Using S3D to Analyze Ship System Alternatives for a 100 MW 10,000 ton Surface Combatant

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Abstract— **The Electric Ship Research and Development Consortium (ESRDC) conducted an extensive design exercise using the Smart Ship Systems Design (S3D) tool with the goal of exercising and improving the functionality of the S3D design environment currently under development by the ESRDC. S3D is a design environment that enables concurrent, multi-disciplinary collaboration and that introduces simulation capability in early-stage ship design [1]. This work examines the S3D design environment's capabilities in a realistic design exercise. To this end, a baseline ship and several variants were designed with a 10,000 ton displacement and a 100 MW integrated power system to explore the effects of new technologies and to determine the capability of S3D in elucidating differences between design variants. Key features and performance effects of each design and an analysis of S3D capabilities are presented.**

Keywords— Ship design, Early-stage design tool, Ship variants analysis, Ship mission performance

I. INTRODUCTION

The Electric Ship Research and Development Consortium (ESRDC) used the Smart Ship System Design (S3D) environment to develop and compare several ship system designs demonstrating key elements of a 100 MW Medium Voltage Direct Current (MVDC) electric power distribution architecture suitable for integration into a future 10,000 ton surface combatant. The goal of this work was to exercise S3D in an extensive ship design process, thus providing user evaluation of the S3D design environment's ability to examine several ship system variants and quantify the differences between them. Through the execution of that exercise, the team provided recommendations for refinement of the environment to improve the design process.

The technical approach for the design evaluation was to develop a baseline ship system design using conventional power system architectures and currently available power generation and power conversion technologies, and use that baseline as a benchmark for comparison of design variants. Guided by the information available in an open-source format and the desire to exercise the current capabilities of the S3D software, three variants were selected for further exploration beyond the baseline: high-speed turbine generator sets, advanced material converter technology, and revised power system topology. By modeling and simulating the variants in the S3D environment, the team was able to evaluate not only the changes in the directly affected equipment, but also the effects on peripheral equipment and on overall ship performance induced through such effects as changes in weight, volume and efficiency.

An overview of the S3D design environment is provided in Section 2. The remainder of the paper describes the design exercise and results, organized as follows. The notional ship design including hullform and payload selections are described in Section 3; Section 4 describes the conventional baseline ship systems; Section 5 provides information on the design variants, and Section 6 compares the resulting designs. Finally, the recommendations for improvements to S3D are provided in Section 7.

II. S3D OVERVIEW

S3D is a comprehensive engineering and design environment capable of performing early concept development and concept comparison (weights, power demand, etc.), and high-level ship system tradeoff studies, as described in [1].

The current S3D environment contains tools for the development and simulation of the electrical, piping, and mechanical ship systems and the arrangement of the system components in the 3D ship model. S3D is currently capable of static power-flow simulation for all major disciplines, and includes the following design and evaluation tools:

1. Equipment library – A relational database tool that houses a set of notional and commercial off-the-shelf equipment that can be rapidly integrated into a ship design.
2. Naval Architecture Designer– A 3D visualization tool that permits the arrangement of equipment within a ship hull model ensuring physical fit of the conceptual design.
3. Mechanical Designer– A tool that enables the design and simulation of mechanical support systems.

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4. Electrical Designer – A tool that enables the design and simulation of electrical support systems.

5. Fluid Cooling Designer – A tool that enables the design and simulation of fluid cooling support systems.

6. Mission Analyzer - A module for the analysis of a design against a mission, facilitating performance comparisons between designs based on achieving the required mission parameters and overall fuel consumption.

7. Design Dashboard & Project Dashboard – Tools to parse metrics and simulation results for a design and for comparing multiple designs.

III. SHIP DESIGN

Threshold and objective performance requirements, shown in Table 1, were selected to guide the notional ship design and enable comparisons between the variants. In addition, a representative list of sensors, communications and weapons equipment was selected and the associated power and cooling system loads, efficiencies, weights and dimensions were compiled from publicly available information. The list of payload equipment is presented in Table 2 along with the associated maximum electrical power demand in MW during battle condition; details are available in [7].

A representative model using ASSET, the Navy's early-stage ship synthesis tool, was created to define the hull structure, propulsion power, vital and non-vital loads. Decisions made in the initial ASSET design are delineated below:

- A destroyer-type hull was selected and sized to achieve a hullform that would displace 10,000 metric tons at an appropriate draft and a superstructure was designed to maintain acceptable stability while providing sufficient area for shipboard equipment and height-of-eye for radars and the bridge.
- The payload items described in Table 2 were arranged on a skeleton ship to determine appropriate locations, and then entered into the Payload and Adjustments table of ASSET.
- A selection of three LM-2500+G4 engines at 29 MW each [2] and three LM-500 engines at 3.7 MW each [3] produce approximately 98 MW of installed power at Navy ratings. These engines were selected to provide a variety of power levels in different combinations, with the additional goal of totaling to approximately 100 MW. Note that this selection was heavily swayed by the 100 MW installed power requirement; there are other combinations of prime movers that may achieve better efficiency and performance for the given ship.
- The generator selection was combined with an Integrated Power System (IPS) and a dc Zonal Electrical Distribution System (ZEDS) using 5 MW power conversion modules (PCMs).
- Two 36 MW permanent magnet motors developed by DRS Technologies [4] provide the propulsion power required to achieve the designated sustained and cruise speeds.
- The manning complement was selected to be 243 personnel total including the air detachment.

TABLE 1: SHIP THRESHOLD AND OBJECTIVE PERFORMANCE.

Parameter	Threshold	Objective	ASSET
Installed Power	95 MW	100 MW	99 MW
Displacement	11,000 mt	10,000 mt	10,000 mt
Maximum Sustained Speed	27 kts	32 kts	30.5 kts
Maximum Battle Speed	25 kts	30 kts	27 kts
Cruise Speed	14 kts	16 kts	15 kts
Range	3,000 nm	6,000 nm	See text

TABLE 2: PAYLOAD LIST AND MAXIMUM ELECTRICAL POWER DEMAND IN MW AT BATTLE CONDITION.

Equipment	Max. Elect. Power Demand (MW)
Armament	
Railgun	17
LASER	1.2
Active Denial System	0.6
Vertical Launch Missile System	1
Command and Surveillance	
Multi-Function Phased-Array Radar	5
Integrated Topside (InTop), including Surface Electronic Warfare Improvement Program (SEWIP) and communications	4
Hull Mounted Sonar, Towed-Array Sonar	0.5

The ASSET algorithms are parametrically based on historical data, so the ship produced by ASSET assumes existing and past technology. It was expected that such a parametric-based conventional ship would be unable to fit the chosen payload, power generation and cooling equipment into a 10,000 ton hull; indeed, the initial ASSET process produced a balanced design but with an unacceptably low range. The goal of the design exercise was to examine the effects of possible ship system design variants on overall ship performance; one evident effect was a substantial increase in range as described in Section 6 below. See the right-hand-most column of Table 1 for the results of the initial ASSET run.

IV. BASELINE SYSTEM DESIGN

To create the baseline system design (as opposed to the ship design), the first step was to transfer pertinent data such as hullform, deck and bulkhead locations, speed/power curve, and total electrical and cooling load from ASSET to S3D. At this point, baseline, conventional distribution systems were created and analyzed and the newly identified components were placed in three-dimensional space using S3D.

The baseline power distribution architecture is a conventional split ring bus with four distribution zones. A simplified block diagram of the distribution system is shown in Figure 1. The primary distribution voltage is set to 10 kVdc

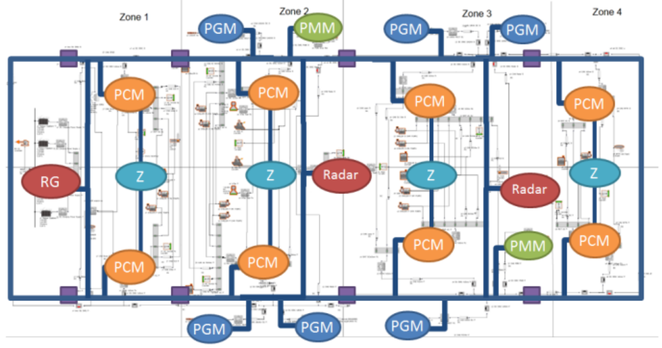

Figure 1: Baseline Electrical Distribution System Diagram.

(±5 kVdc) for the baseline design. Power is generated at 6.9 kVac; rectifiers co-located with each generator immediately convert power to the distribution voltage of 10 kVdc. Propulsion motors are connected to the ring bus on the side closest to the physical location of the motor, via a motor drive that provides 15-phase variable-speed ac power to the motors.

High-power mission loads (e.g. electro-magnetic railgun and RADARs) are supplied from both the port and starboard primary distribution buses via dedicated converters co-located with the loads. All other payloads and all vital and non-vital support loads are powered via converters located port and starboard within each zone. Vital loads are connected to both the port and starboard converters, while non-vital loads are provided a single source of power through only one in-zone converter.

Power conversion elements represent a significant portion of the size and weight of the electric power distribution system for the ship designs. Power conversion required in the baseline design includes:

- rectifiers for the prime power generation for dc distribution.
- dc-dc converters to step down the primary distribution voltage into the zones and for the RADARs.
- inverters for in-zone ac loads.
- dc charging power supplies for the capacitor-based pulse forming network.
- variable speed drives for the permanent magnet propulsion motors.

Dimensions and weights for conventional silicon power converter units were provided by [5], adapted from [6].

The thermal management system consists of a ring header with parallel supply and return lines. Six 1,100-ton chiller units are distributed among the four zones; this number of units resulted from the ASSET run which takes into account both water-cooled and air-cooled equipment along with personnel and ambient loads. Branches for each zone plus branches for rail gun, radars, and propulsion loads group the cooling loads. Piping elements consist of straight pipe, tee, and gate valve models. Tees are placed at each branch junction. Straight pipe connects tees, valves and components. Valves are included on each branch to regulate flow rates throughout the system. Figure 2 provides a graphic of the thermal management system.

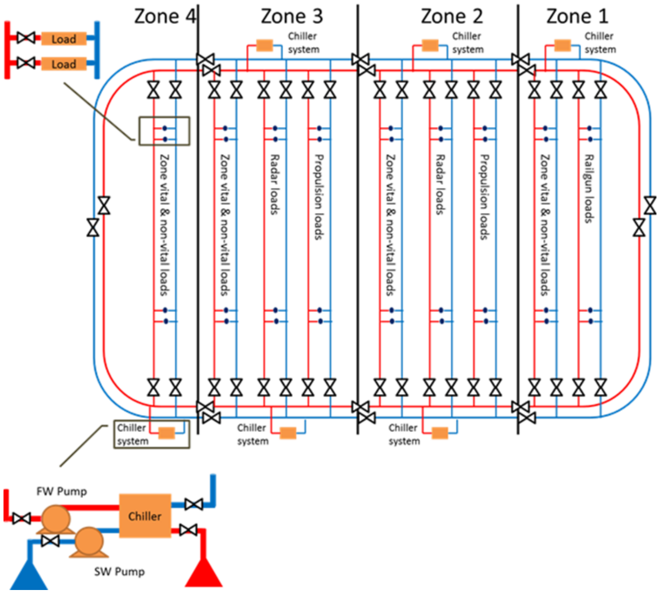

Figure 2. Baseline Cooling System Diagram.

V. DESIGN VARIANTS

We provide a quick overview of the design variants here; a full description of the baseline and variant designs can be found in [7].

A. High-Speed Power Generation

This design variant was explored to assess the ability of S3D to include the effects of a known technology improvement, in which a known machine is directly substituted for the comparable component in the Baseline Design. The Navy is currently evaluating the use of high-speed rotating electric machines to reduce the size and weight of these power system components. DC distribution systems are particularly well suited for high-speed power generation in that the high-frequency output of the generator is immediately rectified. This eliminates the need for synchronization of multiple generators and simplifies the integration of machines with different operating speeds and frequencies. DC distribution systems also allow the gas turbines to operate at their optimum speed for a given load, improving the overall efficiency of prime power generation at less than peak load.

There is a relatively minor increase in generator losses due to operation at higher rotational speeds and electrical frequencies; since data for the efficiency impact on the notional high speed generators was not available, the notional power level versus efficiency curve created for the baseline was modified to reduce the generator efficiency by 0.5%.

One-for-one substitution of the high-speed generators for the conventional generators and the subsequent evaluation of the system-wide effects through simulation was easily and rapidly accomplished in S3D, including the re-parameterization of a generator model to account for the changes in size, weight, speed and efficiency.

B. Advanced Materials

This design variant was explored to assess the ability of S3D to measure the ship-wide impact of changes in specific components within an unchanged topology; specifically, the converter equipment was assumed to be made of an advanced material that allowed increased distribution voltage, reduced losses, higher material operating temperature and reduced size and weight. There are several potential benefits from advanced power conversion technologies:

- Reduced Power Conversion Weight and Volume: the individual converters were assumed to take up less volume and have a lower weight for the same conversion power. This exercise demonstrated the cascading effects of the changes beyond just size and weight of the converters.
- Reduced Cable Plant: a higher distribution voltage reduces current required for a given power level. The reduced copper weight is partially offset by increased insulation requirements but the net effect is a reduction in the cable plant weight.
- Reduced Cooling Requirements: the higher temperature capability allows direct fresh water cooling of the converters as opposed to chilled water; this reduces the required number of chillers and the complexity of the thermal management subsystem, but showed slight increases in piping weight due to the inclusion of a fresh water cooling system in addition to the chilled water system. In addition, the higher efficiency of the devices required less cooling.

The changes to the power converters and the cables were easily made within S3D; similar to the high-speed generator change, this modification required only the re-parameterization of models to indicate the changes in size, weight and efficiency. The cable calculator was used to automatically change the cable weighting. However, the change to the cooling plant required a new cooling system design which was somewhat more labor intensive.

C. Alternate Topology

This design variant was chosen to investigate the effect of changing the topology of the power distribution system. A new zonal topology was developed loosely based on a proposed MVDC architecture circulated by the U.S. Navy [8]. This zonal topology uses cross-zone connections between ac load centers in adjacent zones to provide the required redundant power supply for mission loads and vital zonal loads and introduces several new component configurations and functionalities. A diagram of the alternate topology electrical distribution system is shown in Figure 3.

This design necessitated a new arrangement for the electrical and, to a lesser degree, the piping distribution system, so the redesign was more challenging than the previous variants. However, all payload and major electrical generation equipment along with some of the cooling equipment remained unchanged and was thus re-used from the baseline design (as is true of all the variants).

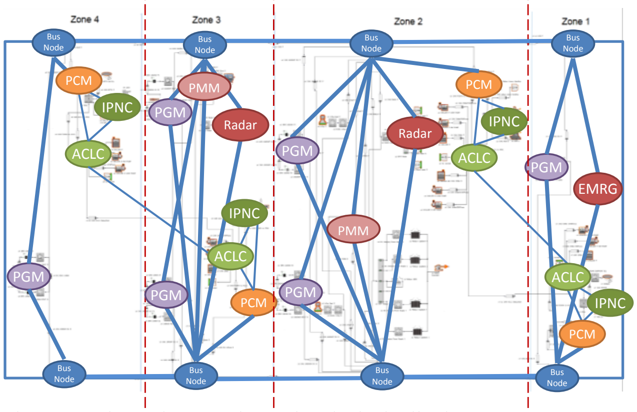

Figure 3. Alternative Topology Electrical Distribution System

VI. DESIGN COMPARISONS

S3D provides the ability to accomplish side-by-side comparisons of different design variants to evaluate the impact of advanced technologies. The design work in S3D was supplemented by corresponding analysis runs in ASSET, allowing the team to leverage the existing data and empirical algorithms for sizing of support structures and tankage that are not explicitly defined in S3D.

The design variable in this exercise was range, which is the distance a ship can travel without refueling at endurance speed with a representative electrical load. Any decrease in equipment weight allowed an increase in fuel load, thus increasing range, and any increase in efficiency caused less fuel to be used for an equivalent load, thus also increasing range. Increases in weight and decreases in efficiency obviously had the opposite effect. Since the overall ship weight and trim were maintained constant, changes in equipment had no effect on ship resistance.

A. Weight

The Ship Work Breakdown Structure (SWBS) is a numbering system used by the Navy for categorizing equipment and systems and the work, information and support provided to them; we use this system to display our results. Table 3 shows a comparison by three-digit SWBS group of the change in weight from the baseline. Some SWBS groups are not affected by the changes induced in this exercise, e.g. rudder weight, so those weights are not included in Table 3. We explore the weight changes for each variant below.

In the High-Speed Generator Variant, the only change to the ship was a swap of the regular gas-turbine generators for high-speed generators; therefore the only weight group that changed was SWBS 311, which includes power generation and conversion equipment.

In the Advanced Materials Variant, the power generation and conversion weight group changed as expected because all of the power conversion equipment was lighter. There is also a change in the propulsion weight group because the propulsion

TABLE 3: WEIGHT CHANGES FROM BASELINE, IN METRIC TONS, BY SWBS GROUP FOR EACH VARIANT.

SWBS Group		**Reduction from Baseline (mt)**		
		High-Speed Generator	***Advanced Materials***	***Alternate Topology***
235	Propulsion	-	3.7	-
311	Power gen. & conversion	207.7	20.6	36.6
321	Cabling	-	19.5	(37.8)
324	Switchgear	-	-	9.8
514	Chilled water equipment	-	76.9	-
532	Piping	-	20.5	2.5

motor drives are lighter. The advanced materials enabled a higher voltage distribution bus, which caused the cabling to be lighter as shown in weight group 321. Finally, all the conversion equipment was allowed to operate at a higher temperature, resulting in lower weights in the chiller equipment and piping SWBS groups.

In the Alternative Topology Variant, a reduction in the number of converters and switchgear for each zone resulted in a reduction in the overall weight for power generation and conversion equipment, even though the remaining converters had to be increased in size to accommodate the increased per-converter power demands. There was also a small reduction in weight for chilled water piping because the removal of some liquid-cooled converters also removed the piping routed to them, although the piping routed to the remaining converters increased in size due to the increased power load and corresponding heat load. Interestingly, there was an increase in the cabling weight because the cross-connect cable from one zone to the next was at the low voltage of the in-zone cabling and was therefore substantial; the two cross-connect cables weighed a total of 43 metric tons.

B. *Number of Components*

The number of components for a specific design or for subsets of the design such as equipment type or SWBS number may be used as an indicator of complexity of the design as long as the designs are at an equivalent level of fidelity. The total number of components modeled in all the S3D variants is shown in Table 4. The number of components in the alternate topology variant is much lower than the other variants, reflecting the much reduced complexity of the design.

C. *Power Demand, Cooling Required and Fuel Consumption*

S3D was also used to evaluate the designs based on quasi-static mission simulations to capture the effects of time-dependent performance parameters such as fuel consumption and range. The S3D mission analyzer calculates total fuel consumption based on the duration of the mission segment, the mechanical power output required from the gas turbines to drive the generators, and the specific fuel consumption (SFC) characteristics of the engine.

TABLE 4: NUMBER OF COMPONENTS REPRESENTED IN S3D.

	Baseline	**High-Speed Generator**	**Advanced Materials**	**Alternate Topology**
TOTAL	873	873	867	806

TABLE 5: MISSION SEGMENT ALIGNMENT SUMMARY.

Mission Segment	**Speed (kts)**	**Duration (days)**	**Weapons**	**Sensors**	**Vital Loads**	**Non-vital Loads**
Peacetime Cruise	15	90	Off	Med	Med	High
Sprint to Station	32	1	Med	High (select loads)	High	Med
Battle	8	7	High	High	High	Med

For the purposes of this study, a three-phase mission was created consisting of a peacetime cruise segment, a sprint to station, and on-station operations. The speed and load settings for each mission segment is summarized in Table 5.

The results of the mission analysis are presented in Table 6. Although the total fuel consumption is very close among the variants, less than 0.5% difference overall, the differences bring out interesting features of the designs, as described in the following.

TABLE 6: MISSION RESULTS.

	Mission Segment	**Baseline**	**High-Speed Gen.**	**Adv. Mat.**	**Alt. Top.**
Fuel Consumed Segment (kl)	Peacetime Cruise	23,164	23,171	23,095	23,264
	Sprint to Station	332	334	329	338
	On Station	1,808	1,809	1,804	1,810
	TOTAL	25,304	25,314	25,228	25,412
Ellect. Power Demand (MW)	Peacetime Cruise	22.985	23.012	21.587	24.047
	Sprint to Station	43.488	43.689	42.611	44.525
	On Station	23.727	23.756	22.842	24.422
Mech. Power Demand (MW)	Peacetime Cruise	3.442	3.442	3.442	3.442
	Sprint to Station	29.074	29.074	29.074	29.074
	On Station	0.544	0.544	0.544	0.544
Cooling Required (MW)	Peacetime Cruise	12.262	12.354	11.764	12.410
	Sprint to Station	9.280	9.505	8.471	9.398
	On Station	12.610	12.711	12.107	12.830

High-Speed Generator: The slightly lower efficiency of the generators should be and is reflected in a higher electrical demand, a higher liquid cooling requirement, and a higher fuel consumption. The decreased generator efficiency was 0.5%; however, the changes in electrical demand, liquid cooling and fuel consumption are not exactly 0.5% because there is also an increase in power to the chillers and pumps, which is slightly counteracted by the gas turbine operating at a somewhat improved SFC due to the increased power demand.

Alternate Materials: The differences between the baseline and the alternate materials variant include improved efficiency of all converters and reduced power for cooling equipment. This is reflected in the lower fuel consumption, lower electrical load, and lower liquid cooling requirement.

Alternate Topology: The alternate topology arrangement operates at the same efficiency for the converters and with the same cooling paradigm as the baseline; however, there are differences in the number of converters through which power flows in this arrangement. Although the S3D converter models allow efficiency to vary with load, in this simulation, all converters are set to a level 98% efficiency regardless of power flow. In the alternate topology arrangement, all power to in-zone dc loads flows through two converters between the main bus and the load instead of just one converter in the other topologies (the in-zone dc-dc converter). Therefore, all in-zone dc loads draw more power from the generators in the alternate topology variant than in the baseline and the alternate topology should operate at a slightly lower overall efficiency. This difference will be more noticeable when the total electrical load is more heavily weighted by in-zone dc loads; propulsion, ac loads, and major mission loads have the same efficiency as the other topologies in this study.

Mechanical Power: The mechanical power demand is identical across all four variants analyzed; this is as expected because the speed, power train and ship resistance are identical across all four variants.

It should be noted that fuel consumption is significantly affected by the relative loading on generators due to the shape of the specific fuel consumption curves. In general, two equally-loaded gas-turbine generators will consume much less fuel than one lightly-loaded generator and one heavily-loaded generator, since a gas turbine at light load is extremely inefficient. This must be recognized during the comparison of mission scenarios across ships to ensure the differences seen in fuel consumption are due to the installed equipment and not to the operational choices.

A second analysis was accomplished to assess the impact of single-generator operations. The peacetime cruise segment was duplicated for all four designs, operating with a single generator online; the resultant power fuel consumed was approximately 60% of the fuel consumed under two-generator operations, a significant reduction.

D. Range

The range a design can attain is determined in S3D by running the ship model, set in a fuel efficient configuration, through a long-duration mission and noting the distance achieved when the ship runs out of fuel.

TABLE 7: FUEL LOAD FOR RANGE CALCULATION.

	Baseline	**High-Speed Generator**	**Advanced Materials**	**Alternate Topology**
Equipment Weight Saved (mt)	--	207.7	141.2	11.0
Fuel Weight Added (mt)	--	303.5	182.7	25.7
Total Fuel Weight (mt)	23.9	327.4	206.6	49.6
Fuel Volume (l)	28,092	384,814	242,830	58,298

The premise of this study is that total ship displacement is held constant at 10,000 metric tons. Any weight savings realized through advanced concepts were replaced with fuel. The analysis conducted within S3D calculates weight changes of the actual equipment modeled; however, there are also other associated weight changes such as foundations, ship structure, and operating fluids. To estimate these additional changes, the S3D equipment weight changes were input into ASSET using the Payload and Adjustments table in order to use the ASSET algorithms to calculate the changes in foundations and other support and the changes in structural and tankage weight for the additional fuel load. These values are displayed in Table 7.

The fuel tank levels in S3D were set to the amount of fuel available excluding the tailpipe allowance, as calculated by ASSET. The ship speed was set such that the combined speed/power curve and propulsion efficiency produce the highest combined efficiency. For the designs studied, this occurs near 20 kts. Each design was configured with identical power generation (one LM2500 online), and identical hotel and mission load settings.

Cooling systems were configured identically for all but the Advanced Materials design. The Advanced Materials design's cooling system is different than the other three designs, but was configured to be as similar as possible to the others.

The range and steady state power demand results for the range mission using these fuel tank levels and ship configurations are shown in Table 8.

TABLE 8: RANGE AND STEADY STATE POWER DEMAND RESULTS FOR RANGE MISSION.

Design	**Range (km)**	**Fuel Cons. Rate**	**Electric Demand (MW)**	**Mech. Demand (MW)**	**Cooling Required (MW)**
Baseline	140	1.81	28.447	9.698	9.778
High-Speed Generator	1913	1.81	28.496	9.698	9.923
Advanced Materials	1240	1.77	27.508	9.698	9.17
Alternate Topology	286	1.84	29.25	9.698	9.951

VII. RECOMMENDATIONS FOR FURTHER TOOL DEVELOPMENT

The currently existing S3D design environment provides arrangement, connection and load-flow-level simulation of the systems. The tools all function well and the integration between the tools is seamless. As the tools were exercised, the following recommendations for improvement to the tools were noted.

Electrical Designer: At present, the Electrical Designer provides the cable calculator algorithm with an electrical current value for sizing the cable. It was determined during this exercise that the cable sizing should be based upon a different algorithm than that which currently exists inside S3D.

Piping Designer: Automatic sizing of piping is needed for rapid design and evaluation of piping systems. There has been preliminary work in this area within ESRDC, see, e.g., [9].

Mechanical Designer: S3D does not currently support the concept of multi-function machines, i.e. components that can perform differently based on the plant alignment and operational conditions, e.g. electric machines that operate either as motors or generators. These are needed for designs such as a possible mechanical-electric hybrid design.

HVAC Designer: Since the HVAC Designer was not completely available for use at the beginning of the project, it was not employed in this analysis. Initial use has indicated that the design tool may provide better analysis if implemented in a three-dimensional simulation at the compartment level. Work accomplished in [10] may be applicable to this effort. Development of tools to support the design of gas turbine intakes and uptakes is also underway.

Naval Architecture Designer: The naval architecture designer has many features that enable the placement and viewing of equipment, including such things as “fall to deck,” “quickhide” and viewing equipment filtered by deck location. Two specific features further would improve usability: The ability to detect and flag collisions between equipment and other equipment or ship structures such as hull and bulkheads would assist in the arrangement of equipment. The ability to hide and view subsets of equipment, such as by equipment type or SWBS, would facilitate the arrangements and error-checking procedure.

Mission Module and Controls: The current Mission Module requires manual system configuration for each design, prior to running a mission analysis. This is labor intensive, potentially prone to error, and can result in non-optimal configurations. Automated optimized system configuration (i.e. high-level controls) are required to reduce the time to prepare to run a mission, reduce the risk of user error, and to ensure that designs are fairly evaluated.

Data Availability, Scalable Models, Verification and Validation: One superb feature of S3D is the ability to draw components from the equipment library and use them directly in designs. When a specific component at the specific desired design point is not available in the library, a scalable model or a notional model can be used. The use of a scalable model of a component is preferable to the use of a notional model because the scalable models include physics-based algorithms for sizing of components based on the use case; however, development of scalable models requires significant effort to establish, validate and verify the proper scaling laws.

Aggregated Loads and Assemblies: At the very early stages of design when the level of detail is low, it is desirable to use representative loads and components that amalgamate the functionality and impact of many smaller components. The current design exercise relied on ASSET models to capture the weight and volume of the “balance-of-plant” elements of the ship power system; these elements were included as lumped vital and non-vital zonal loads designed to represent the power and cooling demands of a wide range of small loads that were not individually modeled, e.g. lighting, hotel loads, firefighting equipment, etc. Support equipment for weapons and sensors were also represented as single components although some represent multiple cabinets and enclosures containing equipment that performs multiple functions. In addition, some or all components that are individually modeled in S3D actually comprise assemblies of many small components, e.g. a gas turbine generator includes the gas turbine, shaft, generator, lube oil pumps and piping, fuel oil service, fans, enclosure, and more.

As the design progresses, these aggregated loads and assemblies should be modeled more explicitly in the S3D designs to accurately reflect how the equipment can actually be packaged most effectively and to analyze performance in more detail. Obviously, there must be a balance between complexity and accuracy. When breaking an aggregated item into constituent parts, every constituent part may not necessarily be individually modeled. The process of determining how much weight, volume, power, cooling, etc., must be included in the amalgamated loads and how much must be removed when portions of the amalgamated load are modeled is a challenging question that requires more investigation.

Margins, Allowances, Uncertainty and Risk: With the exception of the cable sizing algorithms, the ship system designs created in S3D for this effort did not include any margins or allowances, which led to a discrepancy when comparing S3D data to ASSET data. A method for determining and using margins and allowances as well as consideration of the impact of risk and uncertainty are needed.

Semi-Automated Design Assistance: There are several areas in which design assistance would be valuable to the system development process. One concept that would significantly speed system development, the creation of templates that can be reused and modified from one design to the next, is under development within the Navy, with ESRDC support.

VIII. CONCLUSIONS

This design exercise successfully designed and analyzed a baseline electric ship and several variants, exploring multiple effects of the variations beyond the mere change in the specific equipment such as changes to bus voltage and the effect on cable size, changes to efficiency and the effect on cooling plant capacity, and so on, and elucidating interesting aspects of the designs. Therefore, this exercise demonstrates the utility of S3D in the early stages of ship design. In the process, several recommendations to further improve the performance of S3D were recognized and documented.

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