Design of a Notional Ship for Use in the Development of Early-Stage Design Tools

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Abstract— **In this paper, current early-stage design tools are used to produce a notional ship that includes leading-edge weapons and sensors. These new systems stress the capabilities of current design tools and demonstrate the need for tools that can address the increasingly integrated, powerful and heat-producing nature of future payloads. The data produced in this process are shown to be the required input to new design tools under development, thus establishing the link between the existing state of the art and tools that provide more advanced capability necessitated by advances in ship system technology. A framework for a semi-automated template-based system arrangement tool is then presented.**

Keywords—ship design, design-space exploration, system design

I. INTRODUCTION

It is well recognized that new weapon and sensor systems in Navy ships require significant power and produce significant heat, thus placing considerable demands on the shipboard electrical power and thermal management systems. Traditionally, support systems such as power and cooling distribution were not incorporated in the early stages of design; this is no longer acceptable due to the physical size of the systems and their importance to overall ship performance.

In order for new design tools to model support systems in a realistic manner, they must have a solid basis. In this paper, we concentrate on the U.S. Navy's early-stage ship synthesis tools and demonstrate that the information required to produce and analyze system designs in an automated manner is obtainable from this initial ship synthesis.

Furthermore, the automated nature of the new system design tools is intended to facilitate their inclusion in the Navy's Rapid Ship Design Environment (RSDE) tool, which uses multi-discipline optimization to explore a broad design space. RSDE automatically runs numerous tools for hullform generation, parametric ship design synthesis, stability, and hydrodynamic performance analysis within parameters set by the designer [1]. The process we demonstrate shows that we can bring system design earlier in the process, thus increasing the pertinence of the set-based design results produced by RSDE.

MIT is developing tools to augment the Navy's early-stage ship design capabilities with the long-term goal of automated design and analysis of shipboard distribution systems under the guidance and control of subject experts. These tools are designed to be integrated with the Navy's current suite of early-stage design tools. They use as their input, data generated from a ship design created using the Advanced Ship and Submarine Evaluation Tool (ASSET), the Navy's early-stage ship synthesis tool.

In this paper, we describe the ship design process incorporating the new design tools. The first step involves the development of a notional ship using Navy design tools and the subsequent persistence of the ship data in the Navy's ship design repository. We then show that the data produced from a simple early-stage design is sufficient to support these automated design tools and we describe the process through which this data feeds into MIT tools under development. We then describe the underlying template-based methodology used in the system design tools. Specific examples presented include the space reservation tool for electrical power distribution [2] and the system-level design tool for marine cooling systems [3].

II. NAVY EARLY-STAGE SHIP DESIGN TOOLKIT

As shown in Fig. 1, the current Navy suite of early-stage design tools [4] 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 store design data in the Leading Edge Architecture for Prototyping Systems (LEAPS) data repository. These tools use an underlying Geometry and

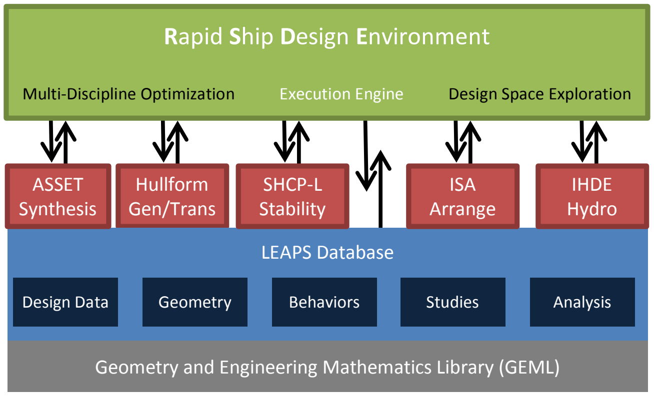

Fig. 1 Navy design tool overview [4]

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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 following paragraphs describe each of these modular software programs in more detail.

The Leading Edge Architecture for Prototyping Systems (LEAPS) is a data repository designed to be stable, controlled, and extensible [5]. It is used to store all data for the ship design throughout the entire design process in an organized manner to support 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.

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, rough arrangement, hull structural design, resistance and propulsion, power plant sizing, weight estimation and satisfaction of area and volume requirements [6]. ASSET is a powerful tool which an expert user can use to fairly rapidly generate and analyze multiple early-stage ship designs. 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 a new hull form [7].

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 [6].

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 [6].

The Rapid Ship Design Environment (RSDE) integrates these early-stage design tools to explore a large design space. The user sets up a range of parameters which RSDE uses to create hundreds or thousands of ship designs by automatically running ASSET, HFT, IHDE and SHCP.

Several other tools are in various stages of development for inclusion in the RSDE process. The Intelligent Ship Arrangement (ISA) tool [8] 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) [7] 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) [9] is an early-stage rough-order-of-magnitude parametric cost model that relates cost to performance along with physical characteristics.

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 [7].

Smart Ship Systems Design (S3D) [10] is a systems arrangement and analysis tool that provides simulation capability for electrical, mechanical and thermal systems along with three-dimensional arrangement and visualization. Whereas this tool is being converted to use LEAPS as the inherent data repository [11], it is not currently configured for automated use under RSDE. It will instead be used to flesh out possible feasible designs. It provides significant capability for hands-on design, arrangement and simulation of systems, and the potential for a gateway to higher fidelity simulations.

III. NOTIONAL SHIP DESIGN

We begin our representative design at the preliminary design stage, assuming that the required operational capability and projected operating environment (ROC/POE) has been established. We chose an all-electric destroyer with selected physical and performance goals shown in Table 1. Since this is an electric-drive ship in which all installed power can be directed to propulsion or ship service loads, in addition to the usual sustained and endurance speeds, we defined a performance requirement of "battle speed" which indicates the maximum sustained speed that can be attained with weapons and sensors fully engaged.

TABLE 1. NOTIONAL SHIP PERFORMANCE REQUIREMENTS AND DATA

Performance Requirement	***Threshold***	***Goal***	***Value***
Installed Power	90 MW	100 MW	99 MW
Displacement	11,000 mt	10,000 mt	10,500 mt
Maximum Sustained Speed	27 kts	32 kts	28 kts
Maximum Battle Speed	23 kts	30 kts	24 kts
Cruise Speed	14 kts	16 kts	15 kts
Range	3,000 nm	6,000 nm	500 nm

To place the design in the realm of future capabilities, we performed a survey of new weapon and sensor technologies in the world's navies and selected several leading-edge technologies that would tax the power and cooling systems onboard the ship. The armament mix consists of the following:

- Electro-magnetic gun (32 MJ per shot)
- Laser Weapons System (LaWS) (300 kW radiated power when in operation)
- Active Denial System (ADS) (600 kW radiated power)
- Vertical Launch System (VLS), 48 cell

This mixture provides anti-air, anti-ship, anti-small boat, anti-submarine and self-defense capability, depending on the missile loadout in the VLS system.

The Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance (C4ISR) systems include

- Multi-Function Dual-Band Radar (5 MW)
- Integrated radio-frequency (RF) suite including electronics warfare and communications (2 MW)
- Hull-Mounted Sonar and Towed-Array Sonar
- Total Ship Computing Environment (Integrated weapons, sensor, machinery and navigation control systems)

thus enabling control of the ship and ship systems, communications, and detection and engagement of airborne, surface and submarine threats.

Shipboard vehicle support is provided for

- Helicopters and unmanned aerial vehicles (UAVs)
- Small boats and unmanned surface vehicles (USVs)

Open-source documents were used to approximate weight, dimensions, total power requirements, and cooling demand for each system.

We developed a single ship design to implement these selections using ASSET. Recognize that the choices made produce only one of a myriad of possible ships that could satisfy the requirements; the resultant ship is used to exemplify the process, not assert the optimum result. The process described below follows the procedure in [12].

The payload items described above were arranged on a skeleton ship to determine approximate locations, and then entered into the Payload and Adjustments table of ASSET.

A hullform similar to DDG-51 was selected as a starting point. A plug was installed to increase length, and sizing parameters were selected to achieve a hullform that would displace approximately 10,000 mt at an appropriate draft.

A selection of three LM-2500+G4 engines at 29MW each and three Rolls Royce RR4500 engines at 4MW each produce 99 MW of installed power at Navy ratings. These engines were selected to provide a variety of power levels in different combinations. This generator selection was combined with an Integrated Power System (IPS) and a dc Zonal Electrical Distribution System (ZEDS) using 5MW power conversion modules (PCMs).

Two 36MW propulsion motors provide the propulsion power required to achieve the sustained and cruise speeds required.

The manning complement was selected to be 243 personnel total including the air detachment.

As mentioned earlier, the ASSET algorithms are based on historical data, so the ship produced by ASSET assumes existing and past technology. We postulated that a ship design requiring 100MW of power would not fit in a 10,000 ton hull using traditional equipment and distribution systems; we were able to achieve approximately 10,500 tons, but only by restricting range to 500 nautical miles. See Table 1 for the results of the ASSET run. This baseline ship can now be run through new design tools such as S3D to incorporate new technologies; the resultant ships will be analyzed to determine whether the weight and volume of support systems can be reduced and fuel load raised to the point that range can be increased to a reasonable distance. This final assessment remains to be accomplished.

IV. NEW SYSTEM DESIGN TOOLS

Since support system performance directly affects mission system performance in an electric ship, it is necessary to arrange, analyze and simulate the performance of support systems to properly analyze the effectiveness of an electric ship design during early-stage design. The system design tools under development will enable the Navy to further the RSDE process in key areas that are necessitated by the integrated nature of the ship of the future. We mention specifically as examples a power distribution system design tool [2] and a cooling system design tool [3], showing that the input data required for these tools is generated by the Navy's current suite of early-stage design tools, and showing that the output of these tools furthers the Navy's design capabilities in necessary areas.

The underlying concept of the system 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. 2. The input is the sources and destinations of the commodity and a description of the physical space available including the space constraints. The user chooses a template that provides the guidelines to automatically design a system and includes some default values that may be left as presented or modified by the user. The output is a system with components logically connected and physically arranged in space, stored in the LEAPS database, and ready for simulation and analysis.

The template is the set of rules by which a distribution system is arranged; it will be modular in nature so the subsets can be combined in different ways as shown in Fig. 3. Possible modules include the following:

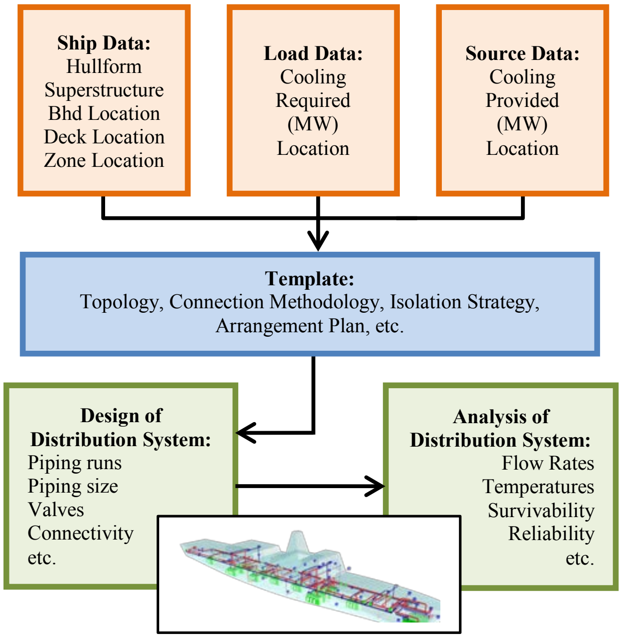

Fig. 2. System Design Framework as Applied to Cooling System Design

- Transport state: the state in which the commodity is transported, e.g. voltage, frequency and quality for power, or cooling medium and temperature for cooling
- Topology: the route of the main transportation corridor, e.g. the main bus for power or the supply and return header for chilled water cooling
- Connection methodology: the approach for connecting loads and sources to the main transportation corridor, e.g. switchboards or taps for power, manifolds or individual branches for cooling
- Isolation strategy: The method or device used to provide isolation, e.g. disconnect/circuit breaker type for power or valve type for cooling
- In-zone arrangement: the grouping and redundancy in arrangement of loads, e.g. whether loads are provided power individually or grouped, and the redundancy of connections and connection equipment

Some distribution systems may use more or fewer modules as required. The original program will contain several templates, and there will be provision in the program to design additional templates, either by combining modules into a new whole or by creating new modules (and therefore templates) entirely.

Since the templates will provide all information required to accomplish a system design, this methodology could become part of a RSDE-style design space exploration process with the template choice one of the parameters in the experiment setup.

A. Electrical Distribution System Design

As an example, we describe the automated design and analysis of an electrical distribution system; more detail can be found in [2]. We begin with a balanced ship design as produced by ASSET and stored in LEAPS. From this design, we are easily able to extract the hullform and superstructure, deck locations, bulkhead locations, and the number of zones and dividing bulkhead locations. This gives us the enclosed space available for arrangement of a distribution system.

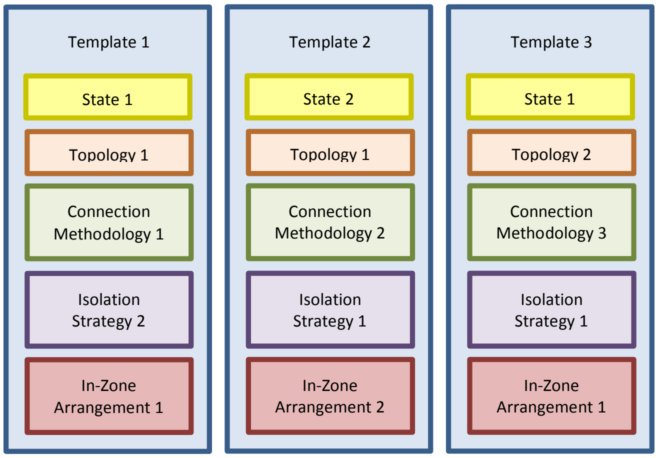

Fig. 3. Modular Template Concept

The location and power generation capacity of the PGMs can be read from LEAPS along with the payload item and propulsion motor electrical demands and locations; remaining electrical loads can be derived from the electric loads report generated by ASSET. Thus, all the input data required by the electrical system design tool is available.

The remaining input item is selection of a template to guide the system design. Fig. 4 shows two sample templates for an electrical distribution system topology, please note that these are provided for discussion purposes only and are not necessarily actual design solutions. The terminology in these diagrams is as follows: a PGM is a power generation module and contains an engine and generator; a PDM is a power distribution module such as a switchboard; a PCM is a power conversion module such as an inverter, rectifier or transformer; a PMM is a propulsion motor module and includes both the motor and the motor drive; and a LOAD is either a single use load or a load center that provides power to many loads distributed within the zone. The dashed red lines separate zones, and the solid blue lines are power cabling.

The two templates shown in Fig. 4 provide the following guidance:

Transport State: Both templates will distribute power as dc power. The main bus is most likely made up of many pairs of cables to carry the total power required; the number of cables is dictated by the power level, voltage, and maximum ampacity allowed per cable. Voltage and ampacity are default values in the template.

Topology: Both templates use a ring bus, shown as the thick blue line. The longitudinal and transverse extent of the ring bus, the height of the port and starboard runs, and the path taken for the cross connect from port to starboard is governed

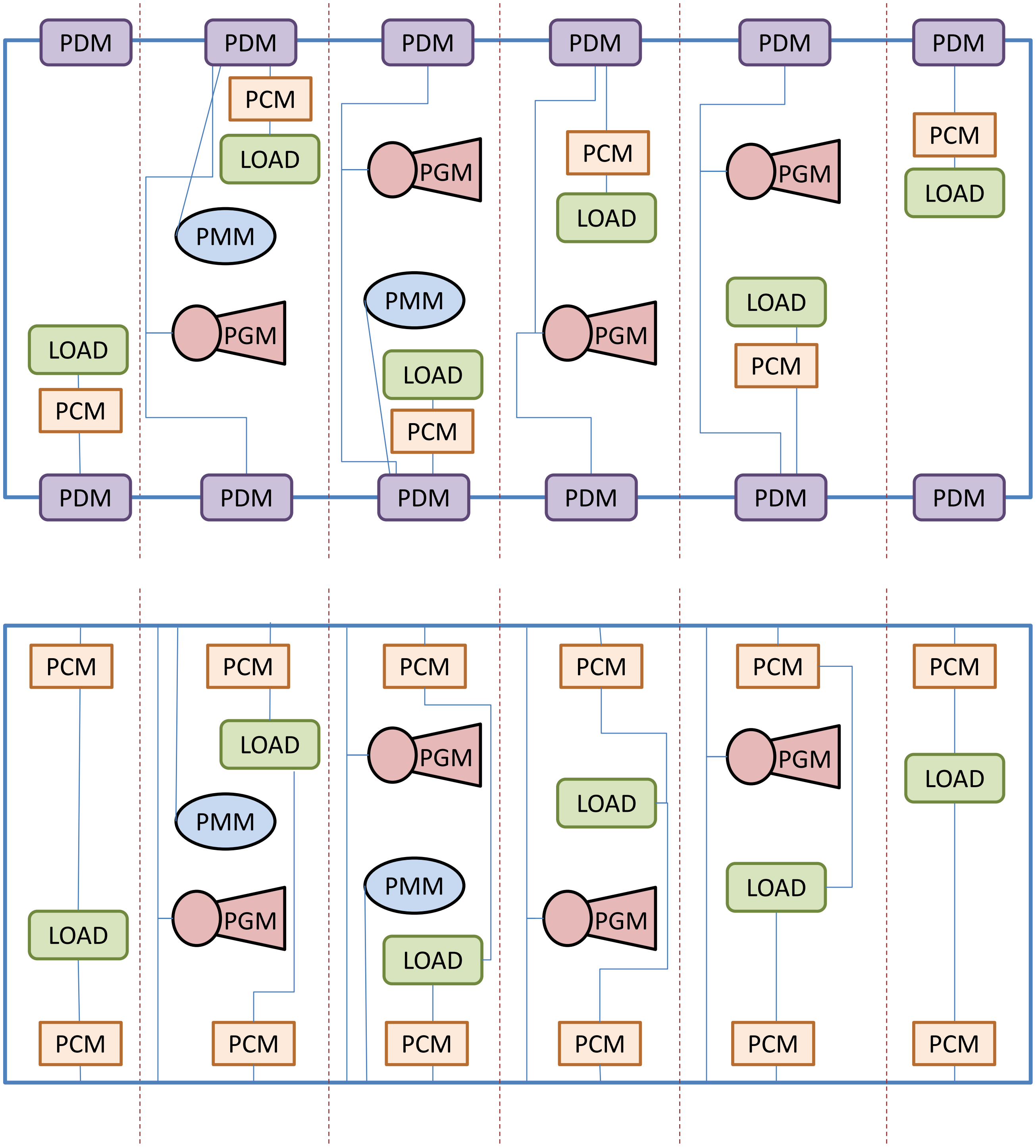

Fig. 4. Two example templates for an electrical distribution system arrangement tool, Template A (top) and Template B (bottom).

by the template using default values that can be changed by the user or left as-is for a completely automatic run. Power level is guided by the template to be the total installed generation capacity on the ship throughout the bus.

Connection methodology: Template A uses switchboards to provide connectivity between sources, loads and busing. Template B is a switchboard-less design in which sources and loads tap directly into or off the main bus.

Isolation Strategy: Both templates use a dc disconnects as opposed to circuit breakers. Thus, power flow is controlled by the power electronics, and equipment is isolated using a dc disconnect instead of a circuit breaker. The main bus isolation in Template A is provided within the switchboards, whereas in Template B isolation devices are provided immediately forward and aft of the zonal bulkheads. Each individual load and PGM is also provided isolation via a dc disconnect. The isolation devices are not shown in the figures.

In-Zone Arrangement: Both templates connect each PGM to both the port and starboard buses. Template A provides one PCM per zone to support the full load within the zone. Template B provides two PCMs per zone, sized to accommodate the full vital load or half the vital and non-vital load combined, whichever is greater.

B. Marine Cooling System Design

Automated design of marine cooling systems is based on the work described in [3]; we briefly describe the applicable template methodology here.

Structural information is available in LEAPS from a balanced ASSET run; this includes hullform, superstructure, bulkheads, decks, and zonal divisions.

The cooling sources are the chillers. ASSET provides the number, size and type of chillers required for the design and stores that information in LEAPS.

The next data items required for input are the list of cooling loads and locations. Some are explicitly defined in the payload and adjustments table; the remainder can be calculated from the total heat load calculated by the ASSET algorithms. We subtract the explicitly defined loads from the overall loads and divide the remainder into lumped loads for each zone, and place them centered in the zone. Future versions of ASSET may have more loads explicitly defined which will increase the accuracy of this method.

The templates for the cooling system design address the same issues as the electrical system design, e.g. transportation state, topology, connection, isolation and in-zone arrangement, but in the cooling realm instead of electrical. For example, isolation devices are valves instead of disconnects, and the defaults and algorithms determine piping size and flow rate instead of voltage and ampacity.

V. CONCLUSIONS

A notional ship has been designed using the Navy early-stage design tools. We have shown that the information provided by this design is the input required for two new system design tools, and present a framework for semi-automated system design for future incorporation in a design space exploration tool such as RSDE. This design methodology can also be used to populate LEAPS with a standard system design for further refinement, simulation and analysis.

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