path towards the zero-emission maritime transport goal set out by the EU and the waterborne community.

Funding: HORIZON 2020 project HOLISHIP, contract number 689074. The HOLISHIP project is the joint effort of 40 representatives of the European Maritime Industry and Research Community. The work was partly funded by EU in the frame of the HORIZON 2020 project HOLISHIP, contract number 689074, www.holiship.eu (accessed on 6 November 2022).

Conflicts of Interest: The authors declare no conflict of interest.

Note

[1] Key-note paper presented at MARTECH22, the 6th International Conference on Maritime Technology and Engineering, Lisbon, Portugal, 24–26 May 2022.

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