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Early-Stage Assessment of the Impacts of Next Generation Combat Power and Energy Systems on Navy Ships

ABSTRACT

The newest suite of weapon and C4I systems for the next generation of Navy ships will have electrical power requirements far greater than any current design. As of today, the Navy does not have processes or the tools for addressing the coupled problems of high power electrical system design, control, and vulnerability analysis. The task of formalizing a process and developing requirements for these necessary tools has been assumed by the Design Tools and Methodology Working Integrated Product Team (DTM WIPT) as part of the Navy's Combat Power and Energy Systems Overarching Integrated Product Team.

This paper presents one of the processes developed by the DTM WIPT which utilizes the concept of ship distribution systems "patterns and templates" combined with a process for design space exploration of ship platforms. The use of system patterns and templates is enabled by the newly developed Smart Ship Systems Design (S3D) tool, and design space exploration is facilitated by the Rapid Ship Design Environment (RSDE), the Advanced Ship and Submarine Evaluation Tool (ASSET), and the Leading Edge Architecture for Prototyping Systems (LEAPS). The envisioned process will be described in detail and anticipated impacts of the process will be presented. The paper concludes with a description of the near- and long-terms plans for the Navy's suite of design tools in regards to novel distributed system architectures.

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INTRODUCTION

We are entering an age where power and energy requirements will fundamentally change the way we design and engineer ships. This is being driven by systems with high power electrical components like lasers and railguns. Ships cannot support these high energy systems with very large pulse loads without modifications to the ship's electric power plant, energy storage, and other complementary and supporting ship systems.

Within the next four years, a new high energy system will come online every two years. These systems will rely on common enabling technologies like next generation power converters and energy storage devices. The Navy has realized that streamlining integration efforts of these common systems is paramount to success. Without a focused effort to develop a common integration approach, the developer of each system will be required to develop his or her own integration solution – with adverse size, weight, cost, complexity, and maintenance impacts. To this end, the Combat Power and Energy Systems Overarching Integrated Product Team (CPES OIPT), under the leadership of PEO SHIPS and NAVSEA 05, was formed.

The CPES OIT has two major functions. For Today's Navy and Tomorrow's Navy, it will provide a path to ship integration for high power and energy weapons and sensors for both existing and future ships by coordinating efforts and resource. For the Navy After Next, it will provide a path for identification, development, and demonstration of technologies leading to a fully integrated power and energy system.

The CPES OIPT found that a lack of coordination between the different high energy system design groups lead to:

- Stove piped approaches producing only point solutions
- Redundant approaches on the same platform
- Unnecessarily complex system integration
- Overstretched technical resources
- Increased acquisition and support costs

The goal is to move towards a more coordinated effort with an integrated approach for high energy systems design that identifies overlaps and gaps in development efforts and seeks to find the most affordable, common solutions. The CPES OIPT is the first step towards this goal. By bringing together a diverse spectrum of organizations within the modernization, new construction, resource sponsor, and research and development communities, the CPES OIPT allows these disparate groups to share lessons learned, leverage investments, seek common solutions for similar issues, and coordinate schedules and budgets.

The CPES OIPT was broken into six smaller Working Integrated Product Types (WIPTS): Business Operations and Costing, Power Systems and Technical Architecture, Requirements and CONOPS, Mission System and Characterization, Ship Systems Engineering and Platform Integration, and Design Tools and Methodology (DTM). The remainder of this paper will focus on the DTM WIPT.

The DTM WIPT was created to coordinate with the Office of Naval Research, NAVSEA 05D, NAVSEA 05T, and PMS 320 to develop, plan, and highlight the funding requirements for updating the Navy's design tools to accommodate advanced power and energy analyses. The DTM WIPT was also tasked to indentify other tools and design approaches that may be required to integrate these analyses into the Navy's design process.

The requirements for high energy pulse load mission systems will require new design methodologies and modeling and simulation (M&S) tools. These M&S tools must support concept design for both platform and system architecture studies. Preliminary design studies will require real time electric and control system M&S capabilities including power mission systems and hardware in the loop options for critical capabilities for all platform variants. Many of these tools do not exist.

This paper will detail some of the M&S findings of the DTM WIPT within the concept and early preliminary design phases with respect to ship design and power and energy system architecture. Namely, it will introduce the "Pattern and Template" approach for designing and determining the representative costs for advanced power systems. Next, the paper will detail the capabilities of a number of the Navy's design tools (LEAPS, S3D, ASSET, and RSDE). The paper will then propose a methodology for combining the pattern and template distributed systems design approach with the Navy's design tools that allows for both point-based and set-based design.

SHIP SYSTEM PATTERNS

A ship system pattern is a non-ship specific instantiation of a ship system technical architecture (Medium Voltage DC, Medium Voltage AC, etc.). Figure 1 shows an example of a six zone, ring bus, Medium Voltage DC power distribution system pattern. In this section the focus is on electrical systems, but the pattern concept applies to any distributed system discipline.

At the highest level a system pattern is defined by the technical architecture requirements it is derived from and its number of system zones, which are typically related to the number of ship subdivision zones. Each system pattern is intended to provide system topology, provide component placement information at the zone level, and associate the system with a technical architecture. The associated technical architecture will provide the design practices and criteria, specifications, and standards based on the type of power system.

The bus voltage and bus type (cable, bus duct, etc.) should be common between all zones. In accordance with best practices, all auxiliary generators, main generators, shore power conversion modules, and propulsion motor modules should be common across all zones. Auxiliary propulsion modules are not required to be common, depending on their application.

Each electrical zone can be unique in its number of auxiliary generators, main generators, shore power conversion modules, propulsion motor modules, and large or pulse electronic loads. System patterns can either be fixed, where the number of components is not adjustable, or flexible where the number of components is adjustable.

Each pattern will include the types of equipment in each electric zone, but will not specify the model of that component, i.e., Zone 4 has two gas turbines vice Zone 4 has two Rolls Royce MT30s.

The intermediate step of creating patterns before sizing any components is necessary because design practices and criteria are not defined for new technical architectures like Medium Voltage DC systems. It is necessary to have a model that can cope with significant uncertainty until rules are created. For more established technical architectures like MVAC systems, current modeling capabilities do not account for energy storage or pulse loads. Modeling capabilities are also lacking for zonal designs, control system properties, high power loads, and propulsion options.

The Patterns Approach is intended to be used in the pre-study phase of an acquisition program. These pre-studies serve to narrow the options considered in concept exploration by providing insight about which design options are *unlikely* to be viable solutions.

By removing these dominated solutions before any component sizing has occurred, the entire concept exploration phase can be accelerated as

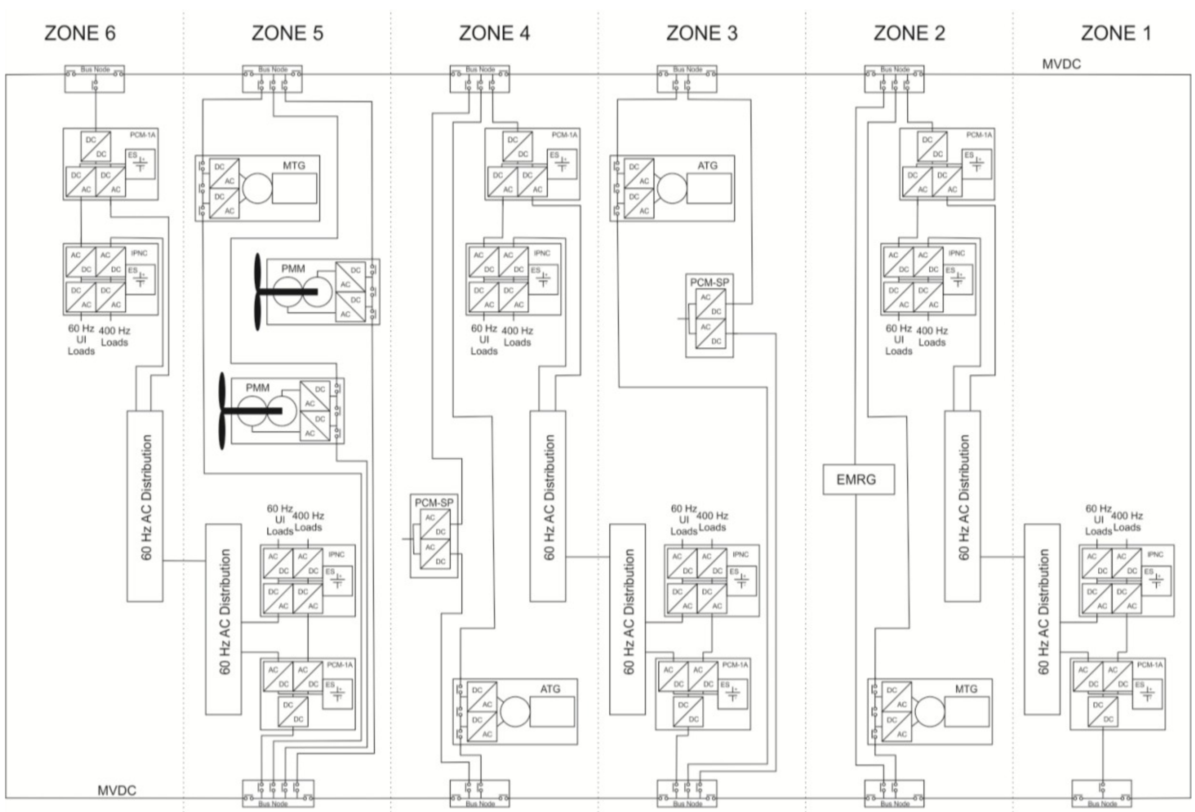

Figure 1: A six electric zone Medium Voltage DC System Architecture Pattern. Notice no specific equipment models have been called out, only the type of equipment required in each electric zone.

it can be focused on just those options which are likely to succeed. Additionally, these pre-studies can inform behavior models and be used to develop synthesis algorithms for sizing those options which are feasible.

Using the patterns requires a way to create 2D system schematics that can be analyzed to make sure all the requisite components are present and properly connected. To transition the patterns to templates one must prescribe values to the previously notional system components and analyze the feasibility of the system. To do an actual concept study that template then needs to be transitioned into a ship design and holistically analyzed to determine the whole ship impacts and feasibility. And for any part of this process to be adopted, this all must easily and quickly achieved

The next section of this paper will discuss how four Navy developed design and analysis tools can be used exactly for this purpose.

S3D

The Smart Ship Systems Design (S3D) tool is one of the products created by the ONR funded Electric Ship Research and Design Consortium (ESRDC). The ESRDC was tasked to research and subsequently develop a collaborative, concurrent, web-based environment for the design of Navy ships, which became S3D (Andrus, et al., 2013).

Though S3D was originally developed as a web-based tool, the realities of the Navy's design process and the desire to integrate S3D with Navy's suite of design tools (the LEAPS software environment) and security requirements made it necessary to develop a standalone desktop version of the tool (Chalfant, Ferrante, & Noble, 2014; Chalfant, Ferrante, Chryssostomidis, & Langland, 2015). While converting to a standalone tool made the collaboration features of S3D superfluous, migrating from an SQL Server for persisting design information to a LEAPS database format allowed for the sharing of design information between LEAPS applications, especially S3D, ASSET, and RSDE.

Additionally, S3D requirements helped to formalize the definitions of ship systems within the LEAPS ship product model, known as the Formal Object Classification for Understanding Ships (FOCUS). Formalizing the system definition allows the user to quickly define and connect systems and assists the creation of models for higher fidelity deactivation and survivability analysis (Dellsy, Parker, & Rigterink, 2015).

S3D is comprised of a number of tools that support various engineering disciplines with the design and analysis of electrical systems, mechanical systems, and air and liquid cooling systems, as well as the arrangement of equipment in 3D space from the naval architect's perspective (Chalfant, Langland, et al., 2015).

S3D can be used to implement the ship system patterns approach in a four step process. First the necessary components (both notional and actual) and their associated solvers would need to be created. Next, systems patterns containing notional components with logical connections are made. These patterns are then populated with additional component and connection data to create a system template. This includes replacing the notional components with their real world counterparts, if they are available. If the design requires a component with attributes not yet available then it will be left as a notional component. The template is then simulated to test feasibility and corrections are made until a feasible system is created. Finally, the user can attempt to place the system within a ship model and again can test the system for feasibility, this time including additional losses due to cable lengths and piping runs. The remainder of this section will cover, in more detail, the aforementioned four phases.

Component Creation

A user would first create the components (generators, gas-turbines, etc.) necessary for modeling the candidate systems. To fully model a component the user must assign a weight, an area and volume requirement, and model the component's electrical, mechanical, and thermal behaviors. Fuel requirements for engines must also be defined.

The user is provided with a number of simulation models for common components like electric motors or gas turbines. These computational solvers characterize the behavior of a component during simulation. Component attributes or properties are used to provide static properties like weight or simulation parameters for each component. These provided components come in two types. The first type is notional components where the user is free to modify the component values, for example creating a hypothetical gas turbine that produces 25,000kW but only weighs 10t. The second type, actual components, represent real products like a GE LM2500 which has locked output production of 24,050kW and a weight of 90t, per manufacturer's specifications.

For next generation components, like Power Electronic Building Blocks, where a simulation model is not already available in S3D, the user would need to code that component's simulation model(s), associate the model with the component, and place it in a LEAPS catalog for use by S3D.

Pattern and Template Creation

To create a system pattern and then a template, the components must first be connected together logically in a schematic view, similar to what has been shown in Figure 1. S3D can be used to create this logical connection in the electrical, mechanical, and thermal fluid domains.

During the pattern creation process, the components are connected using logical connectors rather than specifying wires, cables, shafts, or pipes. Additionally, a majority of the components will not be defined beyond their name and basic properties. Even at this limited level of fidelity, the system pattern can be tested for consistency of things like electrical power type (AC vs. DC) or fluid flow direction.

Once a pattern has been defined with all connections and component placeholders, the user will adapt it to his or her design by replacing the notional components with actual components, to the extent possible. It is highly likely that S3D will be used for future concept studies where there is no actual component that will meet certain requirements, so a notional component will need to be used. At this time, the user would be required to enter all component properties, but in the near future a property estimation tool will be available, thereby allowing the user to specify a few critical properties and then let the tool fill in the remaining properties.

During the template creation process, the user can intermittently simulate the systems at whatever levels of detail are available and adjust properties accordingly. For example, the electrical simulation can be run once all the components are placed, but without calling out the cable properties. If a load is not receiving sufficient power before the cables are included then the user will know that the generating capabilities need to be increased.

The goal is to create a large number of agreed upon patterns that can be distributed with the S3D software so that the designers can for the most part skip the pattern creation step and immediately begin the component assignment process necessary to convert a pattern to a template. It may even be possible to distribute a number of templates so that users can move directly to the component placement process.

Component Placement

Once a template has been created, it is necessary to simulate it to prove that the right components and connections exist in the system, and the system is feasible in a schematic context. While physically arranging components in the 3D naval architecture view is not required for simulation, it is incomplete without it. Creating the physical connections allows S3D to analyze the effects of things like cable length on impedance and calculate the length of the propeller shafts. Placing the components also arranges and associates structural subdivision zones with electrical or other system zones.

The arrangement and placement of components in a ship requires the existence of a LEAPS ship concept. While any tool can populate a concept to a LEAPS database, but in general, S3D assumes that the concept was populated by ASSET, and therefore includes structural subdivisions, deckhouse, propellers, and prime movers. The structural zones, as generated by ASSET, will provide arrangement boundaries for S3D.

Once all components are placed, the user can run an electrical, mechanical, or thermal fluids load-flow simulation to determine if all the components are receiving their required power and cooling. Additionally, the user can run the simulation for a specific discipline at any time during the process of creating the system architecture model. A *system architecture*, as defined within this process, is the 3D arrangement of all components and the subsequent refinement of component properties needed for successful simulation.
At this time S3D only performs a steady state analysis, intended for early-stage conceptual design. This is consistent with other early-state system design practices. The possibility of adding dynamic, time domain analysis and controls systems simulations is currently being explored.

Once a system architecture has been created in S3D it is necessary to assess its impact on the ship platform for which it is designed. Thanks to LEAPS integration, a system model (whether or not it is created around a specific ship) can be easily imported into an existing LEAPS ship concept and the impacts can be analyzed via ASSET or any of the other LEAPS tools.

LEAPS

The Leading Edge Architecture for Prototyping Systems (LEAPS) is a development framework that supports virtual prototyping and analysis of conceptual and preliminary ship designs through integration of many design and modeling and simulation tools. The LEAPS Application Programming Interface (API) contains a set of generic data classes that describe physical and/or functional representations of engineered products.

As mentioned earlier, the FOCUS product model is the specific object formalization for defining a surface ship. FOCUS formalizes the physical and functional characteristics typical of a ship using the available LEAPS classes. Adherence to FOCUS is what ensures all LEAPS applications (shown in Figure 2) can read and write to a LEAPS database and use consistent values during the design and analysis process. One way to think of the relationship between

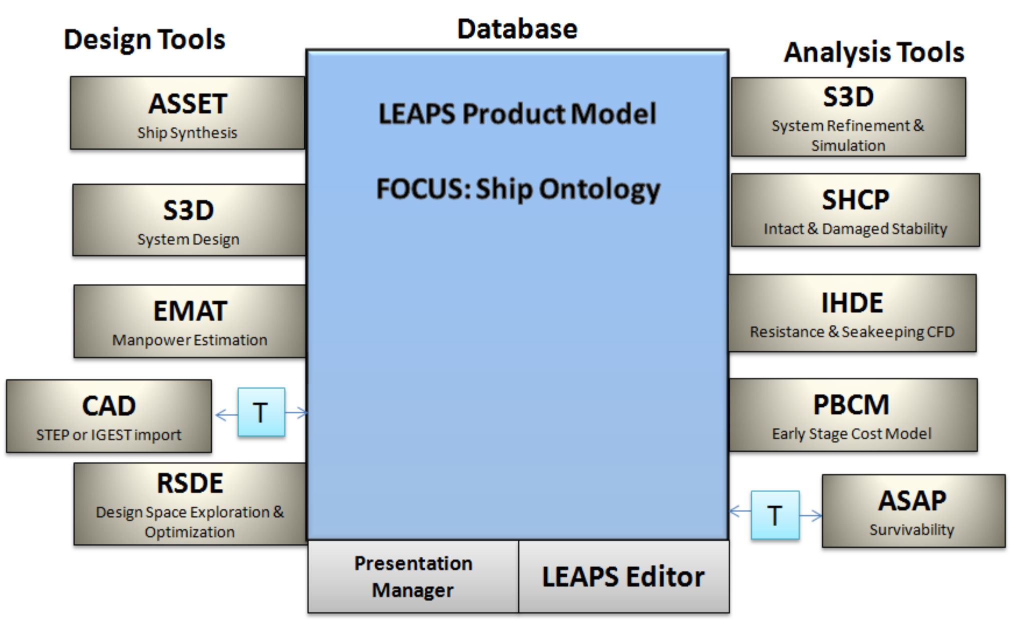

Figure 2: The LEAPS Software Environment

LEAPS classes and FOCUS objects formalization is to draw a parallel between the alphabet (classes) and English (formalization). LEAPS also has formalized object ontologies for air vehicles (AIRSOM) and submarines (SUBSET).

LEAPS applications are typically divided into two groups: design tools and analysis tools, as shown in Figure 2. While the design tools contain both modeling and analysis they provide the bulk of the data used to populate a ship concept into the LEAPS database. Analysis tools are used to simulate and record the behaviour associated with those representations. The tools are represented here for convenience left to right because analysis ususally depends on data created by the design tools. No directionality is implied and no tool communicates to any other tool except through LEAPS data.

The three LEAPS tools that are the focus of this paper are the aforementioned Smart Ship Systems Design (S3D) tool, the Advanced Ship and Submarine Evaluation Tool (ASSET), and the Rapid Ship Design Environment (RSDE). RSDE and ASSET are considered Design Tools while S3D has both a design and analysis component.

ASSET

The Advanced Ship and Submarine Evaluation Tool (ASSET) is the Navy's concept design ship synthesis tool. At the time of writing, ASSET is undergoing a major change in philosophy and work flow. In previous versions of ASSET (up to and including version 6.3) the user entered a set of ship design parameters and then ran a synthesis algorithm which modified the design until a converged ship was produced. This point-based design process is depicted in the upper portion of Figure 3.

The criteria for convergence were a basic stability check based on the GMT to beam ratio, a buoyancy check, and the numerical stability of hundreds of other ship parameters, i.e., over two successive iterations of the synthesis process all calculated ship parameters did not vary by more than a set, infinitesimally small amount. By and large users were leery of the synthesis process and complained about ASSET changing parameters of the ship that they did not wish to be changed.

In response to this feedback, future versions of ASSET (version 7.0 and on) will not have a strong emphasis on automated synthesis. Now, users will be able to change the parameters of the design they wish to be changed and then evaluate what effects that change had on the design. This "User in the Loop" process is depicted in the lower portion of Figure 3.

The users will be aided by a series of "Design Processes" which will assist in modifying the design to meet a number of commonplace naval architecture requirements, namely:

- Area Balance - a process to make the design's deck area equal to that required by the mission and support systems.
- Speed-Power Balance - a process to select the appropriate engines or modify the hullform such that the ship meets a user set speed requirement.
- Design Waterline - Load Waterline Balance - a process to make the full load waterline equal to the original user specified hull design waterline.
- Range Balance - a process to ensure a design meets its required range by modifying tankage and hullform.
- Stability Balance - a process to ensure a design meets it stability requirements by modifying hullform and load placement.

In addition to deemphasizing automated ship synthesis, ASSET 7.0 and beyond will natively store all design information in a FOCUS model as part of a LEAPS database so that all other tools within the LEAPS environment can access that information. Previously, ASSET models needed to undergo a conversion process to make them FOCUS compliant. This conversion was often unstable and time consuming, and any changes made to the ship's model outside of ASSET would not be reflected in the ASSET model.

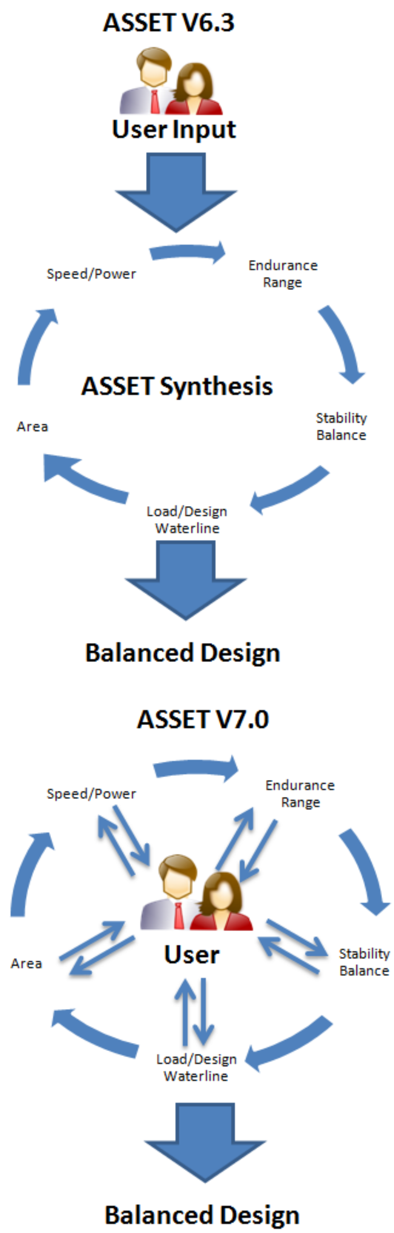

Figure 3: A comparison of the ASSET 6.3 and ASSET 7.0 design processes.

The use of the LEAPS database for storing the ASSET model also means the ship's hull and structural geometry are now saved as Non-Uniform Rational B-Spline (NURBS) surfaces (a standard way of representing 3D geometry in CAD programs) instead of as a series of offsets and stations. This means the ships 3D geometry is captured at all times, which will simplify the transition from an ASSET model to CFD or FEA tool.

At least initially, the next generation of ASSET will be a much more user intensive process, but it will allow the users much more flexibility and control over which ship parameters are being modified. This additional control is the lynch-pin of the integration of ASSET with S3D.

RSDE

The Rapid Ship Design Environment (RSDE) is a computational tool that allows users to harness the capabilities of ASSET and other LEAPS applications to perform Design Space Exploration (DSE). RSDE facilitates DSE through the use of Design of Experiments (DoE). DoE is the formal strategy of developing a collection of experiments in which a set of design variables are varied in a systematic manner. The purpose of which is to predict, and discover, the relationships between design variables and responses.

The current version of RSDE (version 1.2) uses ASSET 6.3 as its ship synthesis engine. Future versions of RSDE (version 2.0 and beyond) will use ASSET version 7.0 for ship synthesis and incorporate other LEAPS applications for additional analysis.

A typical RSDE workflow is shown in Figure 4. The process begins with a user creating a baseline ship design in ASSET and selecting which design variables he or she would like to vary. For continuous variables (e.g., length, beam, and endurance speed) the user selects the range that the inputs will be varied over. For discrete variables (e.g., specific engine models, stiffener sizes, and plate thicknesses) the user selects a set of potential alternatives to the baseline variable.

From there the user chooses the number of designs he or she would like RSDE to create and then populates the design space either with user specified design points (where the user chooses the values of all the variables) or via a Latin hypercube sampling method. RSDE then synthesizes the desired number of designs and runs each design through the requested analyses and stores all the data in a LEAPS database.

Once the set of points is created it is the task of the user to create behavior models to explore relationships between inputs and outputs and produce the visualizations necessary for conveying the information to decision makers.

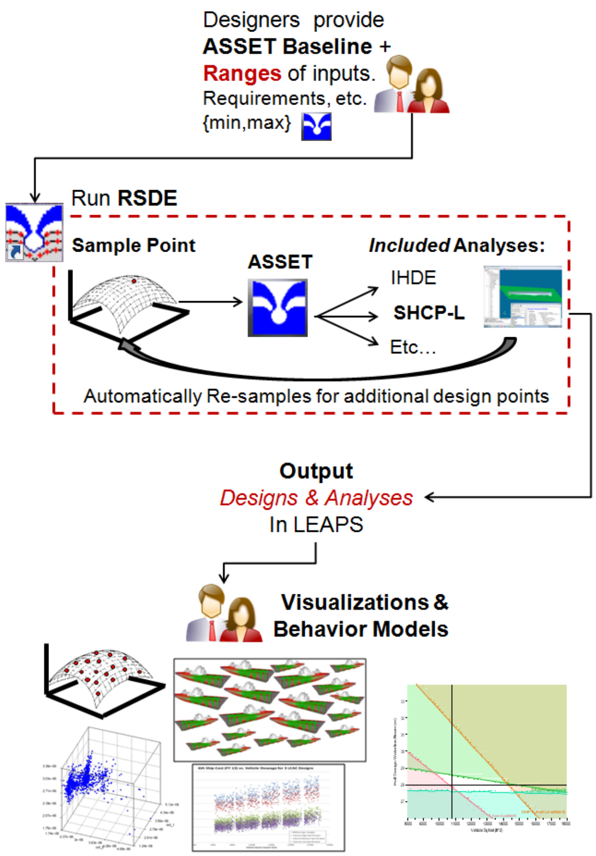

Figure 4: The typical RSDE workflow.

At this point, the user also has the option of refining, or adding more information or fidelity, to a chosen subset of designs from the initial design space in an attempt to gain more knowledge about the interdependencies between the input and output variables. Design refinement can be done in S3D or ASSET and the remainder of the suite of LEAPS applications can be used to produce higher fidelity analysis information about the chosen design.

PROPOSED DESIGN PROCESS

The process detailed in this section is based on the pattern and template approach introduced early in this paper. The process leverages the power of S3D and ASSET to quickly create an initial point design (Chalfant, Ferrante, & Chryssostomidis, 2015) and then shows how S3D and RSDE can be used in tandem to explore the design space around that initial point. The process is an extension of previous RSDE ship design processes (Mackenna, 2015).

To begin, a mixed team of systems designers and naval architectures will need to create an initial ASSET ship design and an initial system pattern and template. The design created by ASSET will not have the correct weights, areas, or power levels for its machinery systems due to the legacy sizing algorithms currently available in ASSET. This model will serve only to give the team a hull with known resistance characteristics and structural weights. Using S3D and the ship's characteristics generated by ASSET, the team will create an initial system design that can then be fed back into the ASSET model and used to rebalance the ship.

This process will be iterative, as major changes in machinery sizing will lead to large changes in the ship characteristics which will necessitate machinery modifications, and so forth. Eventually, the team will settle on a balanced system and ship design. This balanced design is the baseline for the remained of the process.

Once the baseline is agreed upon, the design process begins to resemble a set-based design process. The team could conceivably be split into the systems group and the naval architecture group, and the two groups could proceed independently. The naval architecture group would use the baseline to populate the design space in RSDE. The design space could be defined by variables pertaining to the systems onboard the ship, achieved by assigning ranges to the space, weight, area, power, and cooling requirements of distribution system SWBS groups. Alternatively, the ships principal dimensions could be varied. A combination of the two is also possible and RSDE allows the users the ability to create equations to make one variable the function of another.

Multiple system templates should be created so a family of related design sets can be populated so the systems team can fully explore the systems design space. Each set would contain different power capacities and topologies as provided by their respective baseline. This will provide the user with enough design variability across the family of sets to properly inform decision makers about the consequences of different design decisions. Essentially, the systems group will be manually populating the system design space.

Once both groups are satisfied they have sufficiently sampled their respective design spaces, they will come back together and investigate overlapping solutions (Figure 5). From here, an additional set of criteria can be applied to the design space, and the dominated regions can be removed. The goal is to have a smaller design space that is still feasible in both the naval architecture and systems designs spaces (Figure 6). From here, more detail can be put into a new *refined baseline* using ASSET or other LEAPS tools and a more detailed system template can be created and the process can be repeated. If a sufficient level of detail has been reached, the team may either down select to a single design or, keeping with the set-based design philosophy, capture their findings about the best region of the design space for meeting certain requirements.

It is possible that many of the system templates and many of the ship designs will no longer be included in the non-dominated design space. This should not be seen as a waste. Having studied these dominated areas adds to the Navy's institutional knowledge, as new system patterns and templates have been created which may be useful for future studies. More importantly, if the design requirements change in the future, as they are want to do, an entire new analysis will not be necessary; the design team can fall back on the designs they created in an earlier iteration of the exercise (Arcano, 2015; Ferrante, et. al., 2015).

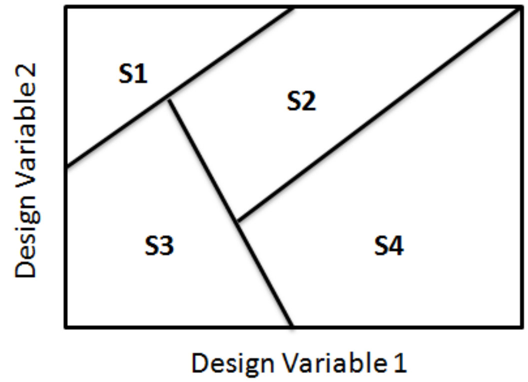

Figure 5: The initial overlapped system and ship design variable design space without outside constraints enforced.

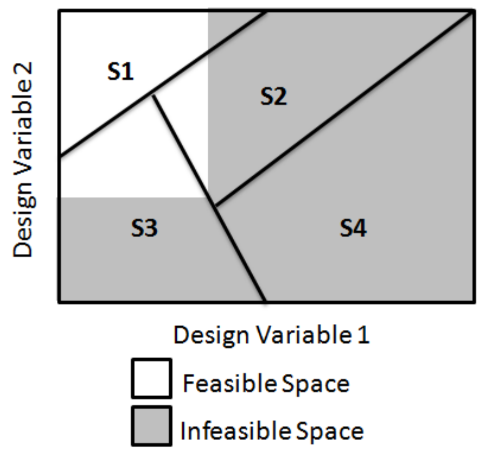

Figure 6: The initially populated system and ship design space showing both feasible and infeasible regions, dependent on additional design constraints.

CONCLUSION

In this paper, the *System Pattern and Template* approach for designing advanced power systems has been introduced along with a suite of tools that can be used to facilitate the approach. The process for enacting the pattern using S3D, ASSET, and RSDE has been proposed.

In the short term, the various component and system models within S3D will be verified and validated by Navy. The process put forth in this paper will be tested on a yet to be decided design study. Additional features, like a mission analysis tool, will be added to S3D within the next calendar year.

In the long term additional capabilities will be added to all the tools, potentially including a controls system design feature for S3D. The integration between RSDE and S3D will also be strengthened with the goal of using RSDE to vary machinery components directly in S3D and then use those findings in conjunction with ASSET models. In general the authors are confident that the use of S3D in conjunction with ASSET and RSDE will allow Navy designers to more efficiently and accurately design and analyze the next generation of combat power and energy systems.

ACKNOWLEDGEMENTS

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