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Integrated ship design: an innovative methodological approach enabled by new generation computer tools

Ubaldo la Monaca¹  · Serena Bertagna¹  · Alberto Marinò¹  · Vittorio Bucci¹ 

Abstract

Ships currently built in the western market, and in particular in Italy, can be considered highly complex and technological. The main products of this market are passenger ships, military ships, mega-yachts, and offshore supply vessels. As opposed to what happens for other vehicles of comparable complexity and cost (i.e., airplanes), the time available to deliver a ship is rather limited. The design process of large complex ships, therefore, requires a long and resource-intensive development cycle. Indeed, it must foresee both the compliance with specific technical and regulatory requirements and the containment of ship's CAPital EXpenditure and OPerating EXpense. Moreover, particular attention must be given to decisions made during the early-stage design, because of their large impact on ship functionality and overall configuration. In order to reduce execution times and costs, computer tools are currently used. However, since they very often are not integrated, time-consuming remaking activities, able to reduce the design robustness, are necessary. To overcome this issue, several software have been developed to implement the innovative integrated design methodology. In this paper, after a review of both the modern ship acquisition process and the computer tools available on market, a new methodological approach is presented. Specifically, it is shown how the integrated use of new design tools can lead to the rapid and undemanding implementation of a ship's virtual prototype, in order to enable the proof-of-concept of new technologies, already in the early-stage design.

Keywords Integrated ship design · Virtual prototype · Computer system integrator · Early-stage design · CAD

1 Introduction

In 1768 the Encyclopædia Britannica gave the following definition of ship: “A ship is undoubtedly the noblest machine that ever was invented; and consists of so many parts, that it would require a whole volume to describe it minutely.” [1]. Obviously, at that time the reference was given by the large sailing war ships. From the eighteenth century to present days, ships have continued to be among the largest machines built by man and their complexity has increased greatly. The

increase in complexity is not only due to the increase in size of current ships, but above all to the high degree of specialization they have achieved. While in the past the difference between war ships and merchant ships was given exclusively by the presence or absence of guns, today we can count dozens of extremely different types of vessels. Ships have evolved in such a disruptive way because many new technologies have become available and consequently cargo transport has been increased. Paradoxically, the traditional problem of naval architects to tailor the hull form on the basis of the payload, in order to ensure the highest possible speed with the lowest possible consumption, is now amplified precisely by the demands about payload.

As for all other industries, also for shipbuilding environmental concerns have become a dominant design driver. Indeed, in recent years, the interest to enhance the sustainability of shipping operations has exponentially increased. About 90% of global trade is transported by ships, and ship transportation can be considered one of the most environmentally friendly modes of transport, accounting for only 3% of global CO₂ emissions. Shipping operations have not

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such a significant impact on fossil fuel depletion as about 350 million t/year, corresponding to 5% of the total transportation sector energy consumption [2], are consumed. Nevertheless, in most cases, port operations are concentrated near residential areas and many technologies are available to increase the efficiency of this mode of transport. In order to speed up the fleets technological update to enhance shipping sustainability, IMO, EU, and national authorities imposed increasingly stringent environmental Regulations. Therefore, increment of ship environmental efficiency plays a major role in decision-making processes of shipowners. Moreover, following lessons learned the hard way, also the safety of vessels, passengers and crew has also considerably improved [3–6].

The possibilities given by the new technologies are so significant to be considered as Key Enabling Technologies (KETs). Therefore, their exploitation is a matter of supremacy towards competitors (either commercial or military). However, most of these technologies are so advanced to lack a proper demonstration of their applicability on board [7, 8]. Since ship design is a complex process, integrating several different systems (power system included) in a single huge entity, which must comply with multiple mandatory constraints [9], is necessary. Each system with respect to the others acts both as a partner (in order to make the ship fully operating) and as a competitor (mainly in terms of weight and volume onboard). Moreover, the final design must not only comply with the given requirements and constraints, but also maximize as far as possible the most important ship design drivers (e.g. weight/volume/footprint reduction, efficiency improvement, cost reduction, payload maximization) [10, 11]. If a new component, subsystem or system has to be integrated onboard, the design complexity rises exponentially, thus making its impact on the ship very difficult to be foreseen. As a matter of fact, also the new technologies that have already proven their applicability through testbeds must pass through another proof-of-concept stage, just in relation to their integration onboard [12, 13]. It is worth noting that in many fields the new components for ships' systems have technologically evolved much faster than ships. Indeed, they were able to inspire what already exists for other means of transport.

Therefore, the problem of the technological update of new ships is essentially the identification of a new design methodology able to efficiently integrate all these innovations right from the early-stage in ship design. The problem to be solved consists in the technological integration of an extremely complex system as the ship is. The theoretical basis for dealing with the solution are already the foundations of modern ship design. Indeed, Mandel and Chrysosotomidis [14] have identified an effective method for dealing with the design of complex systems by dividing them into their component parts, maintaining the overall synthesis

(Fig. 1). According to this method, the ship design can be split so modern multi-disciplinary design teams can accomplish that. In applying this method, three recommendations must always be kept in mind:

- identifying a number of sub-problems such as to minimize the interaction among them;
- minimizing the number of sub-problems;
- providing consistent and reliable communication within the design team.

During all the design stages, and specifically during the early-stage design, the most common and efficient method of dividing a ship (merchant or naval) into smaller component parts is the one proposed by Andrews [15]. Figure 2 reports his building block scheme according to which the ship is split into both Work Breakdown Structure (WBS) and Functions (including float, move, operate, and infrastructure). Many studies have been carried out over the years to provide a recipe allowing the optimization of the use of time and economic resources [16, 17], but professional experience has also shown that the most important decisions are those taken in the early stages of the project.

Such a “ship decomposition” foresees that each module (generally corresponding with a single ship system) is responsible for the addition of a further capability to the ship: the most favorable assembly of the different modules will be the best (or the better one of the bests) design. In order to grade each assembly, according to a scale of Key Performance Indicator established by designers, prototypes of the various systems are often tested. For example, to validate the ship's hydrodynamic performance, recourse to towing tanks is still essential by a physical model. For all the other on-board systems, the adoption of a real prototype is impracticable and inefficient. In these cases, it is rather convenient to adopt a virtual prototype. In the past, the IT hardware and software allowed testing of one prototype at a time, whereas nowadays it is possible both to create and to test virtual prototypes of a whole ship. In this way, it is possible not only to apply the principles of the concurrent engineering, but an interactive approach can be adopted for evaluating projects. Thus, a continuous exchange of consistent information (albeit evolving) within the project team is allowed.

In this paper, after a modern description of the ship acquisition process, a new rational approach for the ship design is presented. It is essentially based on the upgrading of the initial phases, defining an early-stage design. This method takes advantage of the current progress in IT available to designers. In particular, the integration of computer system integrator (CSI) software inside the concept design stage has been fundamental. The computer aided synthesis model uses Multi-attribute-decision-making techniques to evaluate the

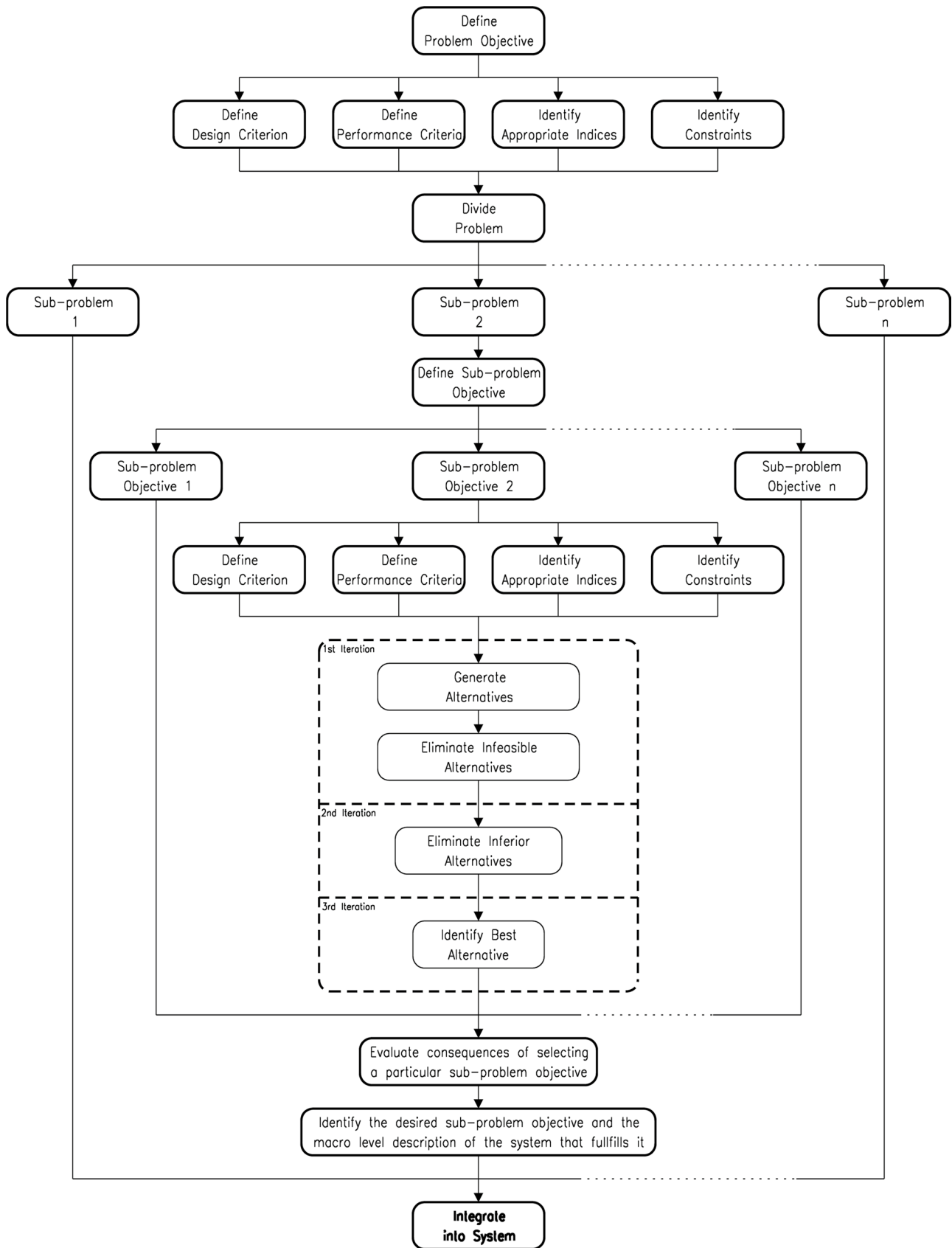


Fig. 1 The exploration phase flow diagram according to Mandel and Chrysostomidis

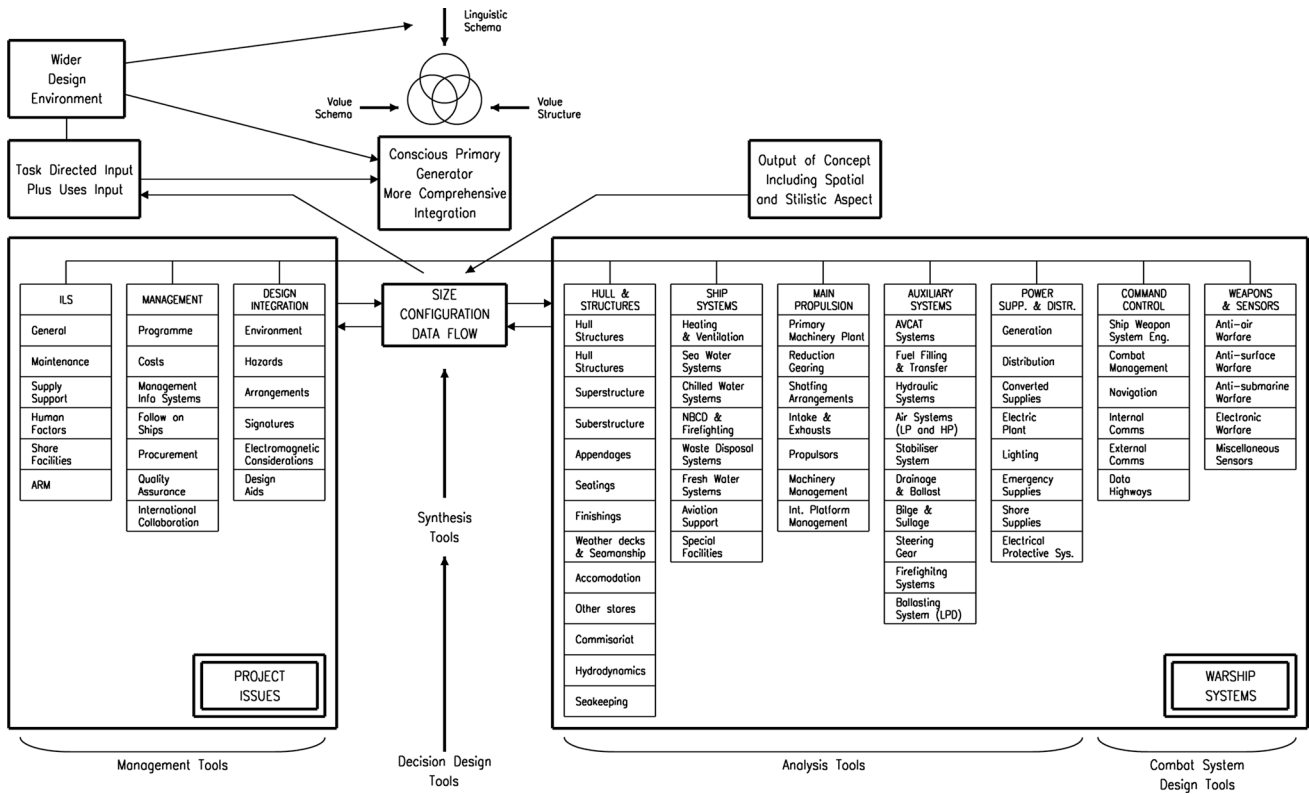


Fig. 2 The project work breakdown structure according to Andrews

quality of the design produced and employs a modern CSI as output tool generator. In such a way, the final best design is modeled as a Virtual Prototype since the early-stage design. Virtual Prototypes can give greater strength to the decision-making process of the whole design team. CSI software are able to interface with the most diffused software commonly used in ship design and construction. They allow to provide smooth information exchange among all of them, making easier for the design team to perform the conventional design verification and modification steps. Moreover, it can be used as a recipient for all the ship design data, setting up an inclusive database accessible by all the stakeholders, thus ensuring data consistency and up-to-date information access. CSI software are based on a modular architecture, thus enabling its expansion towards new tasks, including automatic indexes calculation (e.g. weights and volumes), design optimization algorithms, and so on. As an example, a CSI software can be used since the early-stage design to define the location of the ship's power system equipment on the basis of the different spaces available on board: in this way, an accurate evaluation of related weights and volumes involved, along with their optimization, is possible. In addition, the above mentioned possibility of integrating the software with new modules enables the calculation of additional objective

functions. This allows to evaluate the impact of a system on the others and on the entire vessel, therefore assessing overall ship capabilities regarding each performance aspect (e.g. ship energy efficiency, fuel consumption, seakeeping, thermal management, etc.). In the end, the advantages provided by this new design approach for the early-stage design are manifold: team work, sharing of consistent information even within a delocalized design team, direct and immediate involvement of all the ship acquisition parties (designer, shipbuilder, shipowner, Classification Societies, etc.), and immediate visualization through parametric 3D models of the design process results. Moreover, the Virtual Prototypes generated in this way can be efficiently used in the subsequent design stages, and can be efficiently stored for reuse in future projects.

2 Ship acquisition process

Shipping is a potentially very lucrative activity, but extremely risky. Consequently, when a shipowner has to decide whether to undertake a business or not, he always has the goal of maximizing profit by minimizing expenses. Moreover, the shipowners seem eager to get the

highest possible loan and try to keep their own capital as liquid reserve. There are a number of different paths to obtain a new, expanded, and enhanced maritime transport capacity, that include:

- New ship construction;
- Second hand purchase;
- Lease or chartering (bareboat, time or voyage);
- Ship conversion (jumboizing, re-engining);
- Contract of freighting;
- Ship-sharing or pooling tonnage.

In order to allow the shipowner to make quickly and confidently his decision, a team of professionals with very different skills must work together. Based on the total quality leadership/management (TQL/M) ideas as empowerment of employees and establishing close relationships with one's customers and suppliers, the use of teams as a form of project administration is gaining popularity. Teamwork, or collaborating, attempts to replace the conflicting viewpoints and often-hostile communications typical to multi-organizational projects through open relationships characterized by trust and desire to advance the project towards agreed upon goal [18]. The acquisition of a new ship, from the shipowner's perspective, is a major capital expenditure. It should follow a four-phase process, namely:

1. Planning;
2. Design;
3. Commercial activities;
4. Production activities.

However, there are other procedures that might be preferable under appropriate circumstances. One is to eliminate design and some of the commercial phase, purchasing a standard ship from a shipyard. Obviously, there are some disadvantages because the ship may not exactly meet all the shipowner's needs (speed, capacity, limitation in machinery and outfitting selection, etc.). The main advantages, due to series-built, may include lower price and possible faster delivery.

Throughout the entire ship acquisition process, the use of engineering economics is essential. During the planning stage, economics is used to develop and evaluate strategic alternatives. Engineering economics are also used in developing the technology, financing and business plans. During the design phases and especially in the early-stage design, engineering economics are used to both select alternatives and optimize the preferred one. During the commercial stage, economics is important in evaluating various financing alternatives and shipbuilding proposals.

2.1 Design stages

Ship design process is quite a long and articulated path, which begins with the results obtained from the planning analysis and finishes when the new product is delivered. Drawings and/or 3D computer models, specifications and all the information needed for the production are to be elaborated. The design phase forms a transition from the requirements of the planning phase to the development of a configuration shape, dimensions, layout, and other characteristics. It is the point at which efforts shift from management science to design, particularly naval architecture and marine engineering. The design effort might involve modifying, extending, or otherwise building on previous designs, or synthesizing other design. Hence, another necessary design activity involves research in the field regarding both specialized work and current or state-of-the-art developments. The design team should be aware of the status of research and development worldwide and be alert to potential breakthroughs in the many disciplines in maritime field. In research activities, engineers seek new principles, processes and, obviously, technologies and components. Design team is usually faced with solving problems subject to conflicting requirements, which may be physical (minimum weight), economic (minimum cost), social (maximum safety), and environmental (minimum impact). It must resolve these conflicts and search for optimum solutions with regard to the goals of the shipowner, identified in the planning phase.

The design process of merchant ships (Fig. 3) progresses through distinct and increasingly more definitive stages separated by intervals in which reviews are issued and deliverables are developed as references for the next stage:

- Concept design;
- Preliminary design;
- Contract design;
- Functional design;
- Transition design;
- Work instruction.

It should be noted that the shipbuilder usually executes the three last design stages after the shipbuilding contract is signed. A manner to collect the various stages of the ship design process is based on distinguishing between Basic Design (Concept, Preliminary, Contract, and Functional design stages) and Product Engineering (Transition design and Work instruction). In the Basic Design the ship is treated in its entirety and designed on a system-by-system basis, while in the Product Engineering the deliverables developed in the previous phase are detailed into a form suitable for the production techniques adopted by the shipbuilder [19].

Different approaches are followed if the final product is a merchant ship or a naval one [20]. For the latter, the

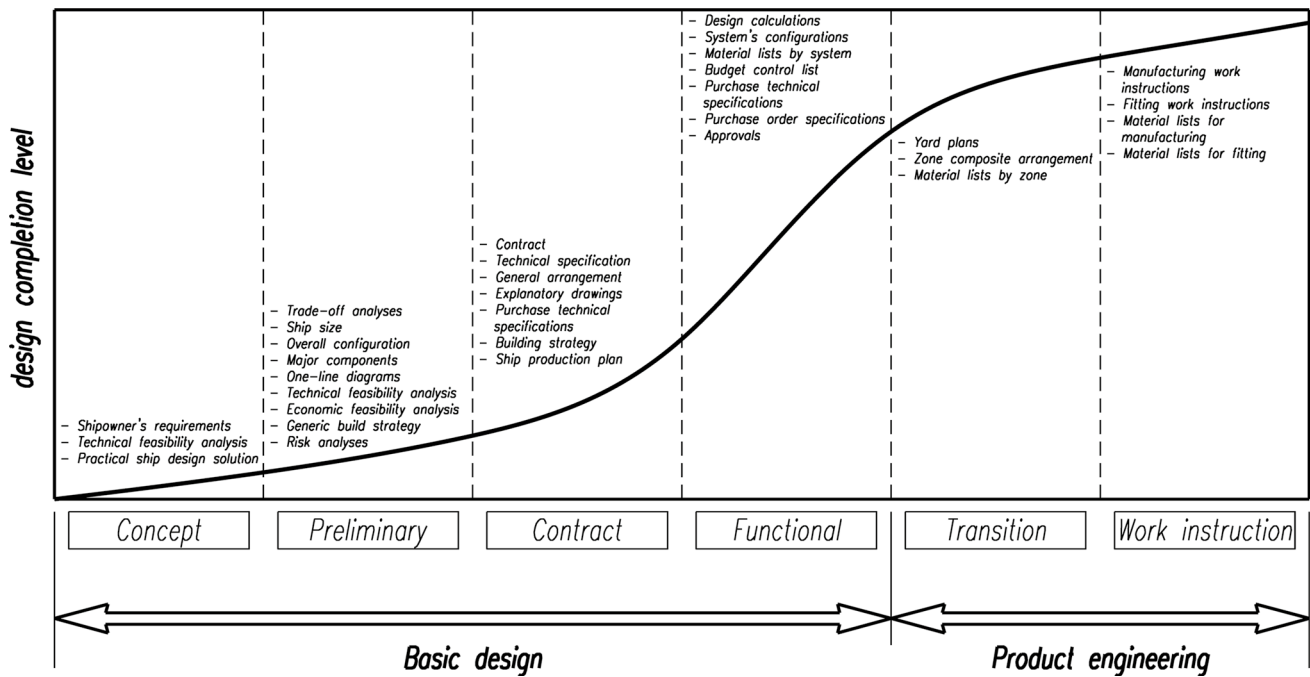


Fig. 3 Merchant-ship design process

acquisition process begins when a gap in operational capability of the overall fleet is identified. It can be caused by new weapons systems that cannot be installed with a simple refit of the existing units, new role for the naval fleet as

humanitarian one, ship classes reaching the end-of-life. The stages that are followed (Fig. 4) are practically the same as a merchant ship, but conventionally they are grouped in another way:

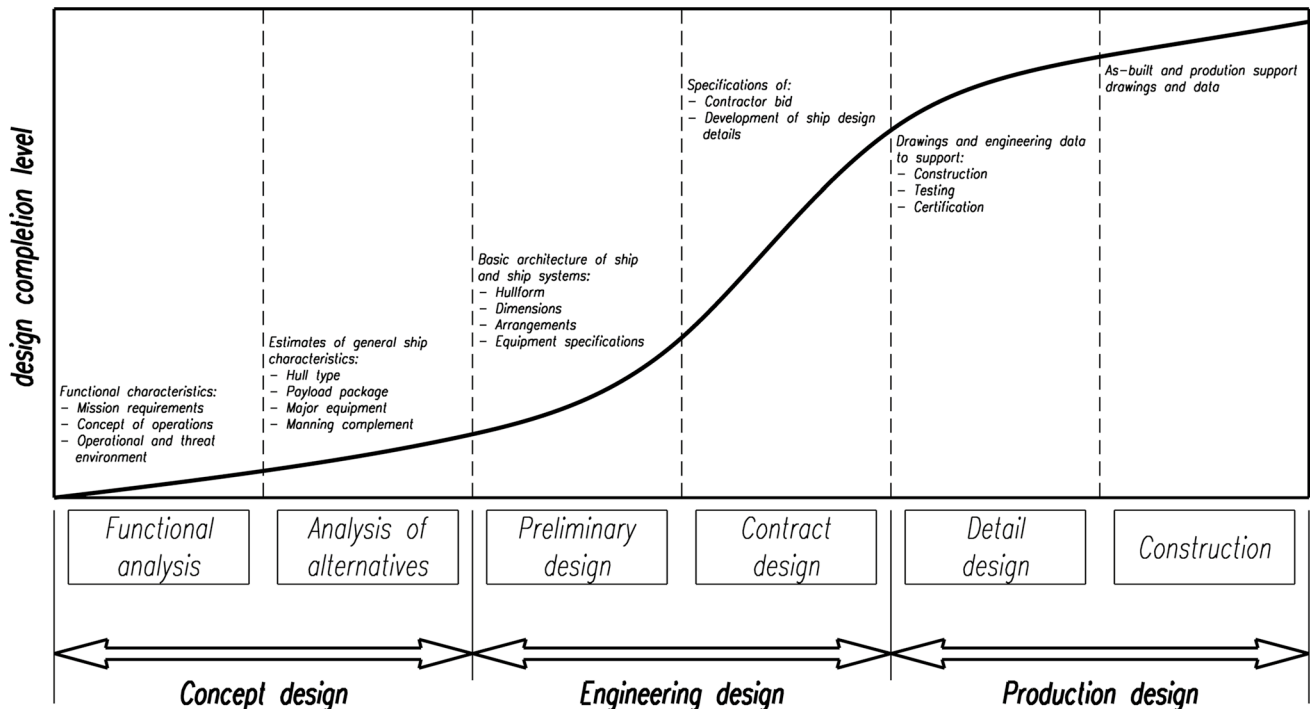


Fig. 4 Naval ship design process

- Concept design, which includes functional analysis and the analysis of alternatives;
- Engineering design, composed by preliminary design and contract design;
- Production design, consisting in detail design and construction.

Usually, the early stages are performed by the Navy technical departments, and the last by a contractor/shipbuilder; the transition from Navy external parties occurs during the Engineering Design. Whether it is a merchant ship or a naval vessel, as proceeding through the various design phases, details increase, but the choices available to be made decrease. A more detailed description of the content of the merchant ship design stages follows.

Concept design is the stage that follows the data gathering and the development of the mission statement. It involves the transformation of a qualitative set of requirements into an early design configuration, with the primary characteristics defined. It is the set point where the project starts to develop hull form and to identify main dimensions and machineries. The concept design effort usually results in a sketch or a drawing, partially or fully dimensioned, and may include a written description. It will normally include more design alternatives (at most 5). The concept should also provide information to permit a reasonably accurate acquisition and an operating cost estimate based on different information as crew number, fuel and lube oil consumption, maintenance, etc. This design stage requires a small number of naval architects and engineers, who should be highly innovative and knowledge-based. The entire process can take some weeks/a couple of months (double for naval ships), therefore is developed very quickly.

Preliminary design is the second design stage. It is the design activity and provides much detail than the concept stage. The preliminary design permits an accurate assessment of the technical performance of the ship. It includes preliminary hull, mechanical and electrical design, service system integration, and continue program documentation development. The level of detail will be sufficient to permit an estimate of building and operating costs accurate enough. The cost estimate is based on the parameters defined in the concept design. The primary parameters are weight and dimensions, which are used as input to some computerized cost estimating model. Any special features of the ship, which significantly affect the construction cost must be identified (e.g. cargo handling equipment, lifting appliance, weapons, special systems, etc.). Preliminary design is much more labor-intensive than concept studies and considerable numbers of individual tasks are contracted out. In addition, a simplified life cycle assessment and a building strategy are carried out. The entire stage lasts from 3 to 6 months (double for naval ships).

Contract design is the third design stage, where the amount of details and improvements of the accuracy of the design is increased. This permits the design team to assess the technical performances and economics of the ship with greater reliability and less risk. The contract design results in a package of contract drawings, contract guidance drawings, and project peculiar documents, which accurately describe the ship to be built, and specifications with sufficient level of detail to allow the shipbuilder to develop a bid. The level of detail in the specifications and drawings depends on a number of factors, including the size and complexity of the ship, the presence of novel features, the possible risks in dealing with some shipyard. Specifications should be just sufficient for both parties to fully understand the requirements of the other. The specifications are also meant to be a companion document to the contract plans and the contract itself. If contradictions between the parties occur, the generally accepted hierarchy is that the contract terms prevail, followed by the specifications and lastly the drawings. It is normal practice for the shipowner to specify machinery or equipment by brand name. As most contracts assign full responsibility for the performances of the ship on the shipbuilder, it is essential for the design team to carry out the calculations very accurately for their own protection: indeed, unmet performances often become the basis for claims. Contract design is the point at which weight, dimensions and acquisition costs estimates are frozen. Decisions made up to this point have a lasting impact in the acquisition cost. In contract design, the size of the design team is doubled, and an effort of about 4–6 months (1 year for naval ships) is forecast.

Functional design is a particularly demanding stage, where each system of the ship is fully defined and all its components are selected and sized, complying with the requirements imposed by the shipowner and the regulatory bodies. The functional design stage, being system-oriented, can be seen as the final stage of the basic design phase. Alternatively, it can be seen also as the first stage of the production engineering phase, because it concerns activities that are preparatory for detailing the systems onboard. Functional design begins at the winning shipyard as soon as a contract is awarded. The initial phases of functional design include procurement of equipment, design and integration of systems and subsystems, production planning and optimization/reliability of structural design. It is during this stage that building strategies are developed within the shipyard. Its duration lasts at least 6 months (1 year for naval ships).

Transition design, where the system-oriented information collected in the previous stages are arranged into zone-oriented information. It incorporates zone design to allow for group technology construction. The ship is divided into a certain number of zones in accordance with the build strategy already established, and yard plans are generated in order to efficiently organize the production work. For each

zone, two sets of yard plans are elaborated: one concerning the detailing of the structures and another one concerning the positioning of all systems' components (no matter how small) to be fitted in the zone considered. The merging of the hull's yard plans with the systems' yard plans makes the zone composite arrangement up. Through the yard plans, it is possible to elaborate a list of materials to be used in the zone as well as evaluate weight and center of gravity of the zone. The main objective of the zone composite arrangement drawings is to detect if any interference (between either the various systems or systems and structures) occurs. Part of the transition design is the development of documentation to fulfill the contract drawing requirement lists, which are the portion of the transition design submitted to the customer for review and/or approval. Modern construction requires a shipyard to have an entire division of engineers and designers dedicated at these activities. The duration of this stage is really depending on the CAD/CAM tools capability of the shipbuilder, and can be of 6 months or more (quite the same for naval ships).

Work instruction, which is the most pertinent stage addressed to production. Indeed, instructions to manufacture the various parts of the ship (systems and structures) and how to fit them together are given, in accordance with both the established build strategy and the technologies adopted by the shipbuilder. Therefore, manufacturing work instruction drawings and fitting work instruction drawings shall be prepared. The components of the various systems in a certain zone are now grouped on a kind basis (for example, pipe pieces, ventilation duct pieces, supports, etc.), and manufacturing work instructions sufficiently detailed are given piece by piece (regardless of where they are to be manufactured). The next step involves the preparation of fitting work instructions that permit to assembly the blocks with the different items previously manufactured. In order to facilitate either the manufacturing or the fitting work, consistent material lists are prepared (i.e., material lists for manufacturing and material lists for fitting). The total time for the development of work instruction is approximately 6–9 months (2 years for naval ships).

3 Concept design within early-stage design

Concept design investigations are vital not only from the standpoint of lifetime costs, but also because they can be used to establish efficiency of candidate vessels with respect to the required mission or transport task. Therefore, an appropriate concept design procedure necessitates a good understanding and integration of three areas that are naval architecture, economics, and decision-making techniques for design assessment and evaluation. Critical goals of concept design model are incorporating all

relevant parameters and allowing effective integration of all ship descriptors. The multiple evaluation of alternative designs has to be based on the control of a broad but not redundant set of attributes, also depending on the subjective and objective relevance of these attributes in the design practice. Even more important, a full co-operation has to be established at decision milestones between different participants (owner's technical staff, experts from the yard). The substantial expectations from an innovative concept ship design strategy are the following:

- providing a higher degree of rationality when structuring the design activity;
- improving performance and reducing the cost of carrying out the design;
- providing insight concerning the way in which design features interact;
- reducing design risk areas;
- applying multi-criterial decision-making tools.

As regards time and money involved in the concept design phase, their amount is substantially negligible with respect to the cost of the overall design. Nevertheless, the most critical decisions contributing to the success or otherwise of a ship are made during the concept design phase, when it is mandatory to account for all possible solutions. Ship size, speed, endurance, and costs together with other economic features should be decided upon then. Many controlling factors such as main dimensions and geometrical coefficients, powering, lightship weight, payload, deadweight, seakeeping qualities, and so forth, are not expected to change substantially upon the subsequent design phases of the ship. Most factors, which have a measurable effect on overall techno-economic efficiency of a ship during her lifetime, are selected at this stage as it can be seen by overviewing the relevance of the different design phases on the impact of her lifetime costs. Concept design philosophy is founded on the following premises:

- most far-reaching design decisions are made at concept design level;
- principal dimensions and characteristics of the ship will not change significantly later in preliminary and contract design phases and even less so in the embodiment design phase;
- design requirements are best formulated via realistic operating cycle of the vessel, as opposed to specifying speed, endurance, etc., directly;
- imprecise nature of concept design may be handled by applying fuzzy logic to design attributes;
- predicting attribute values in the model will be performed based mainly on regression formulae or direct calculations.

Generally, concept ship design consists of two phases, i.e., the phase of generating design alternatives and the decision making phase (screening, scoring, testing), in which one of the candidate alternatives is finally selected as the ‘best possible’ one. This brings up the problem of designing under uncertainty and indicates that more than one criterion is needed as a measure of quality. Minimizing single attribute (e.g., required freight rate) by suitable procedure, will usually find its minimum; however, there will be many other designs close to that which have considerable spread in other important attributes (e.g. speed, cost, seakeeping, etc.) that were not subject to optimization. It is obvious that multi-criterial approach offers much more insight into design characteristics. An implementation of the multi-criterial design procedure requires a suitable decision-making method and an appropriate mathematical design model. The design model predicts values/utility design attributes of a candidate ship via specific design modules (regarding hull form, hydrostatics, resistance, powering, seakeeping, space utilization, cost estimating, etc.) from the set of random variables and design parameters that are input to the design model. It may be argued that composing a design model is a hard work with many arbitrary decisions made in advance and built into the model. If the concept design model is structured conveniently, it is not difficult for the designers to select adequate methods for single subsystem (e.g. powering, seakeeping, acquisition cost, etc.), the permissible range of the independent variables, the set of attributes defining ship performance adequately, etc. Moreover, the introduction of a fuzzy set approach may enable the designers to apply their know—how in a controllable way. The final scope of the concept design is to reduce risk, validate the most important derived ship performance requirements, and establish a baseline for the start of preliminary design. The products and documents of a typical concept design are listed in Table 1.

Because performance, cost and risk are being compared among the different designs, relative accuracy and consistency is stressed rather than absolute accuracy. Collectively, the set of the ‘best possible designs’ must illustrate the capability versus cost as well as versus risk trade-offs of interest to the shipowner. At the conclusion of the concept design phase, the main characteristics of the new ship will have been defined along with the principal ship performance requirements (top-level specifications), that are, the required ship capabilities. Most papers, which describe ship design methods for the concept design, do not incorporate analysis procedures suitable for use at the concept stage, neither do they incorporate procedures which allow production considerations to be assessed when changes are made to the design concept. Modern process control methods facilitate the retrieval and collection of manufacturing process data, which can be used in the development of realistic models for use in a design for production context at the concept

Table 1 Concept design model output

Output	Format
Essential performance requirements	Report
Principal hull dimensions	3D model
Hydrostatics and hullform coefficients	Report
Area-volume summary	3D model
Inboard profile and main deck plan	3D model
Payload definition	3D model
Description of mission-critical systems	Report
Weight breakdown and KG estimate	Report
Radiated noise and vibrations	Report
Acquisition cost estimate	Report
Technical risk assessment	Report
Master equipment list	Report
Body plan and appendages	3D model
General arrangement	3D model
Topside arrangement	3D Model
List of major machinery	Report
Propulsion/generation plant	3D model
Speed/power prediction	Report
Fuel consumption estimate	Report
Endurance estimate	Report
Intact and damage stability check	Report
Maneuvering indexes	Report
Operating cost estimate	Report
Risk management plan	Report
Main machinery arrangement	3D model
Electric load analysis	Report
Manning estimate	Report
Conceptual midship section and structures	3D model

phase. Perhaps the most important problem is the difficulty of deciding overall ship sizing parameters (such as length, beam, hull form coefficients, etc.) at a stage of design when most of the analytical tools of naval architecture may not readily be applied.

Both commercial and military vessels are characterized by great dimensions and high complexity. As a result, they require a long development cycle [21], but have a much longer life-time. Ships are also very costly, and their use is deeply affected by the changing market. The compliance with many strict requirements needs a thorough and difficult analysis, which requires a high level of design definition usually not available until advanced design stages. Indeed, within the current traditional methodology, these information are elaborated when it is no more possible to significantly influence the design of a ship, and sometimes also during its construction.

Consequently, the soundness of several feasible solutions should be assessed during the concept design phase. A similar approach is essentially opposed to the one currently

adopted, in which one design alternative is selected and modified multiple times in order to meet technical and cost requirements, employing a huge design effort. This path is a result of the limited amount of tool integration and does not allow neither an improvement or an innovation to the product. Moreover, at one point it can no longer be sustained from both a physical and economical point of view.

Due to the great complexity required by new ships, the introduction of new technologies is necessary, even though they have not already proven their reliability in operating environment. In order to endorse these choices, the adoption of a new high-level multi-disciplinary design methodology is mandatory. Today, talking about concept and preliminary design separately is no longer acceptable. We need to identify a new and highly reliable approach able to develop and compare complete design alternatives with the same level of detail in a short time, and in which we can move from one phase to another smoothly.

In this framework, early-stage design is an enhanced, quicker and solid design stage that combines all the activities of the concept design phase with the peculiar skill of preliminary design, i.e., graphically displaying the results. Likewise, all the ship technological aspects related to requirements such as CAPEX and OPEX can be investigated through real time cost–benefit analyses. Thus, the new early-stage design aims to be the new methodology to perform the concept design phase.

Further, thanks to the possibility of sharing information with the Computer Systems Integrator, the development of reliable and sufficiently detailed Virtual Prototypes for VR-tools of the designed ships is possible. As a result, several different and complete design alternatives might be compared in a faster and reliable way.

4 Disciplined machinery arrangement

The general arrangement plans define requirements, which are described pictorially rather than in words. The drawings should be as self-contained as possible. They should not repeat the requirements provided in the ship specifications, but should amplify them. Extraneous details not identified in the ship specifications should not be shown, as the risk of changing or conflicting with the specifications is too great. As the design progresses through each design phase, there is a gradual change in the content of the drawings. Information provided on the drawings for coordination and control is first developed and expanded, and later is removed. This takes place as the drawings become contractual documents and deviate from the function of being a design tool. The final general arrangement drawings must reflect only those requirements that are desired as part of the contract package [22]. Therefore, one of the main aspects that needs to

be addressed in ship design is the definition of the general arrangement plans. This is one of the most complex activities that can be done in ship design and requires the highest degree of awareness of the integration of all ship complex systems. Moreover, early-stage arrangement decisions significantly affect the rest of the subsequent arrangement activities. In particular, shipboard machinery arranged on board without a rational and integrated approach can nullify the feasibility of the project. With a set of given machinery components, the arrangement alternatives are numerous. The process is time and resource intensive, therefore during early-stage design vessel layout and distributed systems are considered at low-fidelity, aimed only to measure concept feasibility and requirement satisfaction. At the same time, the ultimate goal is to assure the full integration of machinery into the total design. Current approach is to employ automated tools to generate and analyze potential vessel configuration, but in most cases, still today, machinery arrangements are built upon lessons learned, engineering judgments and personal evaluations based on years of experience. The most profitable design approach is the Design Space Exploration (DSE) that involves the use of design synthesis models to generate a huge number of designs to be examined semi-automatically by means of optimization techniques, such as MODM and genetic algorithms. As reported by Shields [23] there is a proliferation of these tools to generate solutions to the ship arrangement problem; much less semi-automated tools are applicable for distributed system design [20], and even less that consider both arrangements and distributed system design explicitly [24]. The principal drawbacks that can be made to this approach are the following:

- The synthesis models are often complex and may hide implicit design drivers in their structures and database, new models must be developed once a novel vessel is designed;
- It is resource intensive to fill the computer code developing algorithms and analysis method that generate solutions;
- Arrangements and distributed system design often are not explicitly addressed together, and their interdependence is not thoroughly investigated.

The evolution of hardware and software and the ability to integrate different tools today allow to overcome these controversies. In fact, increasing computational power increases the fidelity of the models that may be run. Moreover, after the selection of low-fidelity models has been completed, with a few additional computational efforts it is possible to run appropriate CSI' macro for the creation of Virtual Prototypes, which can be used to visualize and compare the results (in terms of weight, volume, signature, etc.), in order to detail the most promising solutions.

5 Computer-based design tools

Nowadays the usage of efficient and coordinated computer-based tools in ship design and construction process represents an important aspect to evaluate the commercial competitiveness of a shipbuilder. In fact, by means of such tools, quicker responses to shipowner's requests for quotes can be given. Moreover, the accuracy of deliverables shall be increased. Design modifications can be performed in a more flexible way, ensuring also high level of consistency. The possibility to create computer simulations with a 3D product model allows the enhancement of the activities related to both concurrent engineering and production planning. Cost control analyses are improved, and rational and timely materials and outfit acquisitions are permitted. Obviously, all these computer-based activities need a common database that should be continuously updated in order to always get reliable information. Computer-aided functions involved in the ship design and production process deal with synthesis modelling, design (CAD), engineering (CAE), manufacturing (CAM), product model, computer integrated manufacturing (CIM), and computer systems integration.

The traditional way to perform the ship design and construction process (Fig. 5) is essentially based on the following classes of programs:

- Computer-Aided Synthesis Modelling (CASM) can be considered the starting point to define a baseline on which successively developing the preliminary design of the vessel. Specifically, the design data are elaborated taking into consideration either a parent ship or a number of similar ships. The outputs obtained may concern design, operation or cost issues.
- Computer-Aided Design (CAD) represents the natural evolution consequent to the introduction of computer in the elaboration of drawings. Although the most of drawings are traced on a computer monitor, the final outputs are still printed on paper. The trend of the modern CAD systems is oriented towards 3D models, so that operators

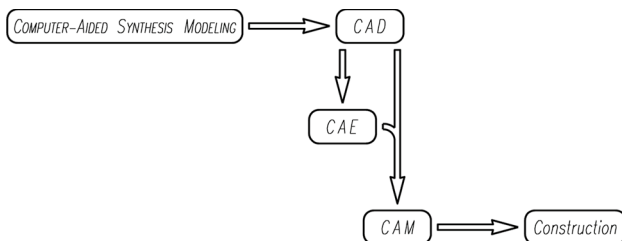


Fig. 5 Computer tools used in the traditional Ship design and construction process

can have a more direct perception of what they are creating.

- Computer-Aided Engineering (CAE) programs enable the various calculations inherent in the design process. There are CAE programs dedicated to specific tasks (for instance, hydrostatics and stability, weight and centers, speed/power, structure, pipe sizing, electric loading, seakeeping, noise, etc.), but modern CAE programs are often made-up of different modules (each for a specific task) linked each other. Some CAE programs are specifically dedicated to give quick responses to shipowner's inquiries. They draw a proper database from which parametric relationships can be derived in order to set up an initial design and then perform preliminary cost estimation, useful to carry out the subsequent trade-off analyses.
- Computer-Aided Manufacturing (CAM) programs represent the tools that allow the transition from the design towards the construction of the ship. In other terms, all the outcomes obtained in the stages regarding functional design are now developed and converted for construction activities (for instance, welding, cutting, painting, lifting, bending, forming, planning, and monitoring). An important aspect that a CAM system should have is the ability to elaborate the necessary digital data in a consistent manner with the shipyard facilities and standards.

An alternative approach to the traditional computer-based tools is given by the Product Model Programs, which include both CAD, CAE and (in some extent) CAM capabilities (Fig. 6). The great merit of such programs lies in their 3-dimensionality. In fact, users work with a 3D model since the earliest stages of the design, against the traditional approach where the work is performed in 2D in the preliminary stages and then is extended to 3D in the detailing stages. The Product Model Programs permit also to simultaneously carry out different tasks within a multi-user environment. In such a way it is quite easy to check interior spaces (with particular attention to maintenance clearance) or interference existing between structures and outfitting. Moreover, an important aspect to be considered is that the different tasks can be performed only with the dedicated modules belonging to the same Product Model Program. In other words, there is no integration with the modules

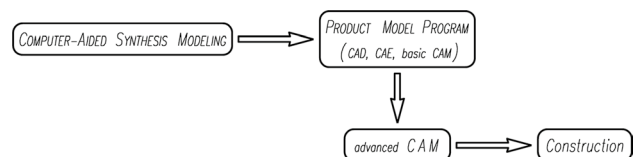


Fig. 6 Ship design and construction process based on product model program

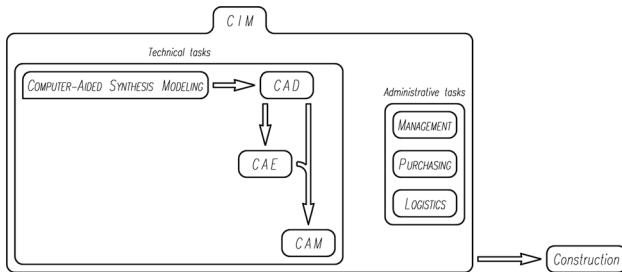


Fig. 7 Ship design and construction process based on computer-integrated manufacturing

of different Product Model Programs (such a capability, instead, is obtained by the Computer Systems Integration, hereunder treated).

A still more advanced approach than Product Model Programs is represented by Computer-Integrated Manufacturing (CIM) programs. The latter could be seen as enhanced Product Model Programs, especially for the manufacturing activities, and with the considerable capability of coordinating stand-alone programs that are interfaced with a common database. However, the stand-alone programs need to be tailored to comply with the individual shipyard's facilities, technologies and standards. Within a CIM environment (Fig. 7), owing to the common database, the management of information between technical and administrative divisions is thoroughly consistent. Further important feature is the possibility to manage the data states in accordance with the different decision-making levels existing in the hierarchical organization of the shipyard.

6 Computer system integrators and virtual prototype

As observed, a ship is a very complex and specific product, with an equally complex value chain [25]. In his analysis of conceptual ship design, Erikstad [26] identified the following seven unique characteristics of a ship:

1. A ship is a self-contained structure operating in the boundary between two fluids;
2. Ship design consists of a multi-dimensional, partially non-monetary performance evaluation;
3. During the ship acquisition process an inefficient design leads to high-cost errors;
4. In case of prototype or new technologies, there is a shallow knowledge structure between form and function;
5. Shipbuilding industry is very traditional with pre-conceived standards;
6. There are strict developing time and many resource constraints;

7. Predominantly one-of-a-kind and engineered-to-order solutions.

The huge amount of data involved in ship value chain is well-known. As already mentioned above, the traditional approach requires the use of several software to elaborate and manage these data, especially during the transition between the different phases of design, construction, and management. Very often these software are not integrated and almost always need remaking activities to render the data accessible by the specific tool. Moreover, due to the complexity of the product each aspect of the whole process is treated independently by different teams, so that the information generated often are not efficiently related to others. As a result, handling data and sharing them among the different stakeholders are very challenging tasks, often subject to the danger of data inconsistency.

Many methods can be used to solve the problem of dealing with all the data generated during the long life-cycle of a ship. Moreover, 70% or more of the ultimate cost and performance of the final product are essentially "locked-in" during the early design stages [27]. Figure 8 highlights that decisions and actions taken in the later design stages, during construction or operations, are more expensive and time-consuming if compared with the ones made during early-stage design, while the design is still in the computer, and changes can be incorporated relatively easily with minimum cost.

Shipbuilding industry and Navies have carried out many initiatives in order to improve and evolve ship design. Four pillars have been globally identified:

1. Concurrent engineering: Integrated design teams, electronically connected, employing a new integrated multi-tasking and multi-functional design methodology enabled by new computer tools.

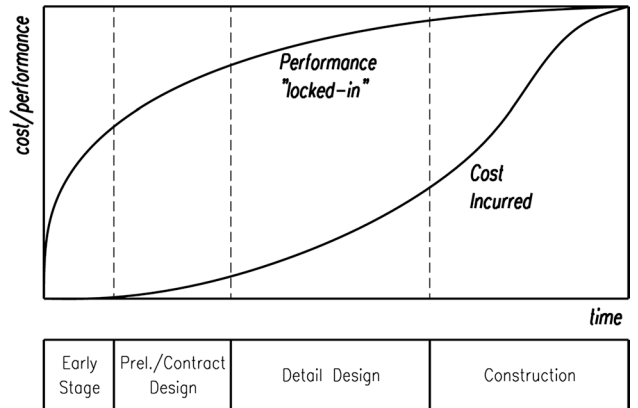


Fig. 8 Cost/performance during the ship design and construction phases

2. Systems engineering: a top-down integration of systems into a ship form the early-stage design.
3. Adoption of new technologies: assessing and integrating emerging technologies with new ship design in order to obtain their fast, cheap, and reliable proof-of-concept.
4. Modeling and simulation: Virtual prototypes based on 3D parametric digital models navigable by means of Virtual Reality.

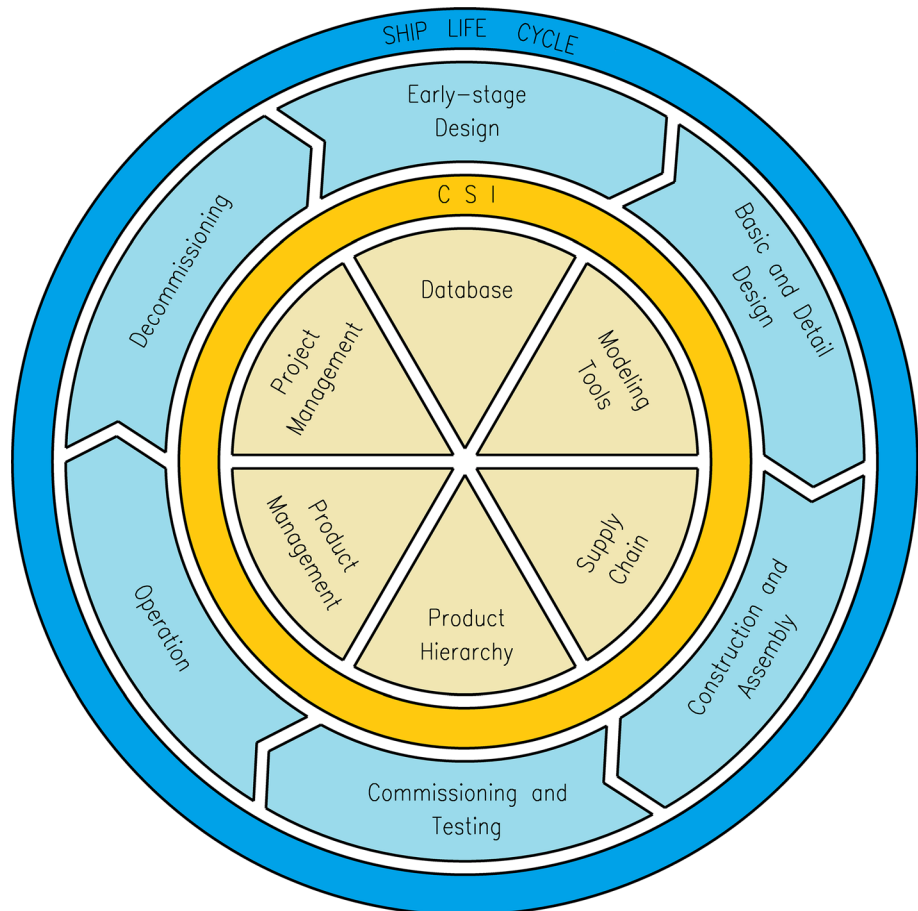
In the new design methodology, these pillars must be improved early in the ship design process, because correcting mistakes and installing new components and technologies are high-cost activities if made after. For prototype ships there is no real “drive before buy”, so in order to minimize risks, new technologies may be tested in land-based test facilities. These, however, are very expensive and useful for component’s tests, and the whole ship is tested only after being delivered to the shipowner. Ship development, therefore, offers a particularly promising application of integrated design concepts, including also virtual prototypes since the early-stage design.

Nowadays, the most promising method enabling all the 4 pillars is based on the adoption of specific Product

Life-Cycle Management (PLM) software tools, called Computer System Integrators (CSIs). PLM is the activity of managing a company product across its life-cycle in the most effective way [28]. PLM is one of the best methods to maintain a good organization of the product different parts, services, costs, and suppliers, from conception to scrapping. Commonly, CSI software are composed by 6 modules (Andrade):

- Database: it is the core of CSIs and contains all the information related to the project managed by proper indexation tools;
- Modeling and Simulation tools: they are CAD/CAE software indispensable for the creation, representation, navigation and investigation of the product virtual prototype;
- Supply Chain: they are tools devoted to the management of the commercial, financial, and logistical process within the ship value chain;
- Product hierarchy: also known as “the design catalogue”, it establishes the classification according to a WBS, and manages the correlations among all the ship systems and components; moreover, it semi-automatically implements the disciplined machinery arrangement concepts.

Fig. 9 Product Life-cycle Management elements, within a simplified ship life-cycle



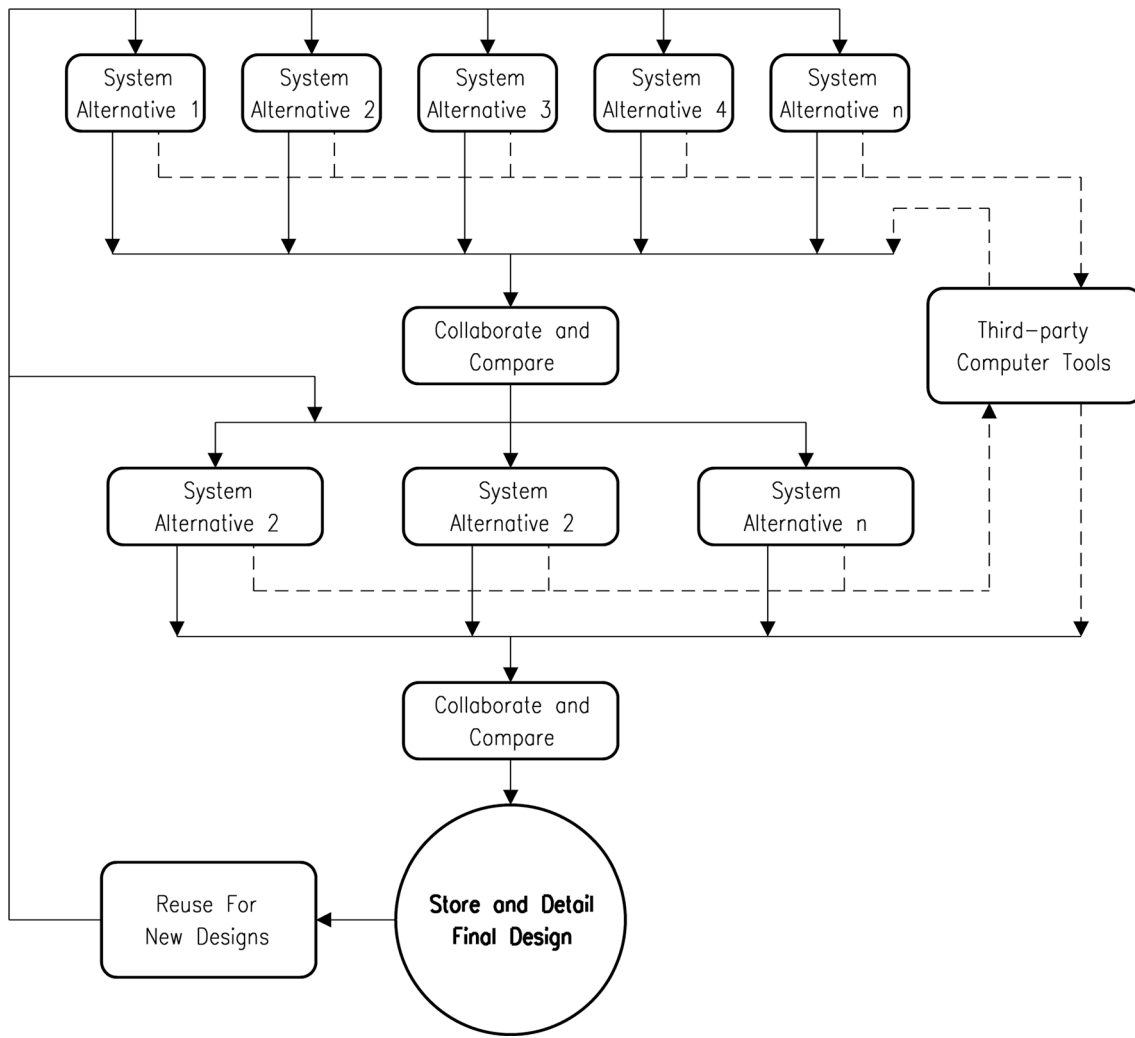


Fig. 10 PLM data-centric design, engineering and information management applications scheme

- **Product Management:** it administrates all the information related to every component.
- **Project Management:** it connects every process during the whole ship life-cycle (also during operation and dismantling).

In Fig. 9 the CSI application to a ship simplified life-cycle is sketched. Specifically, the simplified ship life-cycle is composed by 6 phases: Early-stage design, Basic and Detail Design, Construction and Assembly, Commissioning and testing, Operation and Decommissioning.

CSIs are able to both manage the communication among the various authoring tools and follow the evolution of the design and the engineering due to the change requests coming from each participant (designers, owners, builders, regulatory, and classification bodies). The PLM-based architecture adopted by CSIs can serve as a platform for the integration and data repository functions, where global

project information can be created, managed, reused, and controlled throughout the product life-cycle (Fig. 10). PLM provides a mechanism enabling the use of one or more products from CSI suite in conjunction with a number and variety of third party tools (CAE, ERP,...) that can be integrated through the platform. The solution supports global collaboration between all the stakeholders involved during the ship life-cycle (Designers, Classification Societies, Flag authorities, Shipbuilder, Shipowner, Clients, Contractors, and Suppliers), and helps business processes that share common information.

CSI modeling tools allow the creation of ship Virtual Prototypes (VP). A VP of an asset is any software version, or portion of a product, capable of functioning properly and realistically in a responsive virtual environment. Such particular 3D-parametric models can be considered as the natural extension of common CAD/Product models, providing an accurate geometric description together with kinematic,

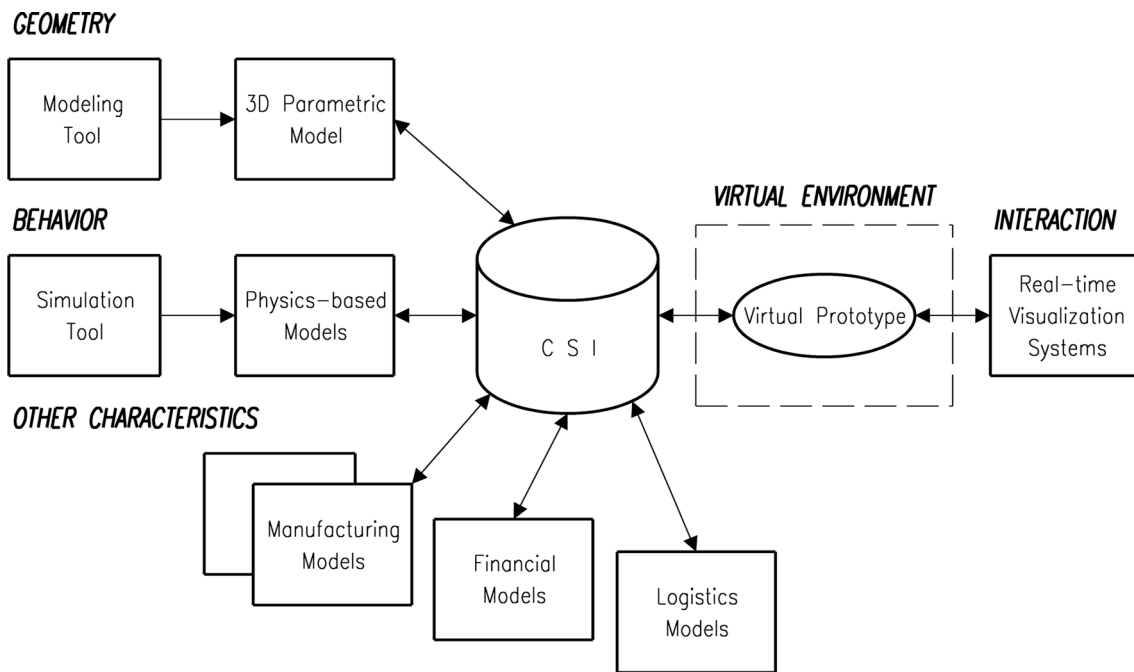


Fig. 11 Interaction among CSI, Virtual prototype and modeling/simulation tools

dynamic, technical, and other behavioral and physical components attributes (mass, volume, materials information, electric power, and fuel consumption). Depending on the design stage, the VP may hold a different content of details. Furthermore, according to the interactive approach of the methodology, all the members of the design team, along with the stakeholders, can continuously query the different components of the VP about their features, characteristics and behavior. In early-stage design visualization is useful to assess ship main characteristics and general arrangement. During detail design VP can be shared with CAE tools (CFD, FEM, etc.) in order to check systems' performance, while during construction VP can be used for plates and pipes prefabrication, or to develop the assembly films (Fig. 11).

Nowadays, different CSI software packages are available on the market: for example, AVEVA, Dassault Systemes, Foran v.80 and Hexagon are representative of the current state-of-the-art.

In 2012, ISDLab (Integrated Ship Design Laboratory) of University of Trieste started a strict collaboration with Intergraph (currently part of Hexagon). We tested the capability of integration, design, and re-design of Hexagon with different case study: design of a rudder for a ro-ro pax ship (from concept to construction), early-stage design of an inland waterway pushboat [29, 30], early-stage design of a Naval Logistic Support Ship [19], early-stage design of the electric current distribution system of a cruise passenger ship [11, 12], early-stage design of luxury sailing superyacht [31],

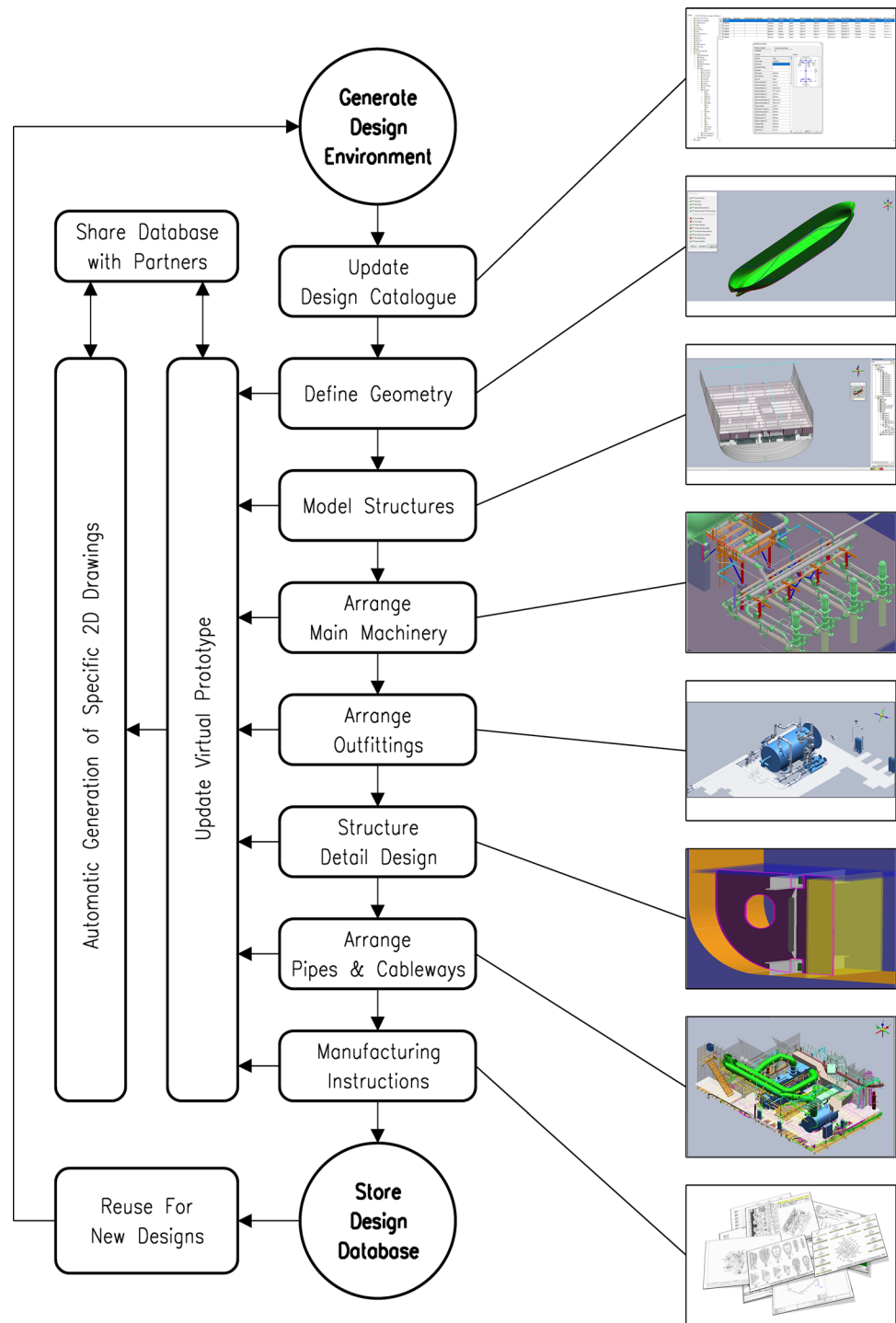
and design and construction of a wooden passenger craft for inland waterway navigation [32]. In previous experiences, we have not only tested the capabilities of the CSI, but also its interaction with third-party CAE software for CFD, FEM calculation, and detail design.

Thanks to the experience gained in these years of participation in the development of this specific CSI and to its application to many case studies, we have developed an operating methodology shown in Fig. 12.

7 Conclusions

Ship design is not a monotonous process at all; quite the opposite, it could be considered nearly singular. Indeed, design teams work with a clear state of mind, based on the intent of continually improving ships. During the last few years, significant and unpredictable changes within the industry of commercial and military vessels have occurred. In the merchant construction framework, new international regulations regarding environmental protection and increase of passengers and crew safety have required the introduction of technologies never used before. On the other hand, naval ships have to undertake whole new missions, which require whole new combat systems. Either way, design teams have to tackle the key issue of efficiently integrating several systems in a highly technical and complex product. The integration process can be extremely difficult due to the relation between the various operational systems.

Fig. 12 ISDLab CSI workflow scheme



In order to revolutionize the ship design process, the current IT technologies must be exploited in the most effectively way through a more comprehensive initial methodology. This approach must be able to completely renew the early-stage design phase, in which ships' overall performance and configuration are determined.

Therefore, the great IT capabilities, e.g., graphics and big data management, are the basis for the new proposed

methodology, which facilitates a considerable number of operations. Among these, the most important consists in drawing the ship's General Arrangements (GAs), which can be seen as the synthesis of the whole concept design. Yet, elaborating GAs is a really complex task with many constraints, numerous interdependences, and infinite solutions. Traditionally, GAs are produced during the preliminary design phase; at this stage, however, several details

regarding either the propulsion system or the main dimensions cannot be changed anymore. To overcome the issue, the proposed approach provides a strong connection between CASM based on MADM and CSI, ensuring the possibility of monitoring results.

Eventually, the latest generation of CSIs allows to build a high-quality parametric 3D model, which can be used as a Virtual Prototype of the ship. The benefits of having a Virtual Prototype since the early-stage design consist in reducing design risks, sharing consistent and reliable information among all the parties involved in the process, and ultimately obtaining a better product. In the next future, further studies will be aimed to develop databases and libraries that will allow the use of this methodology for the design of different types of ship. Moreover, in order to foster the interactive approach within the Integrated Ship Design methodology, Virtual Reality interfaces are already being developed to visualize and query virtual prototypes in a simpler and more intuitive way.

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