Expanding the Design Space Explored by S3D

J. S. Chalfant, Z. Wang, M. Triantafyllou
Sea Grant Design Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
Email: chalfant@mit.edu

***Abstract*—Modern design processes such as set-based design and TIES (Technology Identification, Evaluation and Selection) depend on the ability to explore a large design space rather than attempting to optimize a single design. In this paper, we investigate methods for expanding the design space that can be explored using the S3D (Smart Ship System Design) software environment. We then detail the most recent advancements in the templating process, with the goal of automated system assembly and evaluation using pre-designed system segments called templates.**

Keywords*—*Ship Design, Distribution System Design, Networks, Power Distribution

I. Background

In recent years, the increased capacity of computational resources has allowed the design process to change from a spiral iteration of a few point designs to the automated exploration of a very broad design space. With the use of high-performance computing, the number of designs that can be explored can easily reach the tens of thousands or more. This broad design space can be further parameterized through the use of surrogate model techniques such as those used by Bonfiglio [1]. These surrogate models create a lower resolution parametric method of evaluating areas of the design space for which a specific design has not been created; strategic targeting of additional design in this process can reap huge rewards. These techniques support new design methodologies such as set-based design [2], [3] and TIES (Technology Identification, Evaluation, and Selection) [4].

Smart Ship Systems Design (S3D) is a software framework that can be used to create, simulate and analyze shipboard distribution systems in the electrical, thermal and mechanical energy domains. S3D is currently under development. The initial effort in creating this software has concentrated on the ability to reliably construct and analyze a multi-disciplinary set of systems for an individual ship design, with the user fully integrated into each step of the process. The vision for S3D has always contained the concept of expanding the capability to include an automated, user-directed process in which multiple systems can be created, adapted to different hullforms, simulated, and analyzed. In this paper, we examine methods for expansion of the design space beyond a single instance for a given system topology.

This material is based upon research supported by, or in part by, the U.S. Office of Naval Research (ONR) under award number ONR N00014-16-1-2945 Incorporating Distributed Systems in Early-Stage Set-Based Design of Navy Ships; ONR N00014-16-1-2956 Electric Ship Research and Development Consortium; and by the National Oceanic and Atmospheric Administration (NOAA) under Grant Number NA14OAR4170077 - MIT Sea Grant College Program, and was approved for public release under DCN # 43-4977-19.

The S3D software uses the Navy's LEAPS database system as its data repository. Data is stored in LEAPS using the FOCUS product meta-model, which governs the structure of storing data pertinent to surface ships. This integration of S3D with LEAPS in a FOCUS-compliant manner means that S3D is fully integrated into the Navy's design tools so that data produced by other programs are available to S3D and vice-versa. Further, S3D is coded using the LEAPS Application Framework, which makes all modules of S3D available to other Application Framework programs.

MIT is conducting a body of work with the goal of achieving semi-automated design of ship systems, in which the systems are generated automatically under the guidance of the engineer or designer, using a templating process. Templates in this application are pre-designed sections of systems, and can be created using the S3D software and stored in a LEAPS database. The templates are assembled into fully connected, fully functioning ship systems with components placed in three dimensions in a ship hullform and simulated. Section V of this paper describes new advancements in the templating process.

This paper explores several methods of expanding the ship system design space beyond point designs. Section III describes varying individual properties of instantiated equipment and provides an example. Section IV describes varying the underlying hullform and allowing the system to respond to this variation; examples are provided. Section V describes new advancements in the templating process including a new algorithm for determining the maximum flow at any point in a system. The final section gives conclusions and discusses future work.

Several members of the Electric Ship Research and Development Consortium (ESRDC) along with Georgia Tech have collaborated on a large-scale ship design effort using S3D to explore the ship-wide ramifications of new technologies. Several of the examples in this paper are extracted from this study. For details of the study please see [5], [6] and [7].

II. S3D System Designs

A system design in S3D consists of components arranged and connected in a one-line diagram for a specific discipline such as electrical, piping or mechanical. If a component acts in multiple domains, the same component may appear in each relevant domain, with the associated mathematical model and properties for that domain. For example, a generator will have a model in the electrical domain to represent the electrical power generated including properties such as voltage and frequency. The same component will have a representation in the mechanical domain to model the input mechanical power

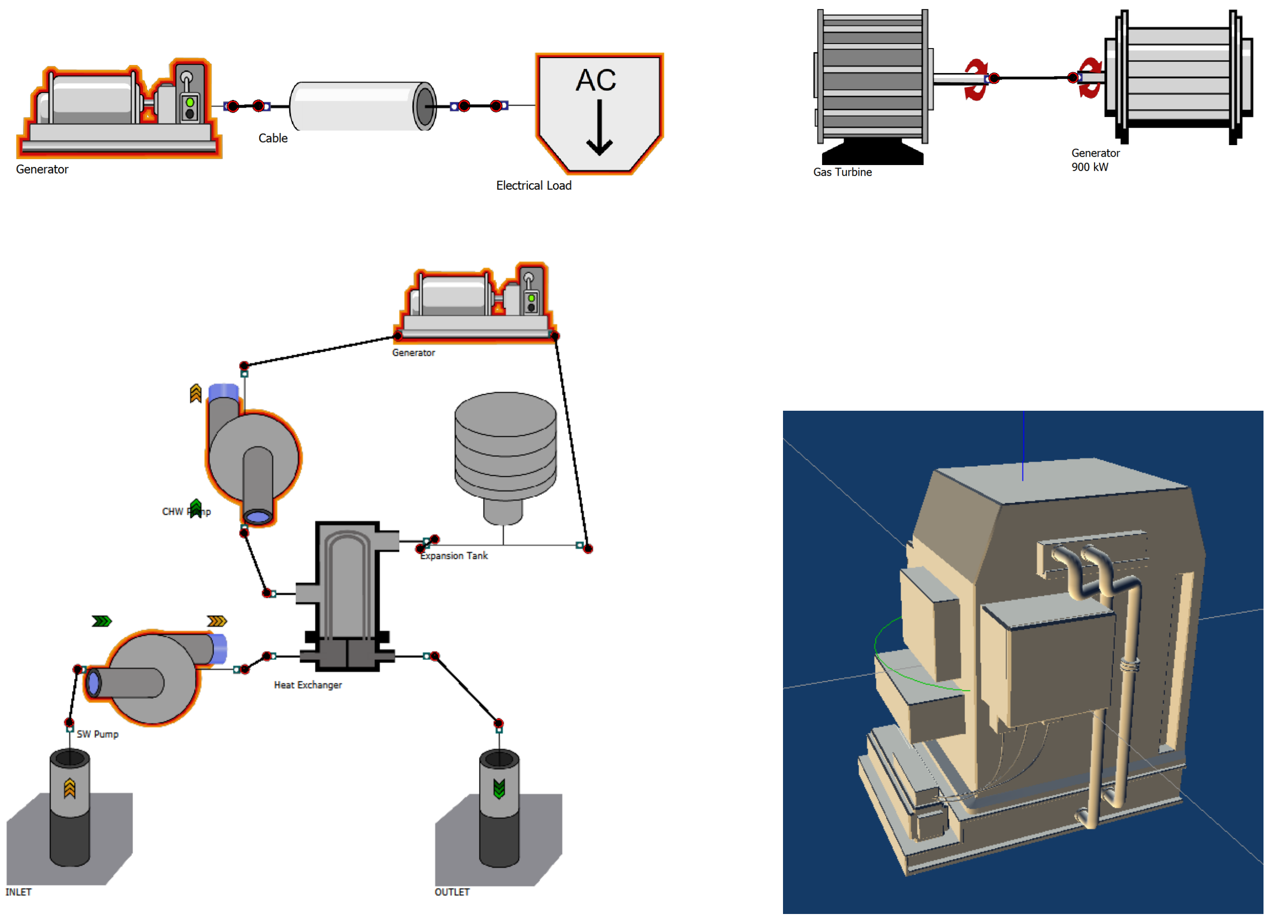

Fig. 1: Views of a generator in four different disciplines: electrical (top left), mechanical (top right), thermal (bottom left) and CAD (bottom right). Note that the CAD representation is not yet included in the current S3D software.

required from an engine, including such properties as rotational speed and torque. If it is a water-cooled generator, it will also have a representation in the piping domain, specifying properties such as cooling water temperature and specific heat. Physical properties such as dimensions and weight are also tabulated. A CAD representation can be stored in LEAPS for three-dimensional placement within a ship hull; the locations of equipment can then be used to determine the length of distribution components such as cabling, piping or shafts. Views of a generator in the electrical, mechanical and thermal disciplines of S3D can be seen in Fig. 1.

The S3D software co-simulates the design in all disciplines to capture the effects of one domain on another. Operational parameters such as valve position, power settings or breaker position can be varied to test the design against different operational missions. Metrics such as power required, fuel usage, losses, weight and volume can be parsed to compare and evaluate designs against one another.

III. Equipment Property Variation

One fairly simple method of increasing the design space is to vary the properties of the equipment in order to simulate different effects. In this case, the topology and connectivity remain unchanged but individual properties of equipment types are varied throughout the design. Properties can be manually changed by editing the properties of individual components or batched using a .csv file import feature. After importing, the synthesis is run and the results are analyzed.

Some S3D components are automatically scalable, based on a small number of inputs. One example is a scalable motor developed by Sudhoff et al. [8] in which the user specifies rated torque, speed, and voltage and a ratio value for length, diameter and mass. Then, for a selected electro-magnetic torque density and aspect ratio type, the component calculates its own dimensions, weight, efficiency, power and losses. Thus, if scalable component models are part of the design, then their properties will change during synthesis according to the individually varied properties.

A. *Equipment Property Example*

We exercised the first of these methods on an example problem in which equipment weight and heat leak were varied for high-temperature superconducting (HTS) cables, transfer lines, and cable terminations in a ship design. A baseline shipboard electrical distribution system was constructed with some of the conventional cables replaced by HTS cables. HTS cables require terminations at each end. In the electrical domain, these terminations allow the transition back to room

TABLE I: Comparison of various postulated insulation capabilities

	Higher Insulation			Medium Insulation			Lower Insulation		
	Weight (kg)	Cooling Required (kW)	Electrical Power (kW)	Weight (kg)	Cooling Required (kW)	Electrical Power (kW)	Weight (kg)	Cooling Required (kW)	Electrical Power (kW)
Cable	742	0.2	0	482	0.3	0	742	0.6	0
Chiller	2300	0.0	123	4600	0.0	243	9200	0.0	487
Junction	2600	1.6	0	1300	3.1	0	650	6.2	0
Transfer Line	0	0.1	0	416	0.2	0	640	0.5	0
Other	380	0.0	0	380	0.0	0	380	0.0	0
Total	6021	1.8	123	7178	3.6	243	11612	7.3	487

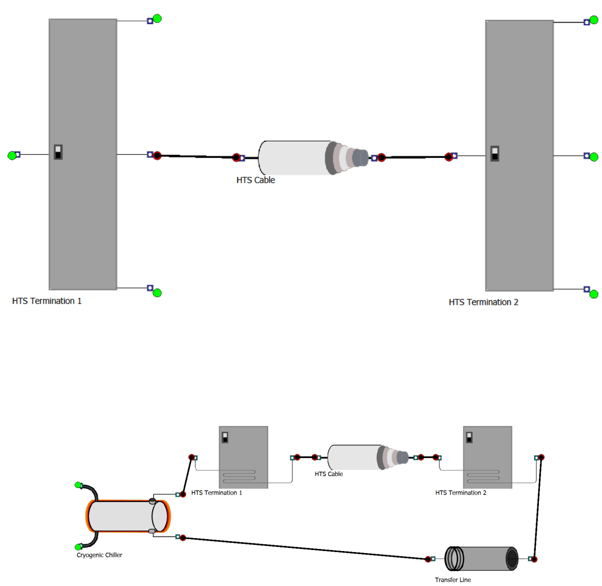

Fig. 2: Views of a high-temperature superconducting cable modeled in S3D. Electrical view of HTS cable and terminations (top), and piping view of a simplified cryogenic system with transfer line (bottom).

temperature cabling; in the piping domain, these terminations provide the introduction of the cryogen to the cable jacket. If the HTS cables do not both begin and end at the cryogenic chiller, then a transfer line is required to convey the cryogen back to the chiller. See Fig. 2 for electrical and piping views of an HTS cable modeled in S3D.

This exercise examined the effects of two variations from the HTS baseline. In one, a heavier but higher-insulating material was postulated that reduced the heat leak into the cryogenic components, reducing the load on the cryogenic chiller and allowing a corresponding reduction in the size and electrical consumption of the chiller. In the second variant, the converse was explored: a lighter but lower-insulating material was postulated with a resulting larger and higher-power chiller. By simply varying the weight per unit length and heat leak per unit length for the cables and transfer lines, and the weight and heat leak of the terminations, the simulation revealed the new total weights and heat lift required, at which point a new chiller was selected. A summary of results can be seen in Table I and Table II. Please note that the higher and lower insulation materials are merely thought experiments and do not replicate any existing material.

TABLE II: Summary of insulation capabilities results

Insulation Level	High	Medium	Low
Weight (kg)	6021	7178	11612
Cooling (kW)	1.8	3.6	7.3
Electrical Power (kW)	123	243	487

While this currently is a manual process in which new values are typed into a spreadsheet and batch-imported into a system design, the next step will be to automate the capability allowing a range of values to be selected and explored. Since S3D is written using the LEAPS Application Framework, the potential exists to use the already existing methodologies to vary properties within a Latin hypercube or other Design of Experiments process. The development of a command-line execution of an S3D simulation would also speed this process, enabling results to be tabulated without requiring user interface to open designs and run simulations manually.

IV. Hull Designs

A second way to expand the design space is to vary the hullform to which a given system design is applied. In this case, the topology of the system remains unchanged, along with such items as the number of zones, payload items, and machinery plant. Various ship hulls are created, and the entire S3D design is copied into the new hull, including all information such as systems, components, nodes, and properties. An affine transformation of equipment locations is performed to match the new hullform, which changes the lengths of the distribution items such as cables, piping, and shafts. The new hullform will also include a new speed-power curve and new hotel loads, which could be updated in the S3D model directly from the LEAPS database if such component models existed. The transformed system is then run through the S3D analysis and mission scenarios to obtain data.

Note that the hullform can be allowed to vary only within a range such that the given system design is still applicable. For example, the system would not be successfully applied if the number of zones were changed, or if the ship was made too small to fit the system within it, or if the ship was made so large that the system design will not provide sufficient services.

A. *Hullform Change Example*

An example of changing the hullform was run using one variant of the HTS study [5]. Ten hullforms of various lengths

TABLE III: Hullfrom variance example ship dimensions

Design Number	Hullform Beam Overall (m)	Hullform Depth Overall (m)	Hullform Length g Overall (m)
Baseline	21	15.1	163
1	24.77	15.1	161.15
2	23.17	15.1	178.38
3	23.73	15.1	131.68
4	18.44	15.1	189.65
5	19.22	15.1	167.23
6	17.45	15.1	137.59 2
7	21.46	15.1	175.73
8	20.88	15.1	149.59
9	22.58	15.1	188.65
10	19.48	15.1	155.20

TABLE IV: Hullfrom variance example simulation metrics

Design Number	Hullform Length Overall (m)	S3D Equipment Weight (mt)	S3D Equipment Volume (m^3)	Electrical Power (kW)	Cooling Required (kW)
Baseline	163	1,632.4	4,333.9	76,495.2	12,195.9
1	161.15	1,636.8	4,394.0	76,501.1	12,196.3
2	178.38	1,641.6	4,412.1	76,502.4	12,196.3
3	131.68	1,623.6	4,343.9	76,492.2	12,195.8
4	189.65	1,639.9	4,405.6	76,496.5	12,195.9
5	167.23	1,631.9	4,375.4	76,492.6	12,195.8
6	137.59	1,617.8	4,321.6	76,482.8	12,195.2
7	175.73	1,638.3	4,399.6	76,498.6	12,196.1
8	149.59	1,627.1	4,357.0	76,491.4	12,195.7
9	188.65	1,627.5	4,358.5	76,490.2	12,195.6
10	155.20	1,644.9	4,424.8	76,503.8	12,196.4

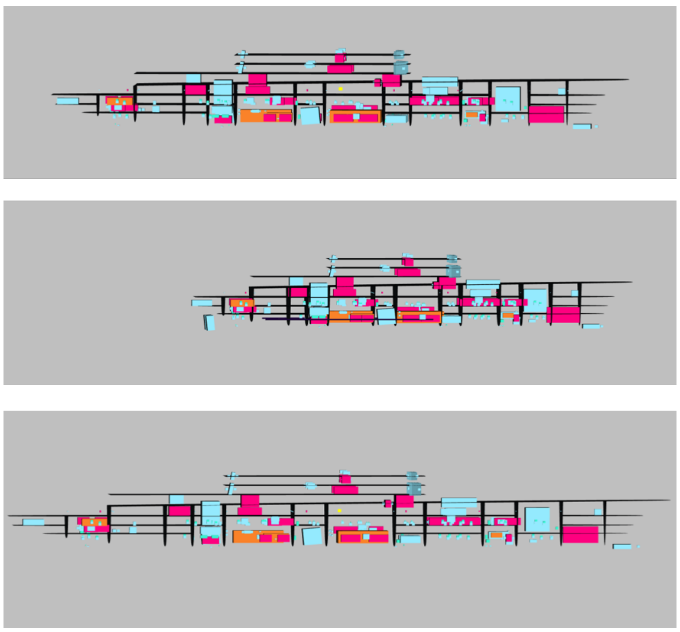

Fig. 3: Three hullform variants with S3D components placed. The top image depicts the baseline, the middle image is design four, and the bottom image shows design three.

and beams were created, and then the S3D system design was copied into the new hullforms and simulated, showing variation in such results as the weight, volume, electrical power used, and cooling required. Table III shows the sizing changes in the ten candidate hullforms.

Fig. 3 shows the baseline hullform at the top and two of the variants: design four, the shortest hull, is in the middle and design three, the longest hull, is at the bottom. Careful observation of design four will reveal that some of the equipment is too long for the space to which it is assigned; planned future work in the templating software described in Section V includes a collision detection and resolution functionality that would detect this and either resolve the collisions or reject the design as infeasible.

Table IV shows the changes in metrics with change in hull size; hull length is shown as a reference, but full dimensioning data is needed. Parsing the simulation results for this variation shows that the larger hullforms resulted in larger weights and volumes for the S3D modeled equipment; this is due to the longer runs required for the distribution components such as piping or cabling. The electrical power and cooling required showed a very small change, due to the increased losses in the longer distribution components. This example did not include components that varied the hotel loads due to the change in hullform; electrical loads such as lighting, heating and ventilation should increase as hull size increases. Further, the power required for propulsion will change, in some cases significantly, as the hullform changes; this example run was not automatically connected to the speed power curve of the new hullform, so these changes were not reflected here.

V. TEMPLATING

Neither of the previously described methods of expanding the design space change the topology or connectivity of a system design, nor do they change any of the components in a design to a new type of component. Using the toolset available today, such changes require active, manual manipulation of a design by the user. MIT is conducting a body of work with the goal of achieving semi-automated design of ship systems, which would allow the programmatic creation and analysis of ship systems under the guidance of the user, assembled from pre-designed templates and tailored to the ship design. The ultimate goal is a software tool which takes as input a set of pre-designed system segments (templates) and integrates them into a fully functioning system model in a ship design, with all components appropriately sized and located. This resultant system model provides metrics such as size and weight and is available for system simulation under various operational conditions. Thus, system designs can be applied to ship hullform designs that are automatically generated.

A. Template Assembly

References [9] and [10] describe the evolution of a templating process in which pre-designed segments of ship systems are assembled into a full system and placed in three-dimensional space in a ship design.

Individual templates are manually created using S3D. Each template is stored as a concept in a LEAPS database and contains components that are connected to one another via connections at nodes; the nodes are termed ports and terminals. Further, the components are stored in systems and common views in a FOCUS-compliant manner. The templating process copies templates from the template database and places them into a ship design database, transferring all data to the new design and integrating the new material with any pre-existing information. For example, if a template adds definition to an existing electrical distribution system, the new components and connections are added to the existing electrical distribution system diagram, and the components are stored in the existing pertinent common views, instead of creating new diagrams or common views.

After testing and implementation, some upgrades to the basic templating assemly process have been made; these upgrades are described below.

Component location is now scaled to the size of the space in which the template is placed. When a template is placed into a ship design concept, the component locations are scaled to the size of the ship space selected, which could be, for example, a compartment, a zone, or the entire vessel. To accomplish this, dimensioning of the overall template is required; new properties of a concept are used: *template overall length, template overall breadth* and *template overall depth*. These define a box within which the components are located in the template. The components are placed in three-dimensional space in a coordinate system relative to this bounding box.

The user has the option of detecting the bounding box from the placement of the components, or setting the bounding box independently. The second option is the more likely scenario; it is used when space beyond the components is desired as part of the template. If a bounding box is automatically detected from the components themselves with no access area defined around them, then when the template is placed in a compartment, the components would be placed so that edges of the components would touch the bulkhead, deck and overhead of the space, which may not be the desired outcome.

Undo capability is enabled. Any template that has been placed in a design can be removed from that design by selecting any component that was a member of that original template and requesting removal of the entire template. If the same template was instantiated several times into a design, the process distinguishes between repeat copies of a template and removes only the designated copy. This is accomplished through the inculsion of a *template id* along with a sequential instantiation number. The template id is a global unique identifier (GUID). This instantiated template id becomes a property of each component instantiated through the application of a template, and a list of template ids is attached to the ship design concept, so that the instantiation number can be properly iterated when a single template is applied to a ship design repeatedly.

Templates are connected to one another at pre-designated node locations, forming complete systems from the template segments. In a previous version, a connecting plug component was used to denote locations where templates connected to one another. This plug component was removed when templates were assembled into a design, and was difficult to reconstruct if a template was removed from a design and replaced. The pre-designated node locations are merely normal nodes of the components that receive a special designation as *template nodes*.

B. Maximum Power Flow Algorithm

After assembling all pertinent templates and components into a full ship system, the next step is to determine the capacity required from each component, which allows component selection and sizing.

Since the templating capability facilitates the creation of ship systems from an assembly of parts or system sub-sections, it is not possible to determine the amount of power flowing through each element of a system until the system is fully assembled and placed in three-dimensional space. Variations in the sources and loads that make up the system and variations in the topology into which they are assembled will affect the power that flows through a component. Further, the location of components will affect the length of distribution components such as cables, pipes or shafts, which will extend or contract in length as components are placed farther apart or closer together. This in turn will affect the losses in the distribution components, as they are usually calculated on a per-unit-length basis.

To determine the capacity required of each component, it is necessary to determine the maximum amount of power that can flow through each component *given any possible alignment of the system*.

In this section, we describe an algorithm and methodology to determine the maximum flow of power at any point in a connected network. For the purposes of this paper, our example system is the electrical distribution system, in which the property of interest is electrical power. Future work will expand the algorithms developed herein to other systems such as liquid cooling.

At the end of the template assembly process, the system design consists of a set of components connected to one another in a logical arrangement and physically placed in three-dimensional space within a ship hull. From this connected and arranged set of components, we extract a graph in which the vertices are components and the edges are connections between components.

It is possible to very rapidly determine the amount of power flowing through each component in a system for a given operational alignment by linearizing the components and solving the resultant system of linear equations. Examples of this process can be found in [11] and [12]. However, as noted above, we must determine the flow *under any possible alignment*. Automatically determining the maximum flow by solving all possible permutations of switch positions produces a set of 2^n solutions, which rapidly becomes unmanageable. Even a simplified electrical distribution system with only four zones and 20 loads can contain over 100 switches to obtain a proper level of redundant paths for power, leading to $2^{100} = 2.37 \times 10^{30}$ possible combinations. Obviously, another method is needed.

We developed an algorithm to algorithmically determine the maximum flow based on the connectivity, regardless of switch state. This new new algorithm is described herein.

1) Single Bus: Doerry [13] introduced an algorithm to determine maximum flow in a single bus, which is summarized as follows; see Fig. 4 and equation (1).

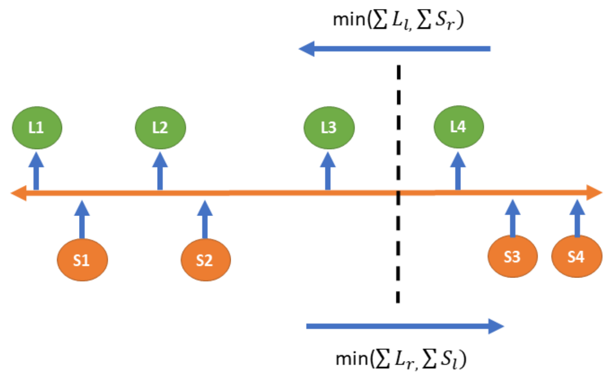

Fig. 4: Push-pull algorithm example

At any point along the line, the maximum flow from left to right is the minimum of the sum of the source to the left or the sum of the load to the right, because the source must have a load to draw the power (load limited), and the load must have a source to supply the power (generation limited). Similarly, the maximum flow from right to left is the minimum of the sum of the source to the right or the sum of the load to the left. The overall maximum flow through any point is then calculated as the maximum of the two flows (left to right or right to left).

$$MaxFlow = max \begin{pmatrix} min(\sum S_R, \sum L_L) \\ min(\sum S_L, \sum L_R) \end{pmatrix} \tag{1}$$

Using equation (1) on the system in Fig. 4 and assuming that $L1 = 1$, $L2 = 2$, $S1 = 1$ and so on, the maximum flow through the dashed line is

$$\begin{aligned} MaxFlow &= max \begin{pmatrix} min(S3 + S4, L1 + L2 + L3) \\ min(S1 + S2, L4) \end{pmatrix} \\ &= max \begin{pmatrix} min(7, 6) \\ min(3, 4) \end{pmatrix} = 6 \end{aligned}$$

2) Acyclical Network: This can easily be expanded to an acylical network. Using the same algorithm, the maximum power flowing through any edge of a graph can be determined by summing the upstream and downstream loads and sources. Fig. 5 shows an acyclical network in which all edges are unidirectional except for three edges shown in bold; one on each main bus at the top and bottom, and one that cross-connects the two sets of converters and load centers on the left and right. Note that the two sources on either side do not provide a cross-connect from one bus to the other; they are connected via directional edges that allow flow only outbound from the sources. Similarly, the converters and load centers on the left and right hand sides do not form cycles because flow between them is directed.

Thus, the flow from left to right through the bold cross-connect in the center of the diagram would be the minimum of the sum of the four loads to the right or the sum of the two sources (as both can be connected to supply the left-hand side of that cross connect). The flow from right to left through

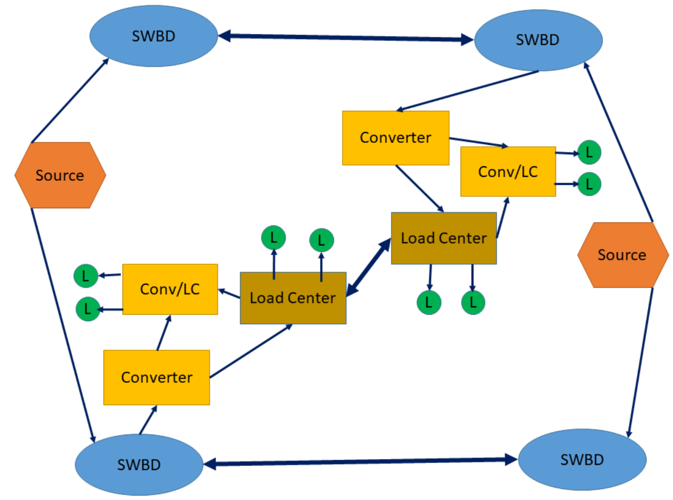

Fig. 5: Acyclical Network

the bold cross-connect in the center of the diagram would be the minimum of the sum of the four loads to the left or the sum of the two sources (since both can be connected to supply the right-hand side of that cross connect as well). And the maximum flow through that cross-connect would be the minimum of those two values.

3) Losses: There is a complication in a real system in that there are losses along the path in each component that is traversed, so following a path through the network adds power demand or reduces power supply due to losses in the components. Therefore, the maximum power at a point in the network can be determined by modifying equation (1) so that the sum of the sources is calculated by tracing the shortest (lowest loss) path from each source to that point, and the sum of the loads is calculated by tracing the longest (highest loss) path from that point to each load; this is represented in equation (2), in which l_{Si} is the sum of the losses along a path from the point of interest to the i^{th} source. Note that the highest weight path is not necessarily the longest path; it is the lossiest path.

$$MaxFlow = max \begin{pmatrix} min \begin{pmatrix} \sum_i (S_i - min(l_{Si}))_R \\ \sum_i (L_i + max(l_{Li}))_L \end{pmatrix} \\ min \begin{pmatrix} \sum_i (S_i - min(l_{Si}))_L \\ \sum_i (L_i + max(l_{Li}))_R \end{pmatrix} \end{pmatrix} \tag{2}$$

4) Cyclical Networks: However, shipboard distribution systems are not necessarily acyclical networks; in fact, resiliency and redundancy constraints almost guarantee cycles within the networks. To determine the maximum power at any point in a cyclical network, one must find the longest (highest weight) path from that point to each load and source, without cycling to repeat any portion of the path.

VI. Conclusions and Future Work

We have shown in this paper several methods for increasing the number of designs that can be explored when using S3D to model ship systems. These methods allow the designer to explore the ramifications of changes to ship systems in much greater detail than just a gross assumed weight and volume impact.

We first showed the ability to change individual properties of equipment within a single design. This required opening each design individually, uploading new properties, and running the simulation. The ability to execute a simulation through an API, without manually opening and running S3D, would enable use of existing code to automatically vary properties and then automatically explore the results.

Creation of components that interact more directly with the ship design structure will make the variation of the hullform have a greater impact on the ship systems. For example, a component that calculated the aggregate power required for lighting could vary the power required with the volume of the hull. At present, no components have been designed for S3D with this functionality.

Third, new systems can be created in an automated manner using templates, which is functionality that is still under development. This paper describes the next major step in the templating process: namely, the development of an algorithm to determine the maximum power in any component in a network. The integration of this algorithm into the templating code is next. Following this, the final step will be collision detection and resolution, to detect and resolve intersections between components and either other components or ship structure.

As these capabilities come online, the use of high-performance computing will enable the exploration of very large design spaces to a greater detail than has previously been possible. Another important step will be the ability to parse the results of so many designs and to visualize the results. We look forward to ongoing collaborations within the electric ship design community for development of all these capabilities.

REFERENCES

[1] L. Bonfiglio, P. Perdikaris, J. del Águila, and G. E. Karniadakis, "A probabilistic framework for multidisciplinary design: Application to the hydrostructural optimization of supercavitating hydrofoils," *International Journal for Numerical Methods in Engineering*, vol. 116, no. 4, pp. 246–269, 2018.

[2] T. A. McKenney, L. F. Kemink, and D. J. Singer, "Adapting to changes in design requirements using set-based design," *Naval Engineers Journal*, vol. 123, no. 3, pp. 67–77, 2011.

[3] D. J. Singer, N. Doerry, and M. E. Buckley, "What is set-based design?" *Naval Engineers Journal*, vol. 121, no. 4, pp. 31–43, 2009.

[4] D. N. Mavris and M. R. Kirby, "Technology identification, evaluation, and selection for commercial transport aircraft," in *Annual Conference of the Society of Allied Weight Engineers, Inc. (SAWE).* SAWE, May 24-26, 1999.

[5] E. Broughton, R. Smart, R. Leonard, R. Dougal, J. Chalfant, I. Leonard, and N. A. Robertson, "High temperature superconducting cable study driving M&S tool development," in *submitted to 2019 IEEE Electric Ship Technologies Symposium (ESTS)*, August 2019.

[6] C. Kim, I. Leonard, P. Cheetham, S. Pamidi, and J. Ordonez, "Progress in evaluating ship-level impact of high temperature superconducting cables," in *IEEE Electric Ship Technologies Symposium (ESTS)*, Arlington, VA, USA, August 2019.

[7] J. McNabb, N. Robertson, A. Sudol, and D. Mavris, "Exploring the design space for an electric ship using a probabilistic technology evaluation methodology," in *submitted to 2019 IEEE Electric Ship Technologies Symposium (ESTS)*, August 2019.

[8] S. D. Sudhoff and R. Sahu, "Metamodeling of rotating electric machinery," *IEEE Transactions on Energy Conversion*, 2018.

[9] J. Chalfant, M. Ferrante, and C. Chryssostomidis, "Design of a notional ship for use in the development of early-stage design tools," in *2015 IEEE Electric Ship Technologies Symposium (ESTS)*, June 2015, pp. 239–244.

[10] J. Chalfant and C. Chryssostomidis, "Application of templates to early-stage ship design," in *2017 IEEE Electric Ship Technologies Symposium (ESTS)*, Aug 2017, pp. 111–117.

[11] A. M. Cramer, H. Chen, and E. L. Zivi, "Shipboard electrical system modeling for early-stage design space exploration," in *Electric Ship Technologies Symposium (ESTS), 2013 IEEE.* IEEE, 2013, pp. 128–134.

[12] R. R. Chan, S. D. Sudhoff, Y. Lee, and E. L. Zivi, "A linear programming approach to shipboard electrical system modeling," in *Electric Ship Technologies Symposium, 2009. ESTS 2009. IEEE.* IEEE, 2009, pp. 261–269.

[13] N. Doerry and J. Amy, "Design considerations for a reference MVDC power system," *SNAME Maritime Conv*, pp. 1–5, 2016.