Early-Stage Design for Electric Ship

Julie Chalfant, *Member, IEEE*
MIT Sea Grant College Program, Massachusetts Institute of Technology, Cambridge, MA 02139 USA

One of the truisms of ship design is that the decisions of greatest impact are made in the early stages of design when the least information and the greatest uncertainty are present. In response to this, ongoing efforts in developing ship design tools are directed toward making more information available sooner and pushing decision points later. The integrated nature of electric ship in which performance of support systems directly affects performance of primary mission systems compounds this concern; design and simulation of support systems are needed earlier, and collaborative design among multiple engineering disciplines is required in the process. This paper reviews the Navy ship design process and recent developments in ship design tools to illuminate the areas in which further development is necessary.

***Index Terms*—Ship Design, Computer-Aided Design**

I. INTRODUCTION

THIS paper presents a tutorial and review of the design of US Navy ships, looking in detail at preliminary design and ship system design. An overview of the stages of design is presented, along with mention of the Navy acquisition process. More detail is provided on specific ship design methodologies, measures of effectiveness for evaluating designs, and methods for the design of ship systems. The effect of computers and some recent advances in Computer-Aided Ship Design (CASD) are explored. With this background in place, the US Navy design tool framework is presented and discussed along with comments on future needs. Although references are provided throughout, the review is not exhaustive; instead, the intent herein is to introduce the concepts and provide examples.

II. STAGES OF SHIP DESIGN

Within the US Navy, ship design begins with the identification of a desired capability and ends with the production of the data required to construct a specific vessel. The stages through which the design proceeds can be classified as Concept Design, Engineering Design, and Production Design. These stages, as applied to Navy ship design, are shown in Fig. 1 and summarized below; [1] and [2] provide further elaboration.

The Navy process begins before concept design when a gap in overall Navy operational capability is identified. Gaps can be caused by such things as new threats (e.g. new weapons systems developed by enemy forces), new roles for the Navy (e.g. humanitarian assistance), or retiring current equipment (e.g. ship classes reaching end-of-life). An analysis is accomplished by operations experts to determine the best method of filling the gap and may result in the decision that a new ship is needed, thus starting the ship design process.

Concept Design begins with a defined gap in operational capability and explores the ability of different concepts to meet the expressed need. Concept studies are undertaken to determine the mission requirements of a specific ship, taking into account performance of the ship both alone and as part of a battle group [2]. This phase includes development of the concept of operations (CONOPS) that describes the way the ship is operated as well as the environment, including the threat environment, in which it will operate. Such things as desired speeds, ranges, and survivability concepts are outlined here. The mission requirements, CONOPS, and operational environment are used to produce measures of effectiveness for future evaluation of ship design alternatives.

The Analysis of Alternatives (AoA) phase investigates possible ship concepts that meet the high-level mission requirements and capabilities, producing several feasible whole-ship designs along with some indication of cost, risk and performance. In this phase, outlines of general ship characteristics such as general size, hull type, payload package, major equipment, and manning complement are developed. Design margins are included with the intent that future modifications to the systems and equipment which arise as the design is refined will not cause major disturbances in the general ship characteristics defined during this stage.

Engineering Design includes preliminary design and contract design. In preliminary design, the basic architectures of the ship and the ship systems are established, including the hull form, dimensions, volume and weight estimates, general arrangements, and major equipment specifications and location. The product is a balanced, feasible design but not necessarily the final or optimum choice.

Contract design adds sufficient detail to the preliminary design necessary to produce the specifications required for a contractor to bid, construct a detailed design, and produce a ship.

Production Design, or detailed design and construction, is the process of producing the drawings and engineering data for shipyard personnel to build the ship, test the ship and ship systems, and certify the ship for operation. Engineering data is used to prove that the ship meets all specifications. Even if a design is fully detailed before construction begins, there is engineering and design work accomplished during construction in response to problems that arise, and as-built drawings may be produced.

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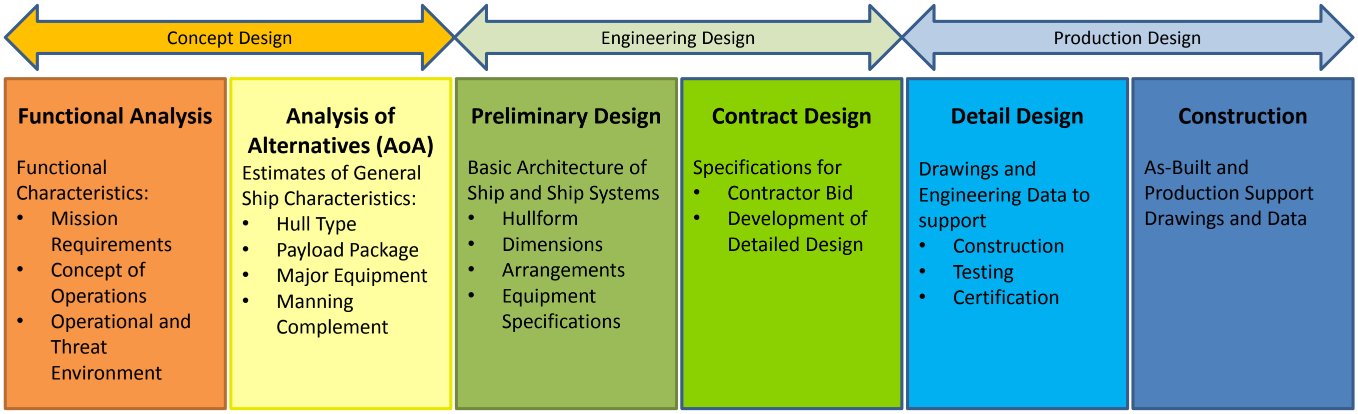

Fig. 1. Design stages

The actual steps in the ship design process will vary depending on the complexity of the type of ship being designed (e.g. cargo ship versus warship) or the extent of the design (limited modification versus entirely new ship), and also with such things as the skills and number of personnel involved, the tools available, and the priorities of the customer or the mission. This is recognized in Navy documentation on design. For example, the Naval Surface Warfare Center, Carderock Division (NSWCCD) defines a process model to document the required steps in a Navy design [1]; in this documentation, it is pointed out that the process model is dynamic and interactive, thus allowing the design team to change the steps that are incorporated in the design process depending on the scope of the design to be accomplished.

Navy ship design must also meet the government regulations on acquisition; Fig. 2 presents the Department of the Navy acquisition process with its attendant gates, reviews and milestones arrayed against the major design stages (seen as arrows across the bottom of the figure). The Naval Sea Systems Command (NAVSEA) [2] provides a thorough review of the Department of Defense (DoD) acquisition policy including a listing of appropriate directives. Most major ship acquisitions follow the Navy's two pass/six gate process, which establishes formal reviews at specific points in the design development. These gate reviews (shown as yellow ovals in Fig. 2) feed into the OSD/Joint-level reviews (shown as blue diamonds in Fig. 2) that are dictated by the DoD acquisition policy.

The early stages of the ship design are accomplished by the Navy and the late stages are accomplished by a contractor; the hand off from Navy to contractor typically occurs during or at the end of Engineering Design.

One challenging aspect of design is that, as one progresses through the levels of design, the detail of the design increases but the choices available to be made decrease. Thus, one makes decisions of the highest impact at the point when the least information is available and the uncertainty in the data is the greatest. To combat this difficulty, there is a drive to increase the level of fidelity and the physics-based nature of the modeling done in the early stages of ship design, and to push decisions as late in the process as possible.

III. THE SHIP DESIGN PROCESS

A. *Design of Complex Systems*

In the design of complex systems such as ships, the design exceeds the capability of a single person to accomplish the entire project; breakdown of the design into component parts and description of the interrelationship of those parts enables the design to be accomplished by groups. Mandel and Chryssostomidis [3] discuss a methodology to systematically break a project into its component parts while maintaining overall problem synthesis. They point out that the sub-problems are interrelated, so that the optimum overall solution is not necessarily the strict amalgamation of the optimum solution to each sub-problem. They delineate three considerations in identifying sub-problems: a) defining the sub-problems so as to minimize interaction with the other sub-problems; b) reducing the number of sub-problems to a minimum while still accomplishing the design; and c) providing communication among the investigators of the sub-problems. These concerns are certainly applicable in ship design.

A common method of breaking a ship design into smaller parts is to organize about function. Andrews [4] describes a building block system in which the ship description is divided into functional building blocks including float, move, fight and infrastructure. The British Navy has adopted this structure as is evident in the design tool Paramarine [5].

The US Navy has long had an organizational structure by function, titled the Expanded Ship Work Breakdown Structure (ESWBS), in which the categories include Hull Structure, Propulsion Plant, Electric Plant, Command and Surveillance, Auxiliary Systems, Outfit and Furnishings, and Armament [6]. This breakdown is used throughout the Navy for purposes ranging from logistical support of spare parts to organizing repair work packages to categorizing weights in ship designs.

Sharma et al. [7] point out that the modularity that has entered the shipbuilding community to decrease manufacturing costs can also be used to decrease design costs; in the later stages of design, modules that are fairly independent can be allocated to similarly independent design teams.

In documenting the preliminary design process, NSWCCD [1] proposes design areas of Hull Systems (float), Mission

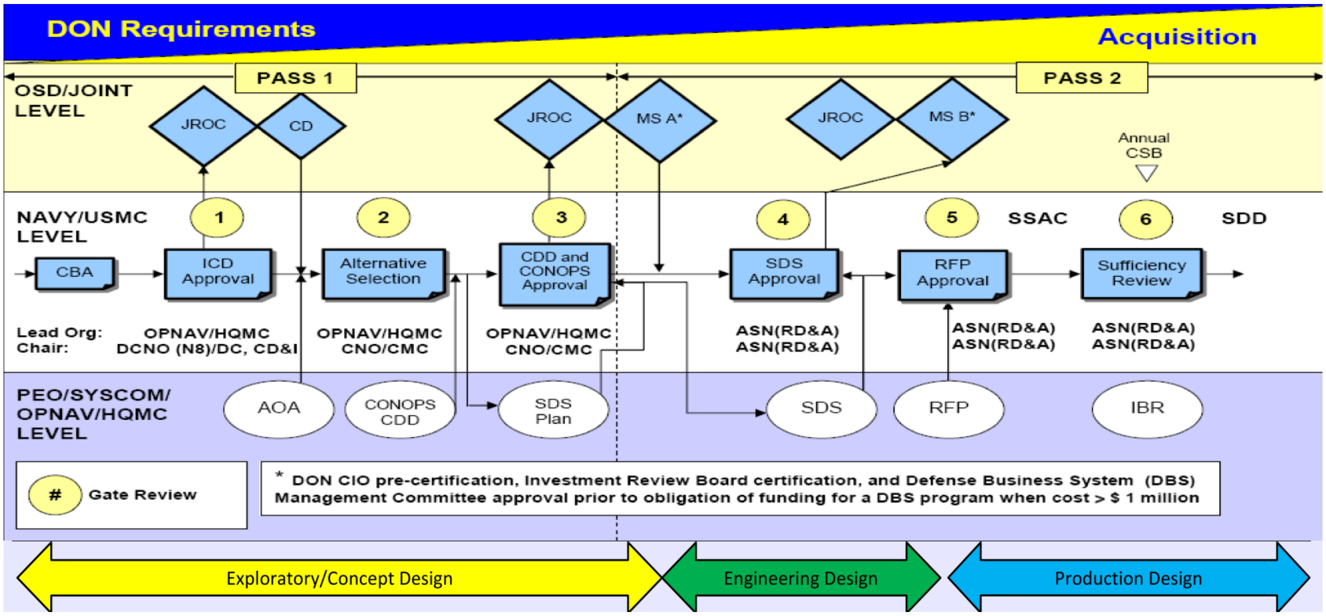

Fig. 2. Design stages arrayed with the steps of the Department of the Navy acquisition process [1]

Systems (fight), Propulsion/Power/Machinery (move), Human Systems (enable), Survivability (survive) and Design Integration and Management (integrate). Each of these design areas is further delineated; for example, the hull systems category includes activity groups of structures, weights, hydrodynamics, stability and general arrangements.

B. Ship Design Methodologies

1) The design spiral

Ship design is traditionally represented as a design spiral [8], depicted in Fig. 3, in which design activities are accomplished sequentially at the most general level with the least detail, then revisited, in order, using the information developed in the previous round to develop more detail. This sequence is repeated until a balanced design is accomplished. The design spiral process produces a single point-design which begins from a baseline and iterates at each turn of the spiral to arrive at a feasible design. The goal is for the overall quality of the design to improve with each turn of the spiral.

2) Collaborative, concurrent design

Although the design spiral is used effectively to teach the concepts of ship design, in actuality these activities are simultaneously more interdependent and independent. Movement around one loop of the spiral is not strictly in one direction, completing a single step then moving on to the next; instead, there is much back-and-forth travel to achieve an initially balanced design. Once the broad outlines of a ship design are identified, the work of the principal disciplines will proceed in parallel. Inherent in the role of the design manager is the requirement to ensure that proper communications occur between disciplines and to identify and resolve conflicts as the design develops. Mistree et al. [9] comment that the spiral approach does not facilitate overall optimization for such concerns as life-cycle cost, modularity, or integrated operations. The best process is one in which the designers work in parallel with significant interaction and discussion: collaborative, concurrent design. Some examples follow.

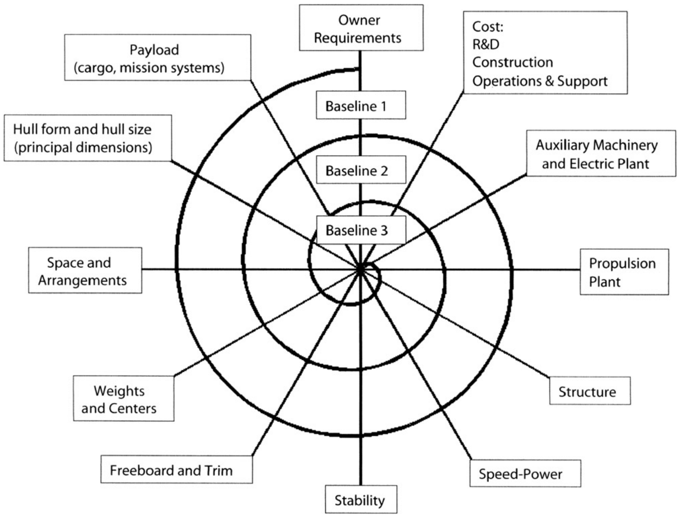

Fig. 3. The ship design process is traditionally represented as a design spiral [8]

Doerry and Fireman [10] examine the ship design process as applied specifically to electric ship; they outline a three-step systems engineering process for 1) determining the operational requirements for a ship design, 2) allocating those requirements to functional components, then 3) synthesizing a ship to effectively include those functional components, with an overarching control/feedback mechanism. Although they lay out a serial and iterative process in order to illuminate the functions that must occur, they comment that in practical application, all of the components of the design process occur

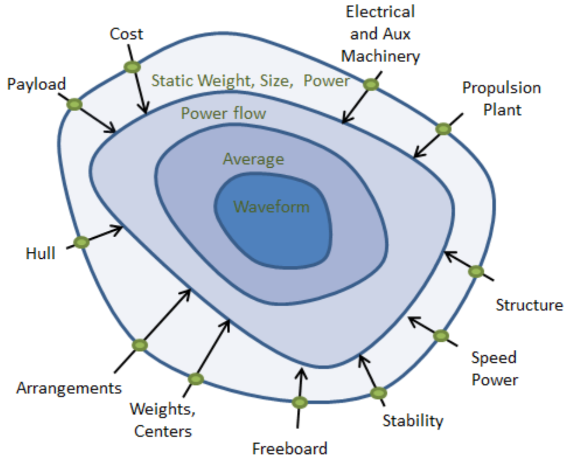

Fig. 4. Concurrent design [11]

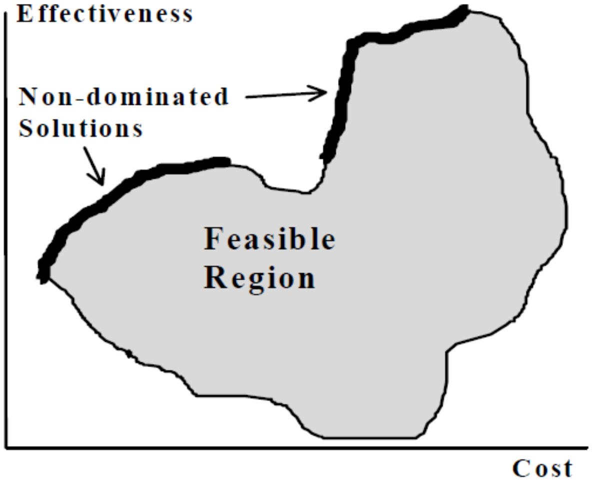

Fig. 5. Non-dominated Pareto front [12]

concurrently.

Langland and Dougal [11] depict the concurrent design process as a somewhat lumpy target, shown in Fig. 4, in which designers of different disciplines work simultaneously to refine their specific area of design while maintaining communication with the other disciplines. Since the design may proceed more rapidly in some areas than others, the profile of the design is irregular.

3) Design Space Exploration

Instead of sequentially accomplishing a single design in an attempt to achieve an optimum ship, or even following the design spiral to the later stages on a few select optimized designs, there are numerous efforts to explore a very broad range of designs at low fidelity in order to select promising areas for further exploration. Hundreds or even thousands of designs are examined semi-automatically by invoking a design synthesis model to produce many point designs within a range of parameters selected by the engineer. Design of Experiment (DoE) methodology can be invoked to determine the range of values to be explored and the criteria for evaluation, and there are a multitude of optimization techniques, such as multi-objective optimization, genetic algorithms, and particle-swarm optimization, that can be used to seek out the most effective designs.

With sufficient data, it is possible to identify feasible regions of specific properties. The edges of those regions for which no better design can exist for one property without degrading the other properties are termed Non-Dominated Pareto Fronts. In their discussion of multi-objective optimization as applied to ship design, Brown and Salcedo [12] present an example of a two-dimensional non-dominated front as shown in Fig. 5. This example plots effectiveness versus cost. One can see that, among the non-dominated solutions, no better effectiveness can be achieved without increasing cost, and no lower cost can be achieved without reducing effectiveness.

Stepanchick and Brown [13] present an interesting case study of the concept design process for DDG-51 in which they point out that, although the final design is superb, the concept design process lasted more than ten years. During this time, several of the review cycles forced a radical change in assumptions for the ship design, causing a new group of point designs to be generated in response. Had the capability existed to explore a much larger design space at the time, it is quite conceivable that the design team would have had some level of information to respond to the questions of each design review panel without initiating an entirely new design process. The authors argue that the design space exploration techniques available today can significantly improve the acquisition process.

4) Set-based design

The design spiral, the collaborative and concurrent design, and the optimization methodologies presented above all follow a process of selecting for further investigation the best design(s) of the options considered given the information developed to date.

In contrast, set-based design [14] rules out areas of infeasible or poor design instead of picking the best design and defers selection until much later in the process. Singer, Doerry and Buckley [15] argue that set-based design is more likely to result in the global optimum. The basic tenets of set-based design are laid out by Doerry et al. [16] as follows:

1) Consider a large design space of possible alternatives.
2) Allow specialists to work from their discipline-specific point of view to concurrently analyze possibilities.
3) Intersect the discipline-specific sets to obtain a globally feasible design space before committing to a single design.

The set-based design concept is shown graphically in Fig. 6.

In one example of set-based design [17], a fictitious new cruiser design was performed using the Navy's current design tools. A range of parameters for length, beam, armament weight, and electrical load were selected along with several discrete engine and cooling plant options. This design space was explored to determine infeasible regions that should be eliminated. Fig. 7 shows results for one discrete engineering plant option consisting of two 9 MW diesel engines, two 35MW gas turbine engines and 25 MW propulsion motors.

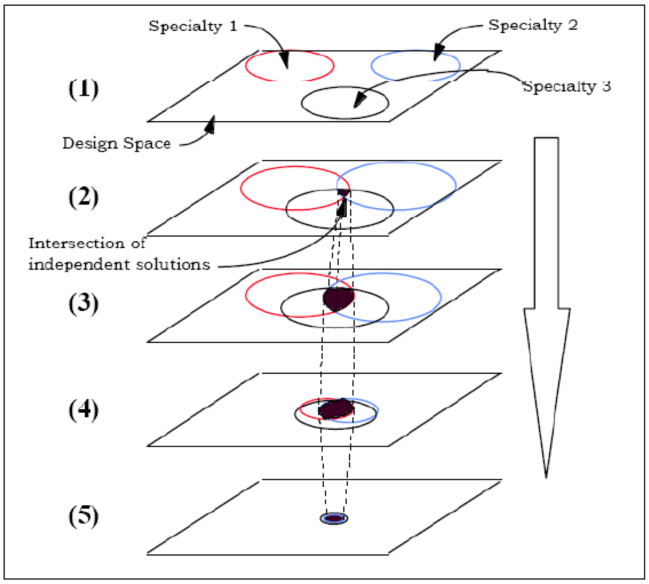

Fig. 6. Set-based design process [15]

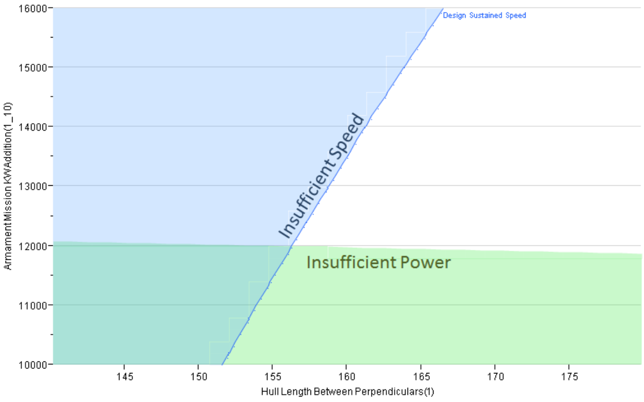

Fig. 7. Set-based design example [17]

For this plant selection, the blue area indicates designs that do not meet the speed requirement, and the green area indicates designs that do not provide sufficient electrical power for the weapons systems. The white area shows feasible designs. By repeating this effort with each possible discrete engineering plant, the design team was able to narrow the design space within which feasible designs could be sought using higher-fidelity modeling tools.

Both point-based and set-based design depend upon the quality of the models used. Increasing computational power increases the fidelity of the models that may be run and allows the inclusion of physics-based models, thus improving the estimates made at this stage; however, this is true only if the models are properly vetted with a thorough verification, validation and accreditation (VV&A) process. Indeed, the US Department of Defense directs that models, simulations and associated data used in support of DoD decisions shall undergo a verification and validation process, and shall be accredited for the intended use [18]. Examples of V&V applied to ship system design can be found in Ali et al. [19] for electrical systems and Yang et al. [20] for cooling systems.

C. *Ship Design Process*

1) *Traditional Navy ship design*

We will investigate the functions accomplished during the ship design process using the example of the design spiral from Fig. 3:

1) The requirements for the ship are identified, including the functions that the ship must perform and some specific capabilities. For a Navy combatant, this will include such things as mission requirements, maximum sustained and endurance speeds, speed-time profiles, signature characteristics, survivability, reliability and cost.
2) The payload equipment necessary to meet the defined mission capability is selected, including the weapon, sensor, self-defense, and communication systems along with any aircraft, small boats, or submersibles to be carried by the ship.
3) The hullform, superstructure and principal dimensions (e.g. length, beam, design draft, depth) are selected.
4) The space required for each function is sized, allocated, and arranged, often using parametric data from past designs.
5) Weights and the associated centers of gravity are estimated, which enables calculation of freeboard, trim, and intact and damaged stability.
6) Based on the hullform, resistance calculations are performed to produce a curve depicting the power required to propel the ship at each given speed.
7) The load profile and hullform also allow the calculation of the ship structure required to withstand assumed wave loading.
8) Propulsion equipment is selected and a propulsion plant is designed to provide the requisite power for the desired speeds.
9) Electrical generation and distribution equipment and other auxiliary machinery is selected and arranged to support the ship's tasks.
10) Cost is estimated for the ship design at the current stage.

One can easily see that information generated in later steps will affect and change the assumptions of earlier steps, requiring repeated traverses of the spiral. Indeed, it is possible to enter a spiral that does not produce a feasible ship; for example, resistance and speed desired may require a propulsion plant that is heavier than anticipated, thus increasing drag and requiring an even larger propulsion plant.

2) *The inside-out ship*

There is a school of thought that argues that the process should be reversed as described by Keane [21]: one should establish what needs to be in a ship and arrange it first, then wrap a ship hull around the resulting equipment. It is often the case in Naval ship design that the external constraints that arise through decisions made early in the design process or sometimes provided externally by the political process result in an extremely dense ship design. This high density causes difficulty in production and maintenance, thus increasing life-cycle cost of the ship class; indeed, Lee [22] proposes an early-stage cost model based on density instead of weight, and argues that it more closely approximates the true cost of ship designs. An inside-out process would preclude this problem.

A series of projects at MIT Sea Grant explore the inside-out ship: Thurkins [23] outlines a program to select modular blocks for payload and machinery and provide a functional arrangement; Jurkiewicz et al. [24] provide pre-arranged machinery spaces at different power levels and different configurations along with the methodology to create additional permutations, and Nestoras [25] produces hydrodynamically-optimized hulls within user-specified constraints that surround a given arrangement of equipment and payloads.

van Oers and Hopman [26] propose a packing approach that uses a genetic algorithm to place components and compartments as close to their preferred location as possible while maximizing an objective function such as packing density. Placement is guided to ensure a ship-shaped result by a predefined envelope which is modified in size during the packing process. Using this approach, the authors can generate large sets of feasible designs that contain the same equipment and spaces with differing arrangements.

While the traditional design requires assumptions to be made about the final size of shipboard equipment when determining general hull parameters, the inside-out design requires assumptions to be made about final propulsion power requirements in order to select an appropriately sized engineering plant about which to wrap a hull. The question then becomes which assumption is more likely to be accurate, and which assumption has less severe repercussions if inaccurate.

D. *Measures of Effectiveness*

In ship design, there are far more variables than constraints, so there is no single mathematical right answer. Therefore, the process of ship design is the process of making decisions to achieve the best ship for the given use. In order to make the correct decision, one must have some method to measure the effectiveness of different designs. While some variables are numerically deterministic, e.g. weight and volume, some are probabilistic such as environmental factors like wind and waves or operational factors such as makeup of enemy forces or annual fuel usage, and some are subjective, determined by tactics and preference of the end users, e.g. whether speed or firepower is more important.

The comparison of ship designs in order to make responsible decisions requires stable, consistent, repeatable measures of effectiveness, or metrics. There are several easily-quantifiable measures that have long been used for comparison: weight, volume and annual fuel usage come to mind. Other metrics, such as cost, survivability, reliability, effectiveness, and flexibility are extremely desirable but more difficult to compute. Following are some examples of current research into such metrics.

Effectiveness for a Navy ship is measured by how well it will perform its mission. Since the exact warfighting scenario that the ship must perform is unknown, the mission is boiled down into requirements such as a mixture of payload details (e.g. number of missile cells or range of radar) and ship hull details (e.g. speed, range and seakeeping). Effectiveness is then judged as how well the ship meets the requirements along with a weighting of the priority of those requirements. Kerns, Brown and Woodward [27] discuss the role of various weighting methods such as pairwise comparison of expert opinion; they also comment that a more physics-based analysis can be accomplished through simulating the ship performance in a design reference mission.

With the integrated nature of the electric ship, the performance of the support systems such as electrical distribution and thermal management directly affect the performance of the ship and of the mission-critical systems, e.g. the repetition rate for firing an electromagnetic gun or the responsiveness of the propulsion motors. Cramer et al. [28] are developing an operational vignette concept in which multiple possible actions are combined in numerous ways to determine system stressing combinations; ship designs are then evaluated against these vignettes through system simulation using an operability measure.

Survivability is a measure of how well a ship and its systems can perform in adverse circumstances and includes whether the ship is likely to be discovered (detectability), if the ship can avoid being hit (susceptibility), how damaging an event is likely to be (vulnerability), and how well the ship can recover from damage by rerouting or repairing (recoverability). Current methods for analyzing survivability are extensive processes that evaluate the mission set of the ship against a series of potential threats [29]. These methods can take weeks to properly calculate; in the early stages of design, the ship may have gone through several iterations in that amount of time, rendering the survivability analysis obsolete before its completion. Two recent approaches to more rapid assessment of vulnerability have been studied. Cramer et al. [30] propose a methodology to compute the response of a ship to damage through a time-domain co-simulation of the support systems in the ship. Response to a single possible event is termed operability; integration of operability over a range of possible events yields two dependability metrics an average overall dependability and a minimum dependability. Chalfant et al. [31] propose a very rapid linear programming methodology to achieve a similar two-level metric for vulnerability that encompasses the average and the worst-case damage possibilities. Both these methodologies assume that the threat is not overmatching in that the ship continues to float and to operate as much as is possible given the state of the support systems.

Reliability is the measure of how consistently equipment works under normal operating conditions. Reliability work has long concentrated on metrics based in mean time between failures and mean time to repair for combinations of equipment applied across systems. Some recent work has developed additional methodology for viewing reliability, especially in shipboard electrical distribution systems. Santoso et al. [32] investigate reliability indices for shipboard electrical distribution system arrangements and develop algorithms to calculate them using Markov models and fault-tree analysis. Doerry and Clayton propose a Quality of Service metric [33] which takes into account the interruptibility of electrical loads, noting that some loads cannot withstand any power interruption, some can withstand interruptions of the length of time to switch from one power source to another (on the order of milliseconds), and some can even weather interruptions of several minutes while another source of power is brought online.

Risk associated with a specific failure event is a combination of the likelihood of that event occurring and the severity of the consequences if the event does occur. Most evaluations of risk include subjective evaluations of both likelihood and consequences produced by subject matter experts; Brown and Mierzwicki [34] provide a probabilistic approach with such a basis. Other suggestions for risk metrics have included Technical Readiness Level (TRL), which may be less subjective. This is an area for further exploration.

Cost estimating is surprisingly difficult. Acquisition cost for a ship includes the price of the materials and systems to be placed on the ship, plus the labor required to install the systems. Complicating this is the additional cost of the design of the ship which is amortized across all the ships in the product line, plus additional costs due to changes in the design during the construction of the ship. Life-cycle cost adds the operating costs of the ship including such expenses as fuel and supplies, personnel, training, maintenance and modernization; life-cycle cost also includes the disposal costs when the ship is deactivated. Cost thus becomes a very complex calculation with many assumptions and many inaccuracies. As a result, ship designers often use small subsets of the cost problem as stand-alone metrics evaluated separately; these can include weight, volume, fuel usage, and manning. Older early-stage cost models have been weight-based, which can lead to decisions that actually increase the cost of the ship by producing dense designs with high production and maintenance costs. As mentioned earlier, Lee [22] proposed a simple model based on density rather than weight. Weight and volume are fairly straightforward in concept, but the application requires consideration of the accuracy of estimates and the role of margins in the early stages of design. Annual fuel usage is calculated against a given mission scenario delineating speed, propulsion power, and ship service power for a typical' annual usage; this will most likely be different for each ship type designed. For an example, see [35].

There is a continued need for the development of metrics and for development of methodology for evaluation and comparison of ship designs against the metrics.

IV. SYSTEM DESIGN FOR ELECTRIC SHIP

An electric ship or all-electric ship in today's parlance refers to an electric-drive ship in which electrically powered motors are mechanically coupled to propulsors, while power generation units are separate. This is opposed to mechanical-drive, in which the engines are mechanically coupled to the propulsors, or hybrid-drive in which electrical power can be used to supplement propulsion or can be drawn off the propulsion system to power shipboard electrical systems. In the US Navy, the recent interest in electric or hybrid drive for the surface fleet is driven by two things: the interest in fuel economy and the increased power consumption of new weapon and sensor systems. Doerry [36] outlines the advantages that an electric-drive ship can bring to the Navy; his points are recapped below:

- Support high-power mission systems by providing the ability to shift power as needed from propulsion to ship service and thus to mission systems.
- Reduce number of prime movers by allowing power from a given prime mover to be used for multiple purposes simultaneously.
- Improve efficiency of prime movers by loading the prime movers that are on line in a more optimum manner.
- Improve propulsor efficiency by eliminating controllable pitch propellers and replacing them with contra-rotating propellers or pod propulsion.
- Provide general arrangements flexibility by breaking the mechanical link requiring alignment of propellers, shafts and engines.
- Improve ship producibility through removal of shaft lines and introduction of zonal distribution systems.
- Facilitate fuel cell integration since fuel cells directly produce electrical power.

There are two aspects of electric ships that affect the ship design: first, arrangements are potentially more flexible than in a mechanical-drive ship, and second, the ship support systems are an integral part of the overall ship performance. More flexible arrangements can be accommodated within the design process as it currently stands, but design tools should be reviewed to ensure sufficient flexibility to support electric ship design and designers should ensure they do not fall into the paradigms of traditional ship designs of the past without thought about the flexibility enabled by electric ships.

The integrated nature of support systems in an electric ship necessitates bringing the design and analysis of ship support systems, especially electrical power and thermal management, much earlier in the design process than has traditionally been accomplished. Several ongoing projects to bring system design into early-stage ship design are discussed below.

A. SEAQUEST

NSWCCD-Philadelphia has developed the Systems Engineering Application for Quick Evaluation of Shipboard Technologies (SEAQUEST) [37] which is a systems-engineering-based approach that lays out a system architecture one-line diagram and analyzes the effect of different technologies on that architecture through modeling those technologies. A Design-of-Experiments is constructed and sensitivity analysis is performed to select a small set of optima for further exploration. SEAQUEST is a modular program encompassing models such as Reliability, Maintainability, and Availability (RMA), Time-On-Station, Time-To-Objective, Fuel Calculation, and Cost [38].

B. ESRDC Systems Design Work

The Smart Ship Systems Design (S3D) tool developed by the Electrical Ship Research and Development Consortium (ESRDC) at the behest of the Office of Naval Research (ONR) is an early-stage tool for the design, simulation and analysis of ship systems [39]. Discipline-specific 2D views for electrical, mechanical, piping, and HVAC (heating, ventilation and air conditioning) system design are combined with a 3D visualization and arrangement tool. The tool provides an extensive equipment catalog populated with mathematical models and properties for equipment pertinent to the appropriate systems. The user can instantiate new equipment in the design, create connectivity, and run power-flow-level simulations, including co-simulations across multiple disciplines. Continued research is directed at developing a mission scenario evaluation module to compare design effectiveness under various mission scenarios.

ESRDC has also developed a reliable and validated thermal management simulation tool that can be used in the initial stages of design to correctly evaluate and mitigate the adverse effects of increased heat loads. This tool can interface with S3D or stand alone. The seeds of this project lie in work that resulted in the initial development of two complementary software tools: the Cooling System Design Tool (CSDT) [40], [41], developed by MIT, and vemESRDC [42], developed by Florida State University. The CSDT arranges and analyzes cooling piping systems, and vemESRDC addresses heat and humidity conditions in shipboard spaces. Continued development has merged these tools [20], allowing the user to design a cooling system using the state-of-the-art methods to study the impact of design decisions at the early stages of design and allow flexibility to evaluate new equipment or new technologies such as two-phase cooling [43] or microchannel boiling [44], when lower fidelity models are available.

Shipboard electric power distribution system design is also under development within ESRDC. Mazzola et al. [45] have developed a tool for the automatic sizing of cables given the operating conditions. Chryssostomidis and Cooke [46] are developing a program that, given the required initial design state and a small number of user inputs, designs the power distribution system and places it shipboard, respecting the constraints imposed by fixed obstructions.

C. *Automated System Design*

Bringing system design into the realm of design space exploration requires the ability to accomplish automated system arrangement and analysis, with guidance from the engineer performing the exploration. There is ongoing work within ESRDC to create a template system that can be employed to automatically arrange and populate systems [47].

The underlying concept of the template design process is the same for the electrical distribution system and the thermal management system; in fact, the methodology framework is applicable to many distribution systems, e.g. electrical power, chilled water, seawater, firemain, data, communications. This framework as applied to a cooling system is shown graphically in Fig. 8. The required input data are the sources and destinations of the commodity and a description of the physical space available. A template is chosen that, along with some user-modifiable default values, provides the guidelines to automatically design a system. The output is a system with components logically connected and physically arranged in space, stored in a database, and ready for simulation and analysis.

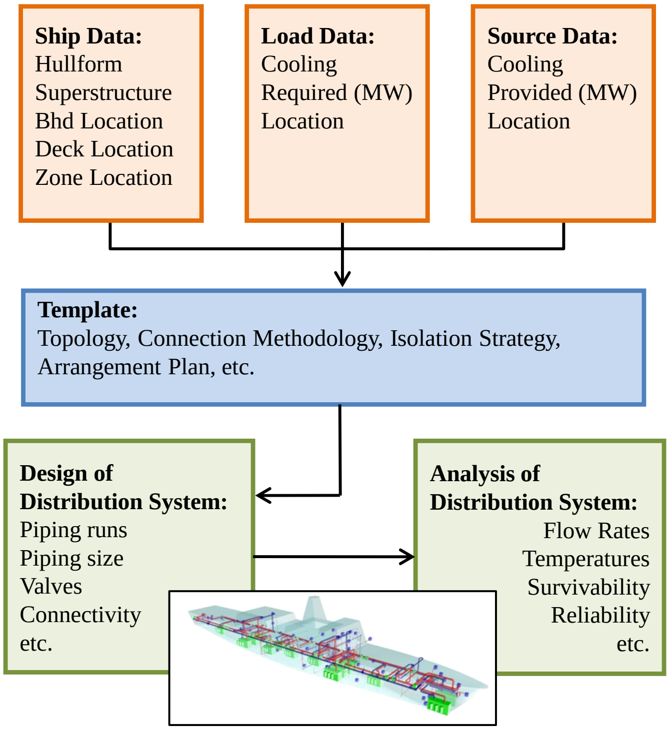

Fig. 8. System design template framework as applied to cooling system design [47]

V. ROLE OF COMPUTERS

The ship design process is constrained by resources - personnel, time, money and tools. By investing in tools, specifically computer tools, we can increase the amount of work that can be accomplished in a given amount of time, and thus increase the level of detail and the amount of information available in the early stages of design. For example, computational fluid dynamics (CFD) simulations, used to calculate resistance or response amplitude operators (RAOs) for seakeeping, allow more hull forms to be tested in a shorter amount of time than building physical models and running tow tank tests on them. Two examples discussed below, the integrated product model and collaborative computing, are methods that fall into this category; they are computational methods to accomplish record keeping and communication, both of which have occurred throughout the history of engineering but which need to be updated in the era of computer tools.

In addition to augmenting the amount of data that can be produced during design, computers also allow us to approach some aspects of the ship design problem in a new way. Revisiting the CFD example above, one can employ optimization methods to automatically search a broad range of possible hullforms for areas of good hydrodynamic performance calculated through CFD simulations, then make small refinements to achieve the optimum shape for a given desired operating range;

see, for example, [48]–[50]. Although this is an extension of what one could theoretically accomplish manually, the labor involved would be prohibitive. The effect of high-performance computing on design space exploration is a similar example of this shift in design practices, and is explored below.

Nowacki [51] provides a thorough review of Computer-Aided Ship Design (CASD) covering the five decades from 1960 through 2010. He argues that computers are an aid for humans to use in making design decisions; the human designer remains responsible for posing the problem statements, establishing priorities, reviewing computational results, and making the decisions. His review covers the application of computers to the problems of establishing principal dimensions, geometric modeling and hull form fairing, and structural analysis and design, by applying the techniques of systems analysis, optimization, nonlinear programming, process design, standardization, and product data technology.

Andrews [52] also discusses the role of computers in ship design. Beyond the obvious capability for numerical computation of hard data, he argues that computers can be used to develop a more creative achievement of synthesis in design. He states that, with improved computational capability, design synthesis can now include:

- Numerical synthesis including algebraic expressions of design rules
- Engineering analysis of physics-based models at various levels of fidelity
- Graphical representation to inform the intuition of the designers
- Simulation-based design to incorporate ergonomics

These valid points should also expand simulation-based design to a much wider range of applications beyond ergonomics.

A. *Integrated product model*

The ship design process has always included methods of recording, storing and transmitting the details of a ship design. As computational technologies have grown, data formats have moved from hard-copy to electronic; with this transition has come the complication of different storage systems and languages, causing the need to translate data from one format to another. A sequence of efforts has addressed the standardization of data format and information exchange. Initial Graphics Exchange Specification (IGES) is a US Standard that specifically addresses the transmission of geometric data in CAD systems [53]; it has been in place for over 30 years. ISO 10303, known as STEP (STandard for the Exchange of Product model data) expands IGES to cover a much wider range of types of data covering the entire life-cycle of a ship [54].

Olivier et al. [55] discuss a system-of-systems framework in which they recommend viewing the same ship data from many different viewpoints, enabling the assessment of the ship design for different purposes. This is derived from the UK Ministry of Defence Architecture Framework, in which data is viewed from Technical, Systems, Strategic, Operational and Acquisition viewpoints. Thus the same information can be used to model and understand the ship performance in many ways: will it meet the military specifications and guidelines (technical) to function as needed (operational) in a timely and affordable manner (acquisition). A well-constructed integrated product model should be able to consistently store the data to support such analyses.

The US Navy has developed just such a product model repository, which is described in more detail in Section VI.

B. *Collaborative Computing*

Collaborative design when accomplished using advanced computational tools requires collaborative computing; the software programs need to facilitate communications among engineers. Keane et al. [56] argue that concurrent engineering using a multi-disciplinary team is key to successful ship design and that advances in computer technology can enable this communication and concurrent engineering. Further, the information that is communicated must be usable, not just a flow of unorganized data.

Lanubile et al. [57] provide an overview of software tools and technologies for collaborative computing. They cite a number of methods and tools used in collaboration such as version-control and trackers, then go on to discuss collaborative design environments that combine these tools. They also point out the difficulty of including legacy programs into a collaborative environment.

One example of collaborative computing applied specifically to ship design is ESRDC's Smart Ship Systems Design (S3D) tool mentioned earlier. S3D can be used by a team of engineers to accomplish concurrent collaborative early-stage design and analysis of ship systems. The software suite is designed to be used in the cloud, allowing a geographically dispersed team to work simultaneously and collaboratively on a single design. Dougal, Langland and Leonard [58] explore the modeling and data exchange techniques that enable the implementation of such a collaborative environment.

C. *High-Performance Computing*

DoD's High-Performance Computer Modernization Program (HPCMP) and Computational Research and Engineering Acquisition Tools and Environments (CREATE) Program seek to exploit the cutting-edge of computer technology as computers become faster, in terms of Floating-point Operations per second, and bigger, in terms of number of cores and the associated memory and data handling components. The goal of the HPCMP [59] is to provide the supercomputer capability, high-speed network communications, and computational science expertise that enables the Defense laboratories and test centers to conduct a wide range of focused research, development, and test activities. CREATE specifically applies scalable, multi-disciplinary, physics-based computational engineering software products to improve the DoD acquisition, design and analysis processes [60]. Under the auspices of CREATE, there are several programs that relate directly to ship design: the Integrated Hydrodynamics Design Environment (IHDE) for hydrodynamic analysis, Rapid Design and Integration (RDI) for design space exploration, and NavyFOAM, a high-fidelity computational fluid dynamics program for the analysis and prediction of resistance, drag, and seakeeping. A meshing and geometry effort, Capstone, applies across all the CREATE application areas.

Parallel computing is the process of using multiple computer cores simultaneously to enable solution of extremely large problems in cases where the problem is of such magnitude that the solution on a single computer either takes too long or exceeds the memory and calculation capacity of a single core. Challenges in parallel computing come in areas such as methods of breaking a problem into smaller pieces, communication between cores during calculations, storing and retrieving the huge amounts of data that are produced, and processing this data for results. One parallel computing example is NavyFOAM [61], a CFD application that calculates the turbulent flow around ship and submarine hulls using Reynolds-averaged Navier-Stokes (RANS) equations; this program is used to predict resistance, wave elevation, hull boundary layer and wake. The NavyFOAM toolkit includes methodology to run simulations in parallel through decomposition of the domain into smaller portions, using an open-source message passing interface (MPI) capability, OpenMPI [62]. The goal of the project is a high-fidelity CFD capability tailored to ships and submarines, and the use of this capability to shorten the ship design process by providing physics-based answers to hydrodynamic questions. The software is based on OpenFOAM [63], an open-source CFD toolkit.

One application of parallel computing, called embarrassingly parallel, is the case where a problem falls very easily into separate problems with little or no interconnection between them. Embarrassingly parallel computing is very helpful in cases where you do not have the laws of physics dictating a single right answer. Instead of solving a constitutive problem for a single mathematical optimum, one repeats the process on a myriad of designs, each calculated on a single node of a massively parallel computer, producing a very wide design space exploration and identifying regions for deeper investigation. RDI falls into this category - hundreds or thousands of separate simple ship design evaluations can be run, each on a different core.

VI. U. S. NAVY DESIGN TOOL FRAMEWORK

As shown in Fig. 9, the current Navy suite of early-stage design tools consists of an overarching design space exploration tool (the Rapid Ship Design Environment or RSDE) running a number of modular programs that perform design and analysis functions for different aspects of the ship design, all of which persist design data in the Leading Edge Architecture for Prototyping Systems (LEAPS) data repository. These tools use an underlying Geometry and Engineering Mathematics Library (GEML) which includes the tools required to support Non-Uniform Rational B-Spline (NURBS) representation, kriging, neural networks, radial basis functions, and more.

The *Leading Edge Architecture for Prototyping Systems (LEAPS)* is a data repository designed to be stable, controlled, and extensible [64]. It is used to store all data for the ship design throughout the entire design process in an organized manner, thus supporting better integration of design tools and an overall reduction in engineering effort for locating, verifying, and transforming information for a design. Currently, the LEAPS database underlies all the early-stage design tools currently employed in the Navy; the goal is for LEAPS to become the repository of data throughout the entire life cycle of the ship.

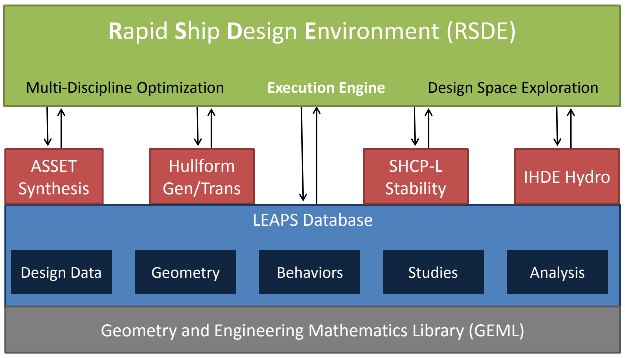

Fig. 9. Navy design tool overview, adapted from [17]

The *Advanced Ship and Submarine Evaluation Tool (ASSET)* is a modular ship synthesis tool that performs a design spiral analysis to converge on a single solution for a given set of inputs by analyzing each discipline-specific module in sequence. The modules include hull geometry, gross arrangement, hull structural design, resistance and propulsion, power plant sizing, weight estimation and area/volume sufficiency analysis [65]. ASSET is a powerful tool which an expert user can use to fairly rapidly generate and analyze multiple early-stage ship designs, and is the primary ship synthesis tool used by the Navy in the earliest stages of design. Many of the modules in ASSET use parametric models derived from previous ship designs, so exploration of new-concept designs that differ significantly from past practice require additional analysis using external tools.

The *Hullform Transformation utility (HFT)* manipulates a baseline hullform using design variables such as length, depth, beam, hull form angles and fullness factors to create new hull form.

The *Ship Hullform Characteristics Program - LEAPS (SHCP-L)* performs hull analysis for intact and damaged stability. The user establishes design conditions, liquid loads, and flooding scenarios which, combined with the ship's lines, are used to determine tank capacities, floodable length, damageable length, longitudinal strength, and intact and damaged stability [66].

The *Integrated Hydro Design Environment (IHDE)* is a hydrodynamics analysis tool for prediction of hydrodynamic loading on a ship or submarine hullform, used in predicting seakeeping and resistance [66]. It provides thin-ship theory resistance predictions based on Fourier-Kochin Slender theory [67] and total ship drag (TSD) [68], which is a combination of slender ship theory for wave-making resistance, ITTC friction line for friction drag, series data for form resistance, and models for transom and spray drag. IHDE also includes multi-hull capability for resistance prediction.

Seakeeping is predicted within IHDE using the Ship Motions Program (SMP) or the Large Amplitude Motion Program (LAMP). SMP [69] is a frequency-domain program that predicts the six-degree-of-freedom response of a ship or small boat to regular and irregular waves at arbitrary direction using strip theory. LAMP is a time-domain full-viscosity approach that uses potential flow theory coupled with a nonlinear body boundary condition below the incident wave surface [70], [71] to calculate 3-D large-amplitude hydrodynamics, and has been expanded to include green-water effects [72]. One of the outcomes of the CREATE program was to produce a parallelized version of LAMPS for high-performance computing applications.

The *Rapid Ship Design Environment (RSDE)* integrates the early-stage design tools to explore a large design space [73]. The user sets up a range of parameters which RSDE uses to create hundreds or thousands of ship designs by automatically running ASSET, IHDE and SHCP; in the future, more design and analysis tools will be added to this capability. Under the CREATE program, RSDE will use high-performance computing to reduce the real time required to perform these tasks. This type of problem is perfectly suited for embarrassingly parallel processing, as each ship design may be run on a separate node and requires no interaction with the designs in process on other nodes.

Several other tools are in various stages of development for inclusion in the RSDE process. The *Intelligent Ship Arrangement (ISA)* tool [74] is an optimization tool that uses fuzzy logic to semi-automatically develop arrangements meeting criteria specified by the designer. The *Early Manpower Assessment Tool (EMAT)* [75] processes the work required to perform shipboard functions and to operate and maintain shipboard equipment, providing an estimate of the number and paygrade of personnel required for the ship configuration; this has direct impact on the size of the accommodations required onboard. The *Performance-Based Cost Model (PBCM)* [76] is an early-stage rough-order-of-magnitude parametric cost model that relates cost to performance along with physical characteristics. These in-development tools will use LEAPS as the native data repository and may be incorporated in the automated design-space exploration performed by RSDE.

In addition to tools that use LEAPS as their native data repository, there are a number of legacy programs that access data from LEAPS via a translator. Such programs include *Advanced Survivability Assessment Program-Lite (ASAP-Lite)* for vulnerability assessment and the *Navy Common Cost Model (NCCM)* for cost analysis. A variety of seakeeping and resistance modules are also available via translators, but this functionality has been replaced with IHDE.

Smart Ship Systems Design (S3D) is being converted to use LEAPS as the inherent data repository [77], thus expanding the system design, simulation and analysis capabilities of the Navy's design tool repertoire.

Kassel et al. [65] provide a discussion of the current state of Navy design tools as of 2010 along with a vision for an automated high-end toolset that integrates many information-dense design definition tools with high-fidelity physics-based analysis tools. Progress toward this vision has been made with such improvements as a mapping of the ship design process to identify gaps, release of IHDE and RSDE under the CREATE program, and new versions of the LEAPS data repository. Progress continues with the development of a version of ASSET more tightly coupled with LEAPS, the ISA ship arrangements tool and the S3D system design tool.

VII. WHAT IS NEEDED?

It is well recognized that Navy ship design and acquisition costs are extremely high, and that cost estimates for lead ships and other new programs are not particularly accurate. Keane [78] argues that the reasons for the excessive cost growth are rooted in inadequate design tools and processes. Significant effort in the last decade has been placed on improving the functionality and interoperability of the Navy's early-stage design tools to include more physics-based tools, new methodologies such as wider design-space exploration and set-based design, and improved metrics especially in cost modeling and ship effectiveness. These efforts are producing excellent advances in the state of the Navy's early-stage design, and efforts should continue in these areas.

It is important to remember that the quality of the information generated through modeling is directly dependent on the quality of the input data and the quality of the models. Verification and validation of modeling tools is essential, and the large amount of uncertainty included in the data must be recognized. Mackenna [16] often points out that the proper design to choose from a design-space exploration exercise is not the one on the Pareto-optimal front because the uncertainty involved in early-stage design makes it unlikely that a design on the very cutting edge will end up being a feasible design once sufficient detail is included. One should instead choose the design slightly set back from the optimum.

Newer areas for exploration should include co-simulation tools that look at the interaction of shipboard systems on overall ship performance, especially in view of the ever-increasing interoperability of systems. Design of controls and control systems is also important, but likely a job for later in the design cycle. Exploration of the effects of uncertainty produce interesting results regarding which areas of the design should receive more attention; uncertainty quantification methods indicate the impact different variables have on the outcome of the calculations, enabling the designer to put additional resources on those variables with the greatest impact. Mining of data developed through broad early-stage analyses combined with higher-fidelity simulations using methods such as kriging and co-kriging can provide more information at later stages of design, and can be retained and re-used for other future designs.

The Navy ship design community is rife with areas for new research and investigators are making healthy progress in important areas.

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Julie Chalfant is a research scientist in the Design Laboratory of the MIT Sea Grant College Program. Her current areas of research include ship design and integration, including the development of early-stage ship design tools. She is a member of the Electric Ship Research and Development Consortium (ESRDC). A former active duty officer in the United States Navy, she also has significant experience in operating and maintaining Navy ships.