Refinement of Surface Combatant Ship Synthesis Model for Network-Based System Design

Nicholas Taylor Stinson

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Alan J. Brown, Chair
Stefano Brizzolara
Seongim Choi

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ABSTRACT

This thesis describes an adaptable component level machinery system weight and size estimation tool used in the context of a ship distributed system architecture framework and ship synthesis model for naval ship concept design. The system architecture framework decomposes the system of systems into three intersecting architectures: physical, logical, and operational to describe the spatial and functional relationships of the system together with their temporal behavior characteristics. Following an Architecture Flow Optimization (AFO), or energy flow analysis based on this framework, vital components are sized based on their energy flow requirements for application in the ship synthesis model (SSM). Previously, components were sized manually or parametrically. This was not workable for assessing many designs in concept exploration and outdated parametric models based on historical data were not sufficiently applicable to new ship designs. The new methodology presented in this thesis uses the energy flow analysis, baseline component data, and physical limitations to individually calculate sizes and weights for each vital component in a ship power and energy system. The methodology allows for new technologies to be quickly and accurately implemented to assess their overall impact on the design. The optimized flow analysis combined with the component level data creates a higher fidelity design that can be analyzed to assess the impact of various systems and operational cases on the overall design. This thesis describes the SSM, discusses the AFO's contribution, and provides background on the component sizing methodology including the underlying theory, baseline data, energy conversion, and physical assumptions.

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GENERAL AUDIENCE ABSTRACT

This thesis describes an adaptable component level machinery system weight and size estimation tool used in the context of a preliminary ship system design and naval ship concept design. The system design decomposes the system of systems into three intersecting areas: physical, logical, and operational to describe the spatial and functional relationships of the system together with their time dependent behavior characteristics. Following an Architecture Flow Optimization (AFO), or energy flow analysis based on this system design, vital components are sized based on their energy flow requirements for application in the ship synthesis model (SSM). Previously, components were sized manually or with estimated equations. This was not workable for assessing many designs in concept exploration and outdated equation models based on historical data were not sufficiently applicable to new ship designs. The new methodology presented in this thesis uses the energy flow analysis, baseline component data, and physical limitations to individually calculate sizes and weights for each vital component in a ship power and energy system. The methodology allows for new technologies to be quickly and accurately implemented to assess their overall impact on the design. The optimized flow analysis combined with the component level data creates a more accurate design that can be analyzed to assess the impact of various systems and operational cases on the overall design. This thesis describes the SSM, discusses the AFO's contribution, and provides background on the component sizing methodology including the underlying theory, baseline data, energy conversion, and physical assumptions.

Thank you -

To my parents, for your never ending belief, support, and love throughout my entire life

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1. INTRODUCTION

Motivation

Naval ship design, Concept and Requirements Exploration (C&RE), synthesis, and evaluation have been the primary focus of the research team at Virginia Tech and MIT for more than two decades. Concept and Requirements Exploration (C&RE) tools have been adapted and improved over that period to generate more accurate and robust models earlier in the design process. A key factor in the design and analysis of naval ships is the design of Combat, Power, and Energy Systems (CPES). Improving the preliminary estimates of combat, machinery, and electric system characteristics in the ship will lead to more accurate models and improve the opportunities for more capable ships with reduced cost and risk based on improved high fidelity system design estimates. Additionally, the ability to improve estimates of system component characteristics and remove reliance on decades old parametric estimates will aid in the broader application of the ship synthesis model moving forward as new technologies and capabilities emerge that were not accounted for in previous data and models.

In parallel with the work of the author to address the machinery sizing issues, the research team has worked on developing an architecture flow optimization (AFO) process and tool where ship systems are represented with logical, physical, and operational architectures. The entire ship can be represented this way as a system of systems. Work has been completed to model the ship's systems in an architecture framework focused on energy flow through the main propulsion, combat, electrical, and cooling components of the ship. This requires each system to be modeled with arcs and nodes to simulate energy transfer paths and vital components. Once the architecture is developed, linear programming optimization is applied to calculate the energy flow of the entire ship system. The energy flow can then be converted to a commodity flow within the ship synthesis model and used for individual vital component sizing.

The Ship Synthesis Model is a large and complicated tool that always has the potential to be improved and made more robust. One key improvement area is in machinery system weight, load, and sizing estimation. The current process relies on response surfaces models and old data for overall SWBS group estimates of weight and size. While these estimates can provide a reasonable model, there is a need for a more accurate initial estimate to better predict the feasibility and performance of proposed designs. The development of the AFO tool enables a component by component scaling of machinery vital components based on their specific energy flow as calculated by the AFO. This thesis addresses the theory behind this scaling tool, its applicability, and a comparison between the parametric results, scaled component results, and empirically estimated data.

This more physics-based modeling approach helps to break reliance on a team of experts to manually design systems and components or provide over-arching estimates during early stage ship design. By focusing on first principles for both energy flow and component sizing the team has developed a high fidelity modeling tool that can adapt to the current technology available and not depend on previous ship result estimates.

Research Contributions

The main contributions to the research group and community as a whole from this thesis are:

1. Developed a theory for sizing machinery components that scales baseline ship machinery component size based on required energy and commodity flow and estimates required component dimensions, electric loads and weight.
2. Developed a comprehensive list of baseline machinery components and their characteristics for use with the scaling procedure.
3. Specifically, with the team: developed a process and tool to use system energy balance and flows to calculate SWBS weight and area contributions from properly-sized machinery components and apply to calculate and optimize the entire ship's weight, size, balance, feasibility and performance.

Outline

This thesis is presented in manuscript format. Each chapter contains a paper that has been or will have been submitted to a peer-reviewed journal or conference for publication. Paper content may be reformatted, edited, or expanded for future paper submission after the date of this thesis.

The first paper serves as an overall introduction and description of the general focus of the current research team. It highlights past work along with the team's current mindset and understanding of a Distributed System Architecture Framework and its application to Naval Ship Concept and Requirements Exploration. The content of this first paper provides a foundation for the following two papers.

The second paper presents a detailed application of Architecture Flow Optimization (AFO) to the team's working case of Early Stage Naval Ship Distributed System Design. The AFO is explained in detail in this paper along with its capabilities, developments, and preliminary comparative results. The AFO provides the necessary energy flow definition for component sizing.

The final paper highlights the author's main contribution to the research group. This paper describes the theoretical and practical development of a tool to estimate ship machinery size and weight based on required energy flow and an initial set of data which can be updated as technological advancements occur. This module also summarizes the integration of this sizing into the overall ship weight and CG estimate in the early stage design process. It investigates the correlation of results obtained from the tools developed in the previous two papers to the empirically derived values previously used. Overall results and specific inconsistencies are discussed and analyzed to assess the validity and future value of the AFO and new machinery module.

Author Paper Contributions

The research team generated three papers describing the above topics and research efforts. The author's contributions to the papers are as described below:

Application of a Distributed System Architecture Framework to Naval Ship Concept and Requirements Exploration (C&RE) – to be submitted to the ASNE Naval Engineer's Journal.

- Assisted in topic development for future research.
- Assisted in paper editing.
- Reviewed the paper for introductory descriptions and for future research.

- Participated in many discussions related to this work over a two-year period.

Early-Stage Naval Ship Distributed System Design Using Architecture Flow Optimization – to be submitted to the SNAME Journal of Ship Design and Production
- Assisted in topic development for future research
- Assisted in paper editing
- Reviewed the paper for introductory descriptions and for future research
- Participated in many discussions related to this work over a two-year period

Naval Ship Distributed System Design and Total Ship Synthesis Using Network Architecture Framework – accepted based on abstract for presentation at SNAME Maritime Convention 2019
- Primary author
- Created modifications to the Ship Synthesis Model for machinery scaling, SWBS weight estimates, and compartmental volume and area estimates
- Generated figures for this paper.
- Ensured tool's development and compatibility with future research efforts
- Analyzed data from previous parametrics compared to AFO scaled components

2. Application of a Distributed System Architecture Framework to Naval Ship Concept and Requirements Exploration (C&RE)

Mark A. Parsons[1], Kevin Robinson[2], Mustafa Y. Kara[1], Nick Stinson[1], Dan Snyder[1], David Woodward[3], Alan J. Brown[1], [1]Virginia Tech, Dept. of Aerospace and Ocean Engineering, Blacksburg, VA; [2]US Coast Guard Academy; [3]Naval Surface Warfare Center Philadelphia

This paper describes a network framework, method and tools for designing and analyzing naval ship Combat, Power and Energy Systems (CPES) in the context of a total ship concept and requirements exploration (C&RE) process. Understanding the relationships between various aspects of these systems with a total system perspective has become necessary for uninterrupted effective operations, performance, reliability, safety, naval ship survivability and affordability. Particularly in early stage design, this framework must enable mathematical analysis to efficiently consider an unlimited design space of possibilities, to create knowledge, to encourage innovation, to provide previously undiscovered insight, and ultimately to support the synthesis of effective and affordable ship designs. This framework decomposes system architecture into three views: physical, logical, and operational. This representation describes the spatial and functional relationships of the system together with their temporal behavior characteristics. The paper provides an overview of design tools developed to implement this process which include objective attribute metrics for cost, effectiveness and risk, a ship synthesis model, hullform and CPES explorations using design of experiments (DOEs) to collect data and response surface models to implement design creation using the synthesis model for application in a multi-objective genetic optimization.

KEY WORDS: ship design, naval ship, vulnerability, survivability, warship

INTRODUCTION AND MOTIVATION

Brown and Sajdak (2015) presented an update describing a naval ship Concept and Requirements Exploration (C&RE) process that was developed, expanded and applied over two decades at Virginia Tech and MIT (Brown and Thomas 1998, Brown and Salcedo 2003, Stepanchick and Brown 2007, Strock and Brown 2008). Goodfriend and Brown (2018) described the application of this process to early concept exploration considering combat vulnerability. Typically, survivability analysis for naval ships is deferred until preliminary design or later, but many important design decisions regarding systems and system architecture are made in concept exploration and are difficult and costly to reverse. Survivability is an important factor in assessing mission effectiveness which is an important objective attribute in concept exploration. Our hypothesis was and is that survivability must be considered in these early decisions and in C&RE.

Combat, Power and Energy Systems (CPES) are fundamental to the design and mission of naval surface combatant ships. CPES design and architecture are critical to determining all aspects of a naval ship's combat effectiveness and survivability. In Goodfriend and Brown (2018), a traditional system vital-component deactivation diagram approach was used to assess system vulnerability. Deactivation diagrams were used both to define the system architecture and assess its vulnerability to vital component loss.

In parallel with this effort, we were also working in a Naval International Cooperative Program (NICOP) exploring the use of networks to provide an alternative approach and different paradigms for preliminary arrangements, architecture, and for considering survivability in early design decisions (Brefort et al. 2018). This network approach has proven to be exceptionally capable and flexible for this application. Our entire C&RE process has been reworked to apply this approach and its associated framework as described in this paper.

CPES systems are distributed systems, most simply defined as mechanical, electrical and electronic components distributed throughout a ship that are connected to work together. These systems, particularly the power and energy systems are traditionally represented in “one-line diagrams” and “machinery equipment lists”. Over time, distributed systems have become increasingly interconnected and interdependent, particularly in modern naval ships. This complexity makes them more vulnerable to cascading failure and to behavior that may become evident only when the system is in operation if not properly discovered and considered early.

Mechanical, electrical and electronic systems are also interdependent with the ship’s general arrangement which itself may be considered a distributed system. The physical locations and connectivity for distributed systems within the ship determine important characteristics of these systems and visa-versa. Understanding the relationships between various aspects of these systems with a total system perspective is necessary for uninterrupted effective operations, performance, reliability, safety, naval ship survivability and affordability (Brown 2018).

It is time for a more rigorous early stage design approach and a different framework to define distributed systems and to model their interaction. Particularly in early stage design, this framework must enable mathematical analysis to efficiently consider an unlimited design space of possibilities, to create knowledge, to encourage innovation, to provide previously undiscovered insight, and ultimately to support the synthesis of effective and affordable ship designs.

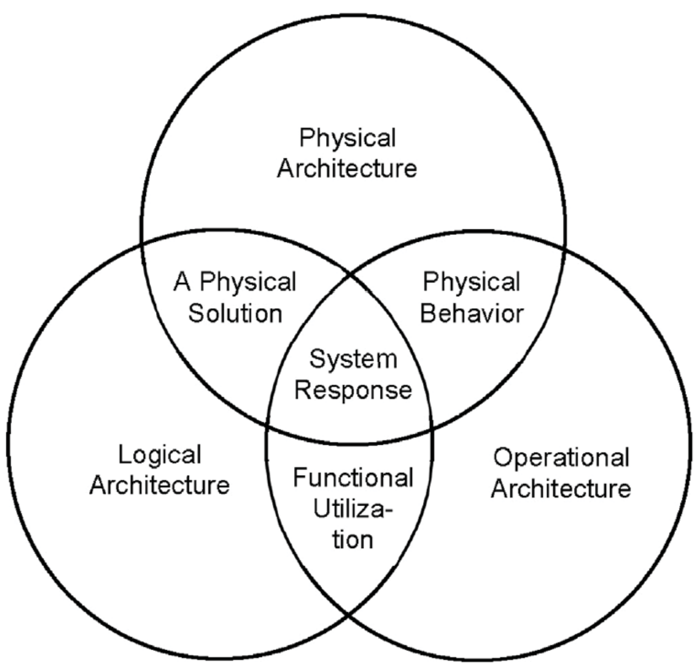

Figure 2-1- Representation of an Architectural Framework for Ship Distributed Systems (Brefort et al., 2018)

This paper describes a network framework, methods and tools for designing and analyzing combat, propulsion, power and other distributed ship systems in the context of ship concept exploration and design. This framework decomposes system architecture into three views: physical, logical, and operational as shown in Figure 2-1. This representation describes the spatial and functional relationships of the system together with their temporal behavior characteristics. Much of this work is featured in *Marine Engineering* (2020). Brefort et al. (2018) provides a more comprehensive architectural framework description.

Design tools are required to support any design process, working with and within the selected design framework, particularly for complex products. Recent tools or approaches that consider distributed systems and preliminary arrangements with the potential to work within the network framework proposed above include the Design Building Block Approach (Andrews et al. 2012, McDonald 2009, Pawling 2007, Pawling et al. 2015), Bin-Packing (Duchateau 2016, van Oers 2011, van Oers et al. 2010, van Oers et al. 2012), Architecture Flow Optimization (Trapp 2015 and Robinson 2018), and the Preliminary Arrangements and Architecture Model (Brown and Sajdak 2015, Goodfriend and Brown 2018). A growing number of semi-automated design and analysis tools that specifically address ship distributed-systems are also being developed. These include the Smart Ship Systems Design (S3D/LEAPS) tool which is intended to perform high fidelity design and analysis of distributed naval systems and is being adapted for the proposed network framework using templates and patterns (Chalfant 2015, Chalfant et al. 2017a, Chalfant et al. 2017b). In order to interface with these tools, we have ongoing research to extract network representations from the S3D/LEAPS data (Dellsy et al. 2016) and then extract deactivation diagrams from the network representations and use them when required for vulnerability and reliability analysis. We are also adapting and using the network representation in architecture flow optimizations (AFOs) (Robinson 2018) to support CPES design and ship synthesis and better assess vulnerability and recoverability considering system capacity, not just deactivation continuity (Chalfant et al. 2017b).

CONCEPT & REQUIREMENTS EXPLORATION (C&RE)

A notional naval ship Concept and Requirements Exploration (C&RE) process is illustrated in Figure 2-2. It begins with a statement of mission need in an Initial Capabilities Document (ICD). The content of the ICD is refined and expanded to better understand the ship's Concept of Operations (CONOPS), operational situations (OpSits), tasks required by the mission, and operational capabilities required to perform the mission (ROCs). This is important for specifying the system operational architecture and calculating an Overall Measure of Effectiveness (OMOE) later in the process. Next, a thorough collection and review of applicable technologies and a comparative naval architecture study of recent ships with similar missions are performed. This includes combat, propulsion, power and distributed system technologies with their logical architectures. From these studies, designers begin to define the ship design space and a very preliminary Initial Baseline Design.

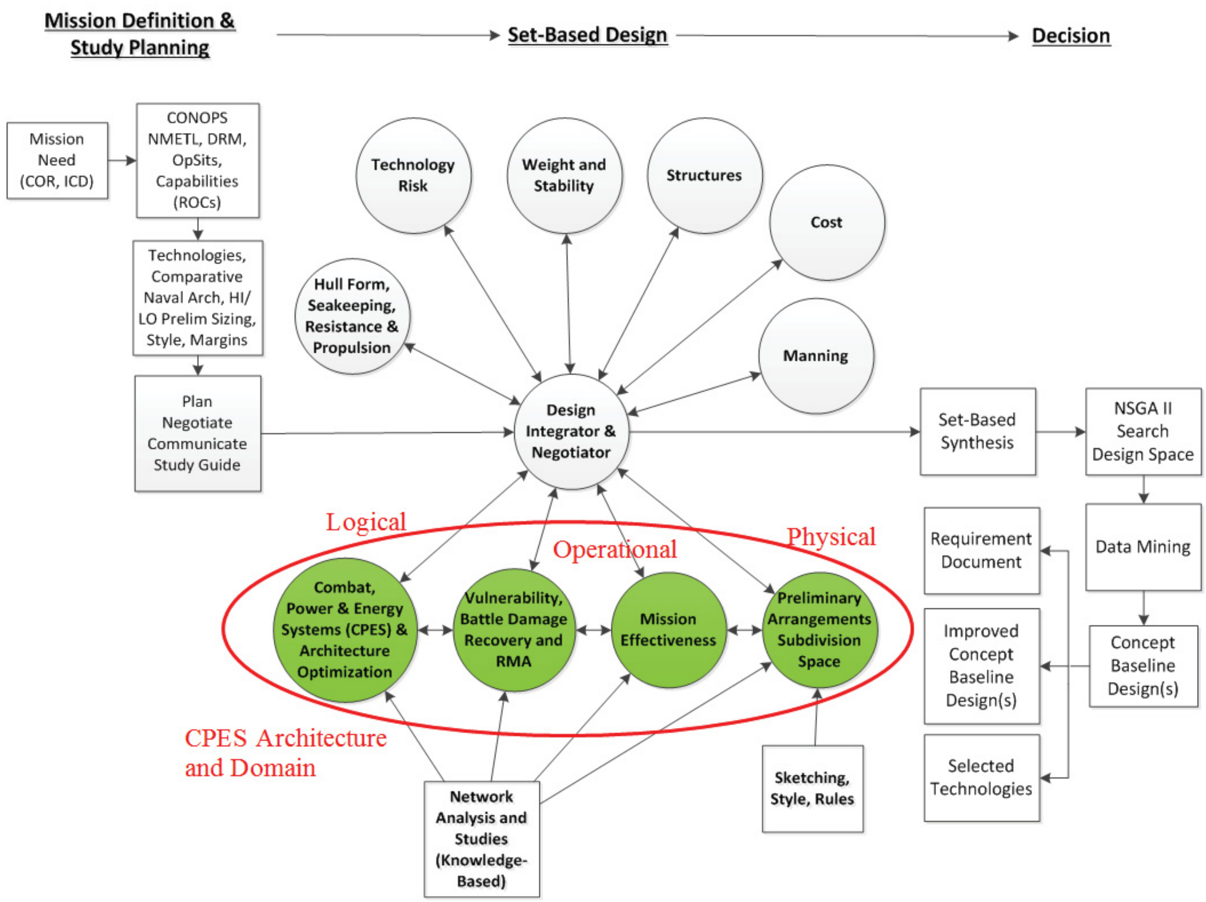

Figure 2-2 - Naval Ship Concept & Requirements Exploration (C&RE) Process with CPES Architecture and Set-Based Domains

Next comes domain-specific concept explorations in at least six important domains: hullform and deckhouse geometry, combat power and energy systems including propulsion and other distributed systems, mission systems, preliminary arrangements, manning and automation, survivability (for naval ships) and reliability/maintainability and availability (RM&A). These explorations are typically accomplished simultaneously by multiple domain experts with interaction through a design manager or system integrator to coordinate the feasible design space definition and any product interdependency assumptions. Important products of these explorations include the collection and analysis of data for each discipline using a design of experiments (DOE) approach, the identification of important design variables and parameters, the definition and refinement of the design space for each discipline, and response surface models (RSMs) approximating the relationship between input design variables and response characteristics for use later in a design-specific synthesis model. Generic parametric equations and a generic synthesis model based on limited data from past ship designs are not sufficiently applicable or flexible for thinking outside the box in new designs. A more physics-based, design-specific approach is required. This is the primary reason for these explorations.

CPES design, preliminary arrangements, survivability and RM&A are closely coupled and computationally extensive so they are explored simultaneously using representative designs constrained by the design spaces in other domains, particularly hullform and deckhouse. The CPES process is illustrated in Figure 2-3 and will be a primary topic in this paper.

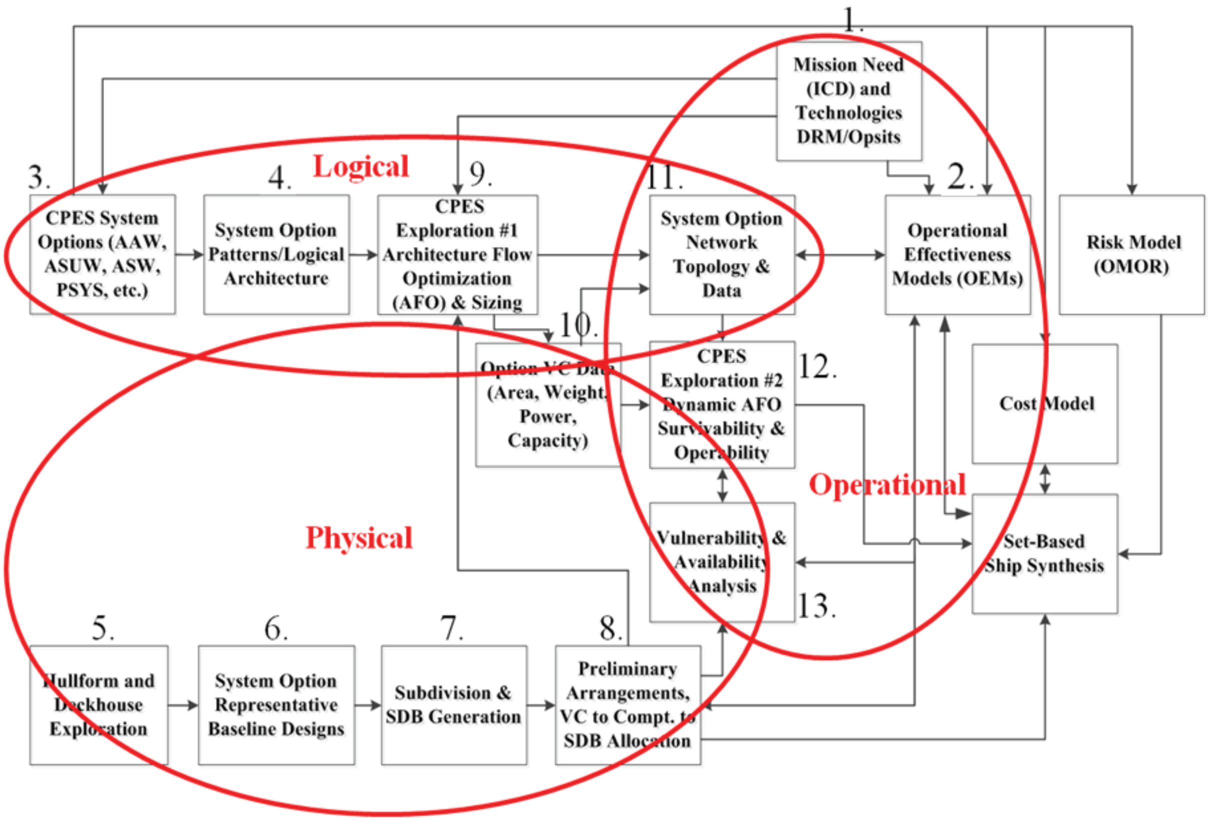

Figure 2-3 - CPES Design Process Using Figure 2-1 Architectural Framework

Once these individual explorations are complete, a set-based integration approach may be used to reduce the large integrated design space for ship synthesis. This approach may include searching for non-dominated (Pareto) designs using a Multi-Objective Genetic Optimization (MOGO) with dominance and feasibility layers, and targeted higher fidelity simulations (Brown et al. 2017). This process is intended to delay decision-making, control convergence until later in the design process, and enable parallel domain solutions. Instead of working towards feasible Pareto-optimal solutions, it works to identify and remove clearly infeasible and badly dominated solutions. High-fidelity physics simulations may be introduced early through variable-fidelity response surfaces to minimize the risk of removing domain solutions that could later prove to be feasible and non-dominated.

Domain DOEs, RSMs and MOGOs initially use domain-specific objectives and constraints, but ultimately these are refined and expanded to overall design objectives and constraints. Typically, these would include life-cycle or total ownership cost, technology risk and operational effectiveness. Indices may be used for risk and effectiveness as in an Overall Measure of Risk (OMOR) metric (Mierzwicki 2003, Mierzwicki and Brown 2004) and Overall Measure of Effectiveness (OMOE) metric (Demko 2005, Brown and Demko 2006). The OMOE may be calculated using the analytical hierarchy process, pairwise comparison and expert opinion or by war-gaming analyses in the case of a naval ship. Maintenance and logistics policy for a ship design should be considered in a RM&A (Reliability, Maintainability and Availability) analysis which is greatly facilitated by having a logical system-architecture early in the design process. A basic manning analysis should also be performed as early as possible (Scofield and Brown 2007). It is essential that maintenance and manning policy decisions are explicit in early stage design because they have a major impact on the design, particularly on space, cost and risk.

Ultimately a design must satisfy functional requirements, be balanced and feasible: it must float so buoyancy must equal weight; it must float upright so the design must have sufficient transverse stability; it must have sufficient space to contain, access and maintain everything inside the hull and deckhouse; and it must have sufficient power to satisfy electric load requirements and provide propulsion. It must also satisfy various performance and cost constraints and various performance thresholds. These are assessed first in the domain explorations and ultimately in ship synthesis. In addition to being balanced and feasible, a non-dominated design must provide the highest effectiveness for a given cost and risk as illustrated in Figure 2-4 where each point represents objective attribute values for a feasible non-dominated ship design, with total ownership cost (CTOC) on the x-axis, effectiveness (OMOE) on the y-axes, and risk indicated in color from low to high, green to red. Important (preferred) design possibilities for the customer are often those that occur at the extremes of the frontier, around the cost threshold, and at "knees" in the surface, but no single design is actually "optimal". Objective attribute models calculate quantitative metrics for each of these and the MOGOs use them to search the design space.

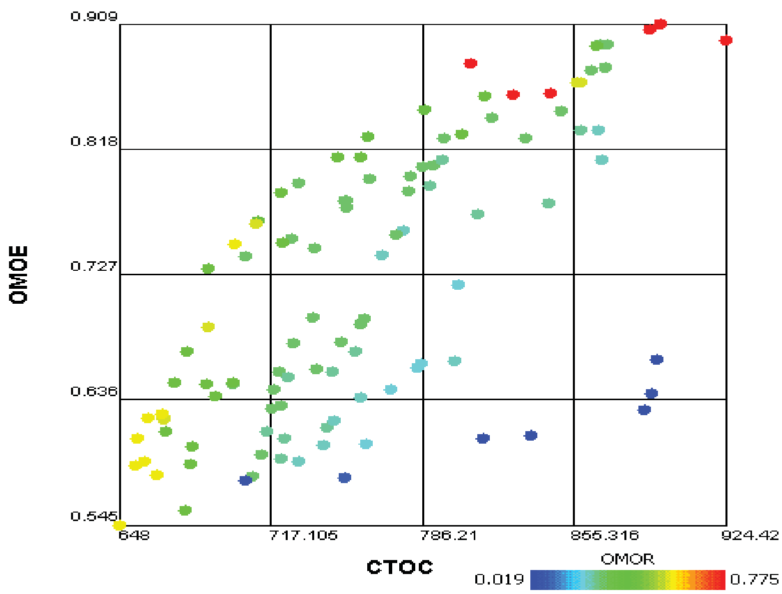

Figure 2-4 - Ship Design Non-Dominated Frontier (Brown and Sajdak 2015)

The Overall Measure of Effectiveness (OMOE) objective metric formulation begins by identifying Required Operational Capabilities (ROCs) for the design. Some of these ROCs must be satisfied for all designs with only a single specified threshold of performance. These become design constraints or they are just satisfied directly by including particular systems or capabilities in all designs. The remaining ROCs may be achieved over a range of performance where there may be a threshold of acceptable performance, and a goal specified in addition to the threshold. Measures of Performance (MOPs) must be calculated for these ROCs, each with its own goal and threshold. These MOPs may be organized into an OMOE hierarchy as shown in Figure 2-5 for a future surface combatant design. This hierarchy includes MOP groups for mission, mobility and survivability. Mobility MOPs may include sustained speed, battle speed and endurance range which depend on available propulsion power and efficiency, propulsor design, hull resistance through the water at different speeds and available fuel. Acoustic, magnetic and IR signatures are largely determined by the noise, vibration and heat produced by machinery and by the materials selected for their manufacture. System vulnerability is largely determined by the architecture and physical arrangement of power and energy systems and most all ship systems require power and cooling.

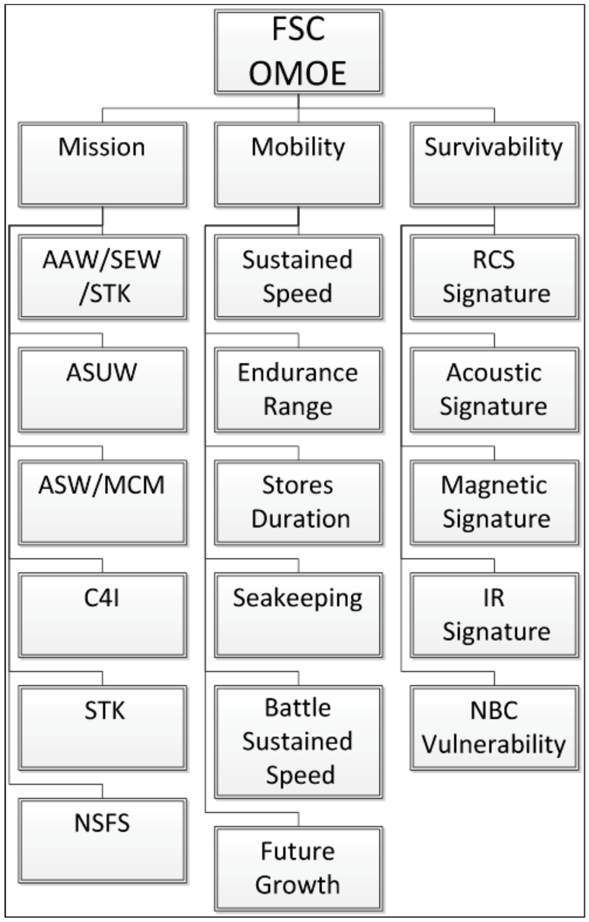

Figure 2-5 - OMOE Hierarchy

This OMOE hierarchy is used to formulate an Overall Measure of Effectiveness (OMOE) function for use in optimization and trade-off studies (Demko 2005, Brown and Demko 2006). There are several inputs that should be considered in this function. These include: 1) defense policy and goals; 2) threat; 3) existing force structure; 4) mission need; 5) mission scenarios; 6) modeling and simulation of war gaming exercises; and 7) expert opinion. Ideally, all knowledge about the problem would be included in a master war-gaming model to predict the resulting measures of effectiveness for a matrix of ship performance and probabilistic scenarios. Regression analysis could then be applied to the results to define a mathematical relationship between the measures of performance and the effectiveness output from the war gaming model. The accuracy this type of simulation relies heavily on the modeling of the interactions of a complex human and physical system and its response to a variety of qualitative and quantitative variables and conditions including the ship MOPs. Being that a large number of inputs and function responses are probabilistic a considerable number of full war gaming simulations must be made for each set of input variables.

An alternative to running these simulations and models is to use expert opinion to directly integrate the diverse inputs, assess the value of the ship MOPs, and combine these in a single OMOE function, Equation (1).

$$OMOE = \sum_i VOP_i\left(MOP_i\right)w_i \qquad (1)$$

The Analytical Hierarchy Process (AHP) (Saaty 1996) and Multi-Attribute Utility Theory (Belton 1986) are two well-accepted methods for structuring these problems. These two methods may be combined to define Multi-Attribute Value Functions (VOP_i), and calculate MOP_i weights (w_i). This method uses an AHP hierarchical structure, Figure 2-5, to organize and control the complexity of the problem, and value functions to calculate achieved MOP value (VOP_i) as a function of the chosen design variable options or calculated performance. Pair-wise comparison and AHP are used to estimate MOP weights, value function weights and option values. AHP also measures the inconsistency of the pairwise comparison and can consider both qualitative and quantitative attributes.

Important terminology used in describing this process includes:

- **Overall Measure of Effectiveness (OMOE)** - Single overall figure of merit index (0-1.0) describing ship effectiveness for all assigned missions or mission types.
- **Measures of Effectiveness** - Figure of merit index for specific missions or mission performance areas (warfighting, mobility, survivability).
- **Measures of Performance (MOP) -** Specific ship or system performance metric independent of mission (speed, range, seakeeping, vulnerability, reliability).
- **Value of Performance (VOP)** - Figure of merit index (0-1.0) specifying the value of a specific MOP to specific mission areas for the specified mission type.

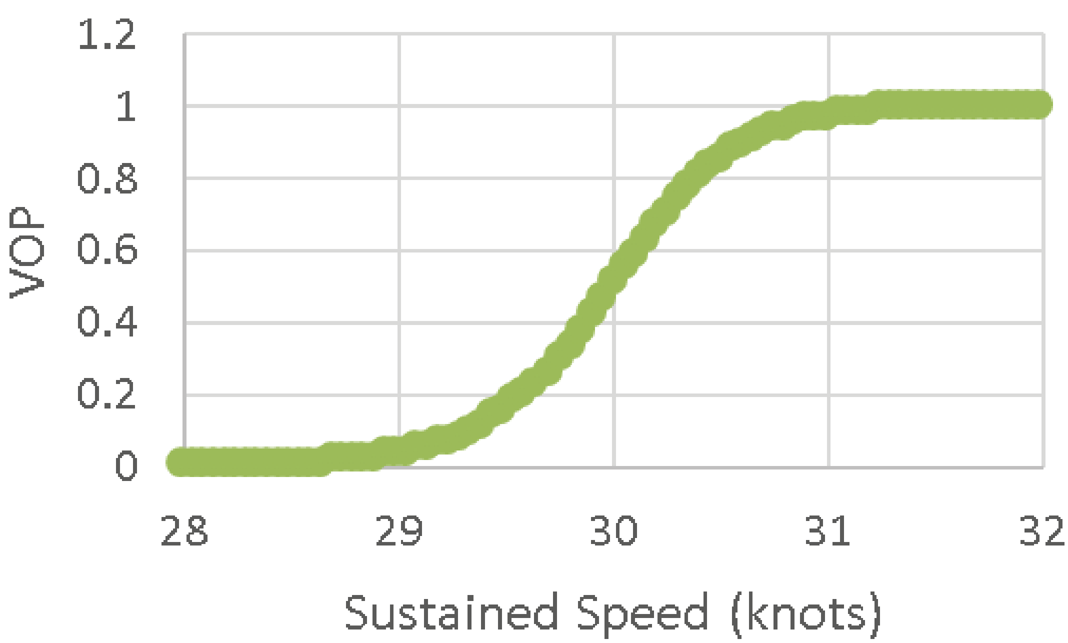

Figure 2-6 - VOP "S" Curve, VOP_i

In the naval ship example, MOPs are organized into an OMOE hierarchy which assigns the MOPs to missions and into groups for warfighting, mobility and survivability. MOPs are grouped with similar MOPs maintaining a balanced number of MOPs in each group. Otherwise this grouping is very flexible. Pairwise comparison works best when comparing three to six attributes at each node in a balanced hierarchy. Pairwise comparison may be performed using a simple questionnaire or by voting in a facilitated gathering of experts. Expert opinion is usually processed starting at the bottom and working up node by node. This process may be performed with groups of experts or with individual experts assigned to their particular areas of expertise and portions of the hierarchy. Calculated performance such as sustained speed and endurance range are normalized into VOPs using their design goal and threshold values and S-curve value functions as illustrated in Figure 2-6.

AHP pairwise comparison results are rolled up to a single set of weights for each MOP, illustrated in Figure 2-7. The sum of these weights is equal to one. The OMOE Equation (1) is used to calculate a single OMOE value for a particular design given its selected design options and calculated performance.

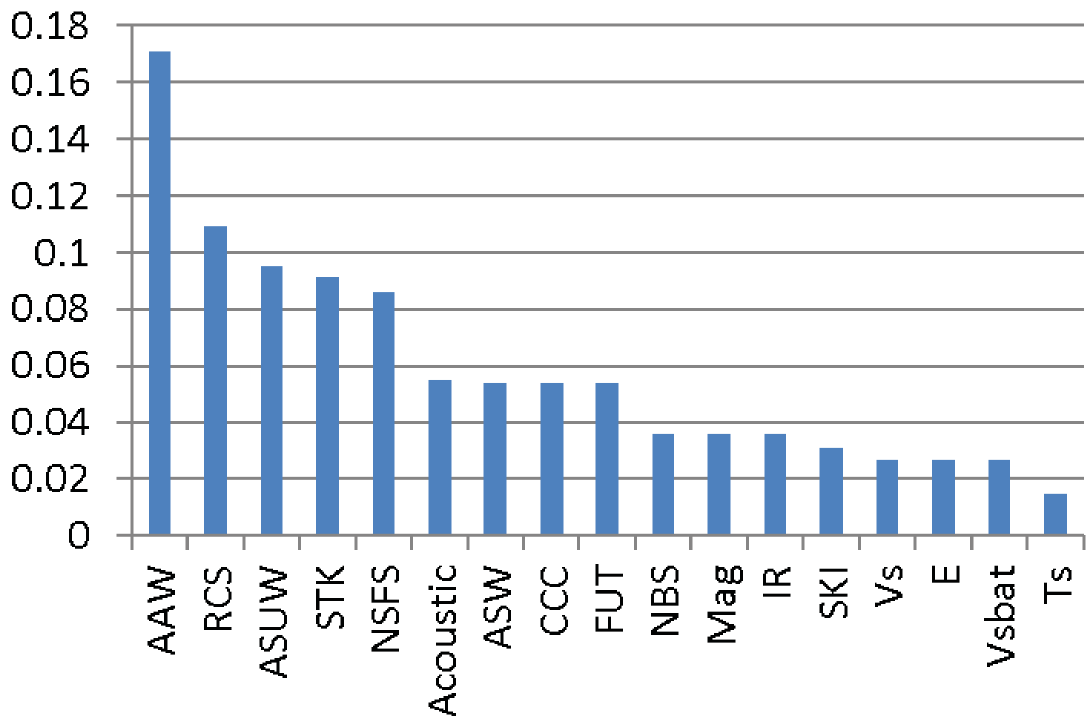

Figure 2-7 - Notional Surface Combatant MOP Weights, w_i

The MOP weights shown in Figure 2-7 for a surface combatant seem to emphasize combat systems, but AAW, ASW, ASUW all require electric power, all require cooling and all require some capability for propulsion which are provided by distributed power and energy systems. Except for radar cross section (RCS), signatures are largely determined by the design of power and energy systems. Sustained and battle speeds and endurance range, although given lower weight, are still significant capabilities determined by the design of distributed and propulsion systems.

Simultaneous consideration of proven and unproven technology also requires a risk metric (Mierzwicki 2003, Mierzwicki and Brown 2004). Performance, cost and schedule risk must be considered for developing technologies. An Overall Measure of Risk (OMOR) is a quantitative measure of the total risk for a specific design based on selected technologies. As with the OMOE, OMOR is a merit index with a value of 0 to 1. The risk for each technology is the product of the probability of risk event occurrence (P_i) (Table 2-1) and the consequence of the event (C_i) (Table 2-2) as calculated in Equation (2):

$$\text{Risk} = R_i = P_i * C_i \qquad (2)$$

Table 2-1 and Table 2-2 are used to estimate probabilities and consequence level to evaluate the probability of the risk, P_i, and the estimated consequence, C_i, for each selected technology. A risk register is used to list possible risk events depending on the technology selected. A pairwise comparison, again completed using AHP, is then used to calculate the OMOR hierarchical weights (W_{perf}, W_{cost}, W_{sched}) for each risk event. Technology Readiness Levels (TRLs) may also be used to quantify OMOR. The OMOR function is assembled as shown in Equation (3).

Table 2-1 - Event Probability Estimate

Probability	What is the Likelihood the Risk Event Will Occur?
0.1	Remote
0.3	Unlikely
0.5	Likely
0.7	Highly Likely
0.9	Near Certain

Table 2-2 - Event Consequence Estimate

Consequence Level	Given the Risk is Realized, What is the Magnitude of the Impact?		Cost
	Performance	Schedule	
0.1	Minimal or no impact	Minimal or no impact	Minimal or no impact
0.3	Acceptable with some reduction in margin	Additional resources required; able to meet need dates	<5%
0.5	Acceptable with significant reduction in margin	Minor slip in key milestones; not able to meet need date	5-7%
0.7	Acceptable; no remaining margin	Major slip in key milestone or critical path impacted	7-10%
0.9	Unacceptable	Can't achieve key team or major program milestone	>10%

$$OMOR = W_{perf} \frac{\sum_i P_i C_i}{\sum_i (P_i C_i)_{\max}} + W_{\cos t} \frac{\sum_j P_j C_j}{\sum_j (P_j C_j)_{\max}} + W_{sched} \frac{\sum_k P_k C_k}{\sum_k (P_k C_k)_{\max}} \qquad (3)$$

The OMOR risk register almost always contains combat, power and energy system risk items that can have a major impact on the design such as energy storage, energy recovery, integrated power, control and automation technologies. Many of these systems are large or pervasive, buried deeply in the ship, installed early and very difficult to change or replace once a ship is built or even just designed, so that risk mitigation strategies may be very difficult to implement. Collectively this means that the selection of high risk combat power and energy technologies can have a major impact on cost, schedule and performance.

The third critical metric is cost. In early stage design, acquisition cost is typically estimated using weight-based or modified weight-based methods. Complexity and producibility factors consider the technology selection for a particular design, including hull, machinery and combat system technologies and various producibility metrics such as deck height, outfit density and maintenance clearances (Brown and Barentine 1996).

Acquisition cost is important, particularly in the short-term decision whether or not to purchase or fund a purchase, but over time, time-discounted life-cycle or total-ownership cost of a design is the most rational design cost objective. Additional life-cycle costs such as research and development, manning, fuel, maintenance, parts, logistics support, training and related infra-structure can be very large over time and must be considered.

Figure 2-8 shows our C&RE Exploration and Ship Synthesis model (E&SSM) model implemented in Model Center (Phoenix Integration 2017). Different regions and modules in this model are used to perform the various steps in the C&RE. Table 2-3 shows the C&RE design space for a notional surface combatant. The first eight of the DVs in this table apply to hullform design. These DVs are followed by various system option DVs. Additional design parameters (DPs) are constant for all designs.

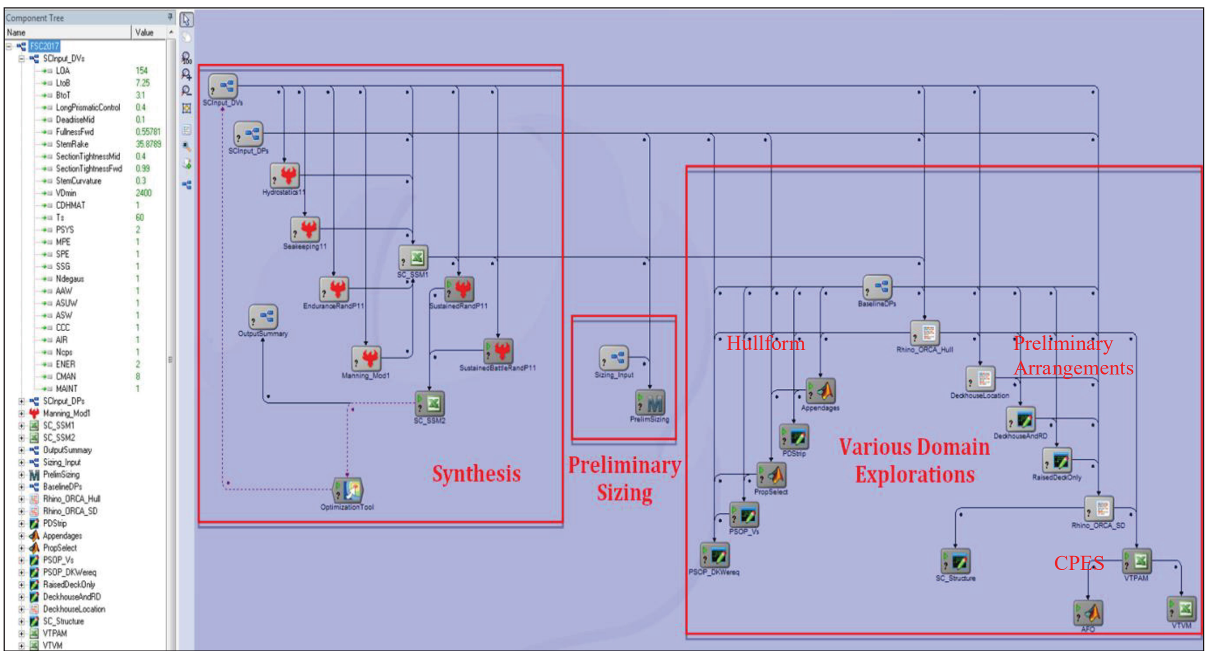

Figure 2-8 - Exploration and Ship Synthesis Model (E&SSM) in Model Center (MC)

Table 2-3 - Notional Surface Combatant Design Space for C&RE

Input Value	DV	Design Variables	Values	Description
158.00	1	Length on Deck (LOA)	150 to 175m	
7.25	2	LtoB Ratio	7 to 7.65	
3.10	3	BtoT Ratio	3.25to3.6	
0.400	4	Long'l Prismatic Control	0.1 to .4	
0.100	5	Deadrise Mid	.1-.4	
0.558	6	Fullenss Fwd	.3 to .6	
35.879	7	Stem Rake	35-45 deg	
0.400	8	Section Tightness Mid	.4 to .99	
2400	9	Minimum Volume of Deckhouse (VD)	2000-5000 m3	
8.00	10	Manning and Automation Factor (CMAN)	0.5-1.0	
1	11	Maintenance	1to3	Maintenance Plan
1	12	Degaussing (DEGAUS)	0,1	0=none, 1=yes
1	13	CPS	0,1,2	0=none, 1=partial, 2=full
60	14	Provisions Duration (Ts)	30-60 days	
2	**15**	Propulsion System (PSYS) - Architecture	1	IPS,2 pods, 2xGTPGM,2xDSPGM, MVDC
			2	IPS,2 FPP, 2 shafts, 2xPMM,2xGTPGM,2xDSPGM, MVDC
			3	COGAG, DDG-51, LVAC
			4	HED, 2 CRP, 2 shafts, 2xGTMPE,2xDSPGM,2xSPMM,2xSSG, MVAC
			5	CODAG,2 CRP, 2 shafts, 2xGTMPE, 2DSPE,4xSSG,CODAG
			6	IPS,2 FPP, 2 shafts, 2xPMM,1xGTPGM,2xDSPGM, MVDC
			7	CODAG,2 CRP, 2 shafts, 1xGTMPE, 2DSPE,4xSSG,CODAG
			8	HED, 2 CRP, 2 shafts, 1xGTMPE,2xDSPGM,2xSPMM,2xSSG, MVAC
			9	
1	**16**	MPE/PGM Main Propulsion Engine or PGM	1	MT30
			2	LM2500+
1	**17**	SPE Secondary Engine or SPGM	1	MTU 20V 8000 M91L (10MW)
			2	20PA6B STC (8.1 MW)
			3	16PA6B STC (6.48 MW)
			4	CAT 280V16 (5.06 MW)
1	**18**	Ship Service Generator	1	Allison 501K34 SSGTG
			2	CAT 280V12 SSDG
			3	CAT 280V8 SSDG
1	**19**	AAW,SEW,GMLS	Option 1	AMDR-S/X,AEGIS BMD (ACB), MK41 VLS - 32 and 64 CELL,IFF,2xCIWS,2xAIEWS,8xMK53 SRBOC&NULKA,2xLaWS
			Option 2	AMDR-S,2xSPG-62,AN/SPQ-9B,AEGIS BMD (ACB), 2xMK41 VLS - 32 CELL,IFF,2xCIWS,2xSLQ32,8xMK53 SRBOC&NULKA,2xLaWS
			Option 3	SPY-3,2xSPG-62,AN/SPQ-9B,AEGIS BMD (ACB), 2xMK41 VLS - 32 CELL,IFF,2xCIWS,2xSLQ32,8xMK53 SRBOC&NULKA,2xLaWS
1	**20**	ASUW/NSFS	Option 1	Rail Gun, SPS-73, IRST, 50 cal machine guns, ADS, VLS Hellfire missiles,LaWS,2xCIWS
			Option 2	5in/62 Gun, SPS-73, IRST, 50 cal machine guns, ADS, VLS Hellfire missiles,LaWS,2xCIWS
			Option 3	5in/62 Gun, SPS-73, IRST, 50 cal machine guns, VLS Hellfire missiles,2xCIWS
1	**21**	ASW/MCM	Option 1	5M Dual Band Sonar,ASWCS,ASWTCS,NIXIE,TRIPWIRE, 2xLAMPS and Hangar,SVTT,ASROC,TACTAS,SSDT,CATT/TWS
			Option 2	5M SQS-53D Sonar,ASWCS,ASWTCS,NIXIE,TRIPWIRE, 1xLAMPS and Hangar,SVTT,ASROC,TACTAS,SSDT,CATT/TWS
			Option 3	SQS-53D Sonar,ASWCS,ASWTCS,NIXIE,TRIPWIRE, 1xLAMPS and Hangar,SVTT,ASROC,TACTAS
1	**22**	CCC	Option 1	ExComm Level A, Cooperative Engagement Capability (CEC) and Link 11, Navigation System, TSCE, InTop,MK 37 Tomahawk Weapon System (TWS)
			Option 2	ExComm Level B, Cooperative Engagement Capability (CEC) and Link 11, Navigation System, TSCE, MK 37 Tomahawk Weapon System (TWS)
1	**23**	**AIR**	Option 1	Embarked 2xLAMPS w/ Hangar, 2 x UAV
			Option 2	Embarked 1xLAMPS w/ Hangar, 2 x UAV
			Option 3	2 x UAV w/ Hangar

Comparative naval architecture and preliminary sizing with simple transport factor algorithms (Kennell 2001, 2010) are used to establish the initial hullform exploration design space. Hullform generation, hydrostatic analysis and a Holtrop-Mennen resistance calculation are performed using ORCA3D software as implemented in Rhino. Orca3D includes a number of Hull Assistants that allow the user to specify a set of practical design parameters and create a 3D NURBS hullform as described in Winyall et al. (2012) and shown in Figure 2-9. Separate modules size hull appendages, perform low fidelity seakeeping analysis (PDStrip), and perform propeller selection and optimization (PSOP). Data is collected using a series of design of experiments (DOEs). A number of constraints are applied after data generation, and the design space is refined based on feasible response ranges. DOEs are used to create RSMs and in optimizations for various performance responses like seakeeping, resistance and hydrostatics. Higher fidelity hull resistance prediction and seakeeping methods can also be used in variable fidelity optimizations (Brown et al. 2017).

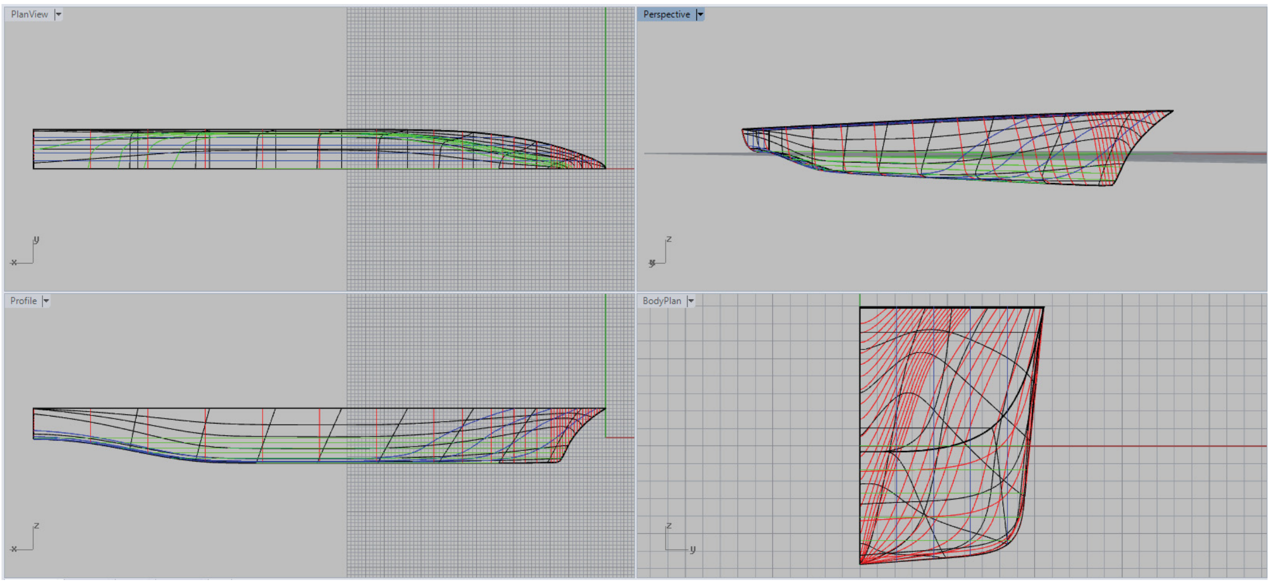

Figure 2-9 – ORCA3D Hullform in Rhino

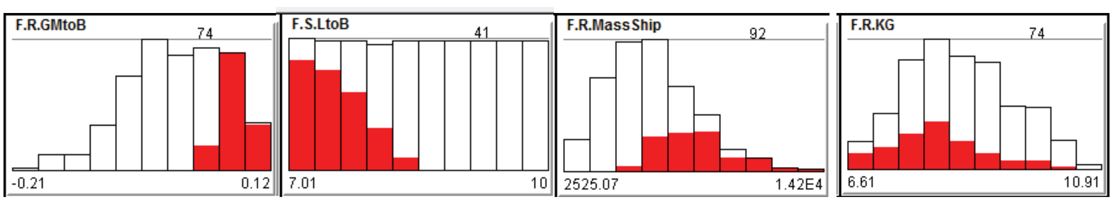

Figure 2-10 – Initial DOE Result Histograms with GM/B>.05 Constraint (in red)

Figure 2-10 shows how histograms may be used to assess hullform DOE data. The full tall white and red bars represent the total data set. An intact stability constraint requiring GM/B>.05 is applied to the data resulting in feasible designs represented by the red bars only. The most significant impact on the design space input in this example is in L/B ratio. Values above 8 did not provide sufficient beam for stability. The L/B range was adjusted to 6 to 7.5 for the next DOE.

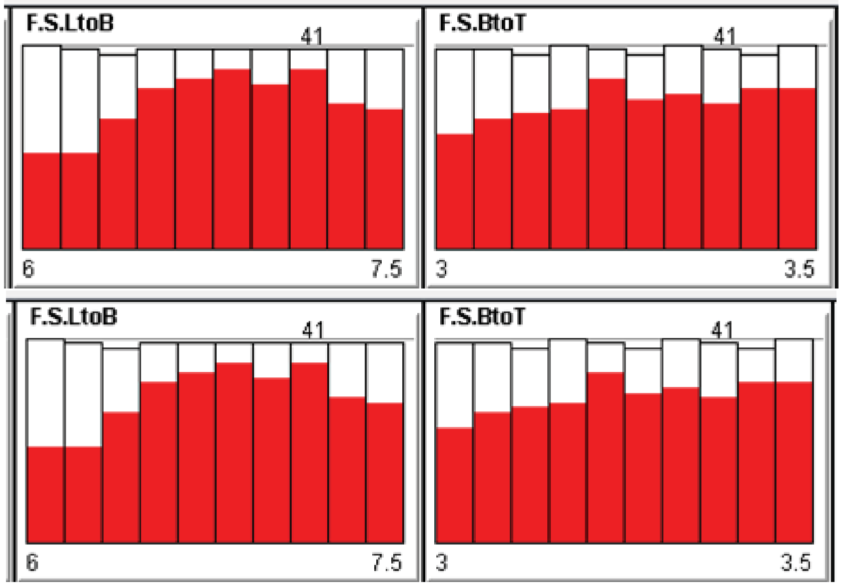

Figure 2-11 – Final DOE Result Histograms (feasible in red)

After a series of design space adjustments, Figure 2-11 results with all constraints applied show excellent feasibility balance across all design variables. The shapes and fullness of critical response histograms are also well distributed and full. This is a significant improvement from the original distributions.

When hullform exploration is complete, RSMs are created from the final data and final design space. These RSMs are shown in the Figure 2-8 Synthesis Model block. RSMs work in conjunction with SSM Excel worksheets in place of traditional parametrics that are applicable only for a narrow range of designs. RSMs include hydrostatics, seakeeping, endurance and sustained speed resistance and propulsion and manning.

The CPES Exploration runs down the right hand side of Figure 2-8. It includes the generation of hullform and deckhouse geometry, subdivision, preliminary arrangements, architecture flow optimization for architecture refinement and vital component sizing, and combat vulnerability assessment. In order to keep the computational burden reasonable, representative designs are created for all combinations of system options listed in Table 2-3, specifically for all combinations of PSYS, AAW, ASUW and ASW DVs. Single midrange hullform DV values except for LOA are used for all representative designs and representative LOA values are calculated as required to support system option weight, space and electric power requirements. Vital Component (VC) sizing data, capability vulnerability probabilities, reliability and architecture are saved for each system option combination in their respective representative designs for recall in ship synthesis. The CPES process is discussed in more detail in a later section.

Once explorations are complete, ship synthesis and optimization are performed using the revised design space, response surface models and CPES data developed in the explorations.

Architecture Flow Optimization (AFO)

Linear programming network flow optimization has been used extensively in transportation networks for shipping, manufacturing flow through production lines and in the design and optimization of telecommunications networks (Ashish 2008, Chinneck 2017, Konak and Smith 2018). Fundamentally, a linear program seeks to minimize or maximize a linear objective function constrained by a set of linear equations. Here, we use a linear programming network flow optimization to insure that all system and operational constraints are satisfied, to calculate necessary commodity flows (mechanical, electrical, fluid), to size vital components, and to minimize the flow capacity cost of vital components, piping and cable. The optimization can also be used to identify unnecessary components in a system architecture that is purposefully designed to have many redundant components and redundant connectivity; hence we have called it an Architecture Flow Optimization (AFO). Vital components are represented as network nodes and piping or cables are represented as network arcs connecting the nodes.

Simultaneous Multi-Commodity Flow (NSMCF) allows multiple commodities or the same commodities at different times or in different scenarios (non-simultaneous) to flow through the network. The objective function can optimize over the aggregate use of the network and instead of minimizing flow cost with arc capacity constraints, it can minimize the required arc capacity or cost over its aggregate use (Trapp 2015). In this AFO application, the number of flow solutions equates to the number of scenarios being evaluated and thus, each scenario is run in the network one at a time with the greatest required flow capacity over all the scenarios (aggregate) being represented in the objective function. Scenarios may be represented as a set of damaged arcs in which flow is not allowed (Trapp 2015) or they may represent various operating conditions. All flows are energy flows in kW. These flows are converted to commodity flows at the conclusion of the AFO.

Trapp introduced the idea of using this NSMCF network optimization method to design an Integrated Engineering Plant (IEP). Trapp considered two interrelated plexus, electrical and thermal subsystems, modeled as a single multiplex system and optimized to minimize cost with constraints for operational flexibility and survivability (Trapp 2015). Trapp focused his research on this method and writing code to prepare the optimization for running in simplex linear program form. IBM ILOG CPLEX Optimization studio (CPLEX) was used to perform the actual optimization once the equations were assembled. CPLEX is a commercially available software optimization package (IBM 2014).

Robinson extended Trapp's NSMCF method to consider 8 plexus (or subsystems) each with its own commodity and dedicated arcs in a total ship system architecture flow optimization (AFO) (Robinson 2018). Subsystems interact at a few common nodes and particularly through the electric and HVAC subsystems. Connections between nodes of a common plex and commodity are described using explicit arcs. Connections between nodes of different plexus and commodities are described using dependencies or implicit arcs. Ship and system data, logical architecture, operational scenarios and preliminary arrangement necessary for formulating the simplex optimization are extracted directly from a ship synthesis model using a representative ship sized for the selected system options.

The definition of the physical solution is effectively completed in three steps: 1) complete a preliminary assignment of compartments and VCs to SBDs; 2) complete an architecture flow optimization considering energy and data flow in all subsystems with VC locations; and 3) transform the energy solution into a complete physical solution including the actual commodity flows (LO, SW, CW, electrical, mechanical, EC, Glycol, HVAC) and the sizing of physical components.

The major differences between this AFO formulation and Trapp's NSMCF are:

1. Only energy is explicitly tracked in the AFO as carried by the various commodities. The calculation of commodity flows and component sizing is postponed until post-AFO.
2. Nodal equations do not just consider continuity. They specify the allocation of energy to alternative commodity arcs entering and leaving nodes as presented in Section 4. Continuity is enforced indirectly. Commodities do not interact directly with one another but transfer their energy from one to the other via nodal connectivity and energy conversion. This requires a different formulation of the optimization problem from Trapp's NSMCF formulation, particularly in the nodal constraints and energy conservation/partitioning.
3. The number of plexus included in the multiplex model is much larger and essentially unlimited.
4. System architectures (logical, physical and operational) and other input data is extracted directly from a total ship model as part of a ship C&RE.

Nodal equations and optimization constraints model nodal continuity, energy allocation and conversion into arcs of various commodities, and determine the electrical load required to transport these commodities using pumps and motors.

The AFO execution process is shown in Figure 2-12.

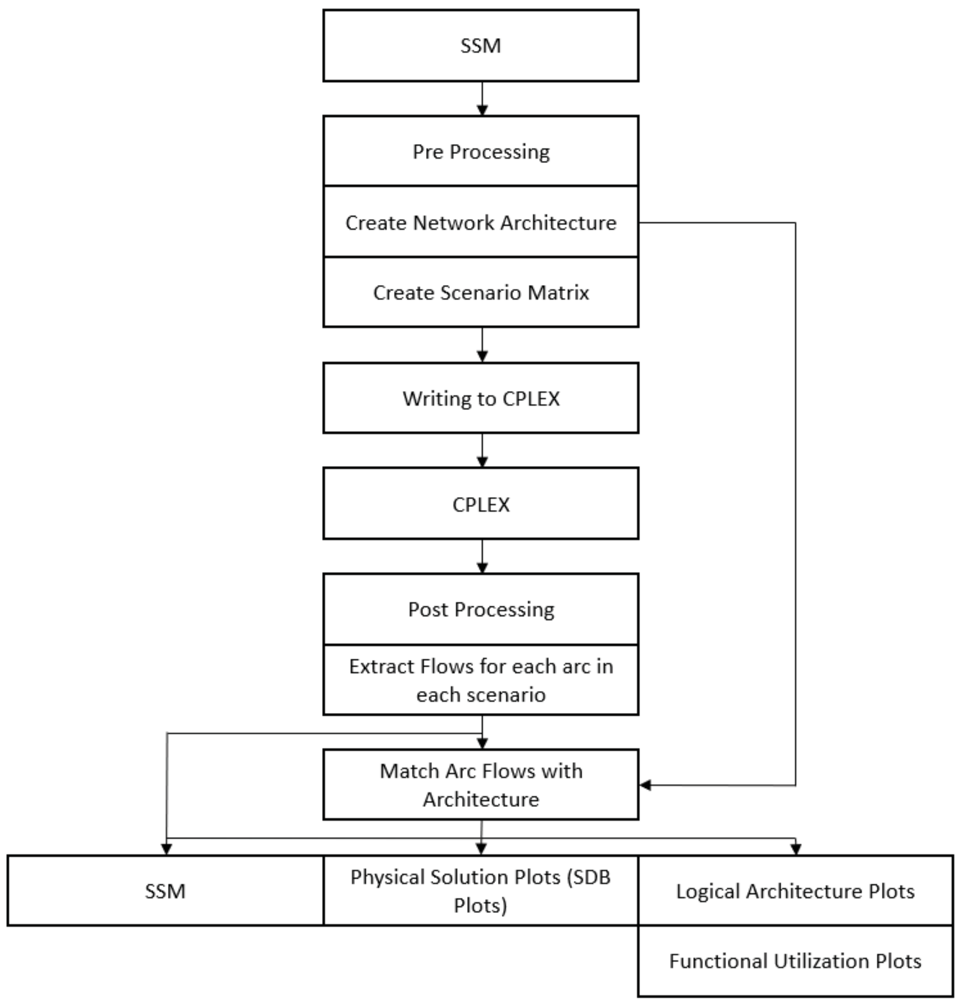

Figure 2-12 - AFO Execution Process

CPES Exploration

Figures 2-3 and 2-13 show process and notional views of how the CPES architectural framework, Figure 2-1, is implemented in the Figure 2-2 C&RE process. In Figure 2-3 Step #1, an Initial Capabilities Document (ICD) identifies the mission need and capability gaps used in a technology review to identify combat, power and energy system technology options consistent with the ship mission and at a stage of development that would make them available in time for use in the ship. In a future naval surface combatant, this might include a rail gun, laser weapon systems, new radars, permanent magnet motors, new power conversion technology and new energy storage technology. Each of these technologies is evaluated in terms of their potential performance and technology risk and the results of this analysis is considered in the OMOR and OMOE metrics discussed previously. A Design Reference Mission (DRM) with specific Operational Situations (OpSits) is developed to define the Operational Architecture.

In Figure 2-3 Step #2 Operational Effectiveness (War-gaming) Models are used to implement missions and OpSits specified in the DRM often using agent-based simulations. Data from these simulations is extracted to create probabilistic event trees as shown in Figure 2-14 and applied in the operational architecture as scenarios in the AFOs (Brown and Kerns 2010, Kerns et al. 2011a, Kerns et al. 2011b, Brown 2013).

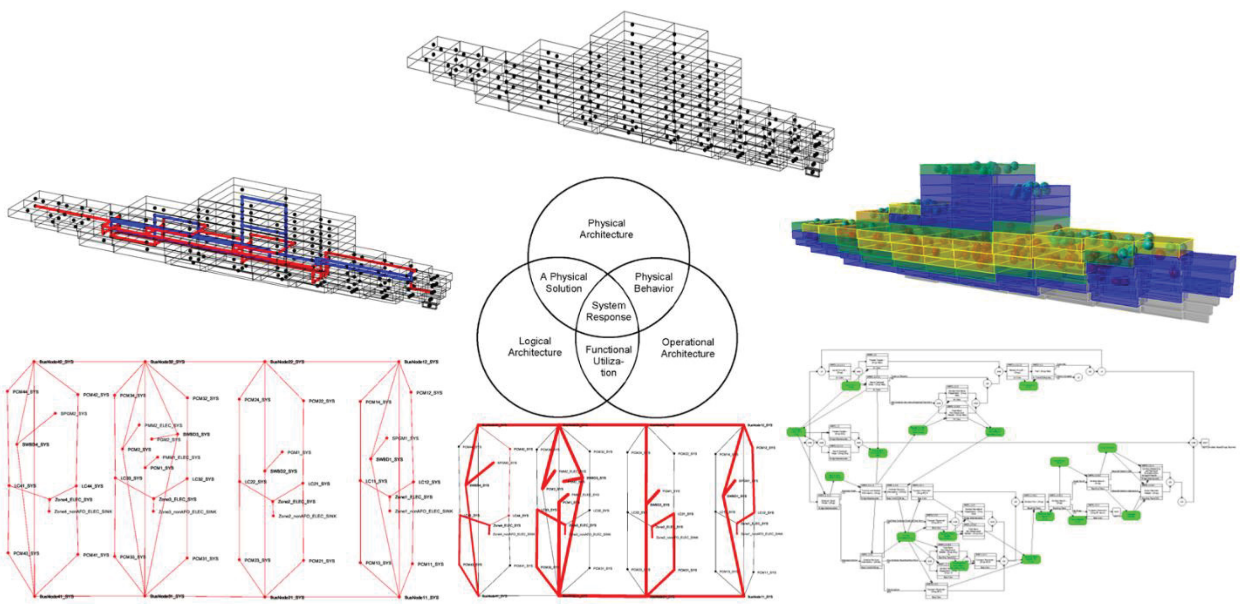

Figure 2-13 - Notional Network Architecture Implementation in C&RE

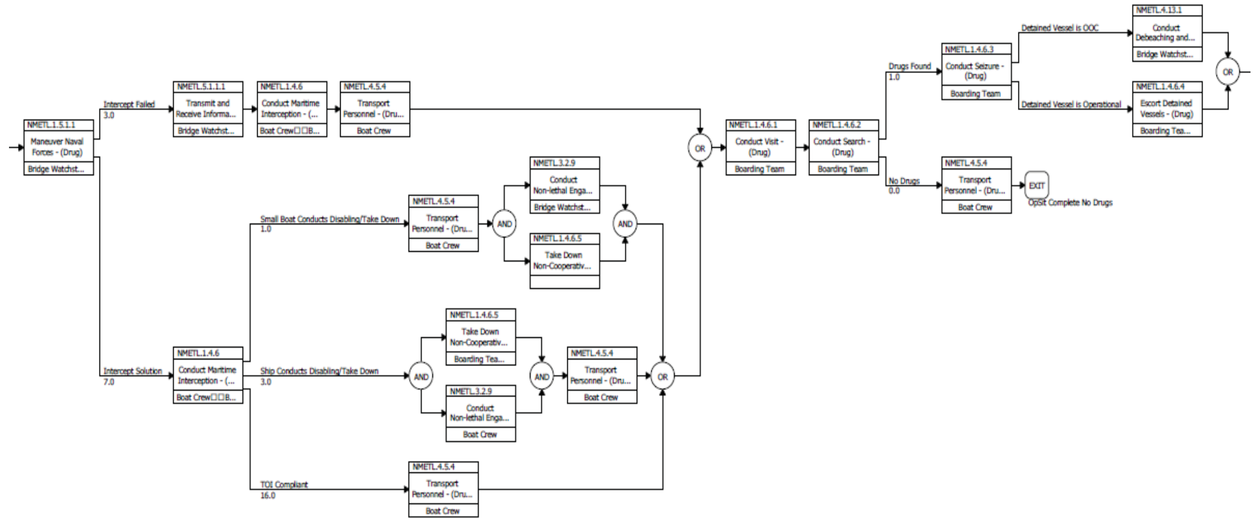

Figure 2-14 - Drug Interdiction Event Tree (Kerns et al. 2011b)

In Figure 2-3 Step #3, CPES System options are defined using the selected technologies and organized using design variables (PSYS, AAW, ASW, ASUW, etc.) as listed in Table 2-3. Data describing these options (space, weight, power, compartment locations) is collected in combat system and machinery equipment lists (CSELs and MELs). The technologies become logical architecture vital components (VCs) or nodes.

In Figure 2-3 Step #4 system baseline logical architectures are defined for each system option by integrating selected technology components in systems that provide specific capabilities required by the ship. In the naval mission area these include Anti-Air Warfare (AAW), Anti-Submarine Warfare (ASW) and Anti-Surface Warfare (ASUW) systems. Power and energy systems typically include propulsion, electric distribution, fuel oil, machinery control, steering, and thermal systems (lube oil, HVAC, seawater, chilled water, electronic cooling, and glycol cooling). The logical architectures for these systems may be developed manually from scratch, using automated architecture generation (de Vos and Stapersma 2018), by modifying and updating existing system architectures, or using software like the Smart Ship Systems Design (S3D/LEAPS) tool.

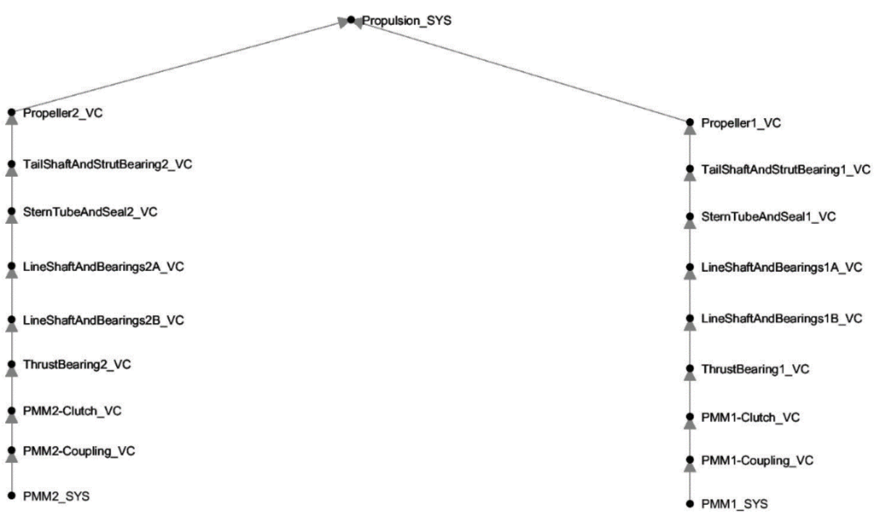

Figure 2-15: Mechanical (Propulsion) Subsystem. (MECH)

A simple logical system architecture for a mechanical subsystem in an integrated power system is shown in Figure 2-15. Each component or node in this architecture has physical attributes and is ultimately located physically in the ship in the “physical solution”. It is also part of the larger total ship system of systems shown in Figure 2-16.

The mechanical subsystem logical architecture in Figure 2-15 is very basic. It begins with two Propulsion Motor Modules (PMMs) that also appear in the Electric Distribution subsystem. These PMMs connect to fixed-pitch propellers through couplings, clutches, bearings, stern tube and seals. There are two redundant shaft lines in parallel, with components in each shaft line in series required for operation. Each node represents a mechanical subsystem vital component (VC). Electrical distribution and other architectures are typically more complex.

Figure 2-3 Step #5 begins development of the physical architecture. Physical architecture has two important classes of information: (1) the constraining architecture defined by the ship arrangement and relationships with compartments and subdivision; and (2) the physical attributes (weight, dimensions) of components of a given distributed system and their locations relative to each other in the ship. The constraining architecture defines the organization and overall layout of major compartments and thus the possible spatial configurations that a given distributed system can take within and between these spaces. It creates bounds on the possible layout configurations of distributed systems. In early stage design, physical architecture must be kept as simple as possible.

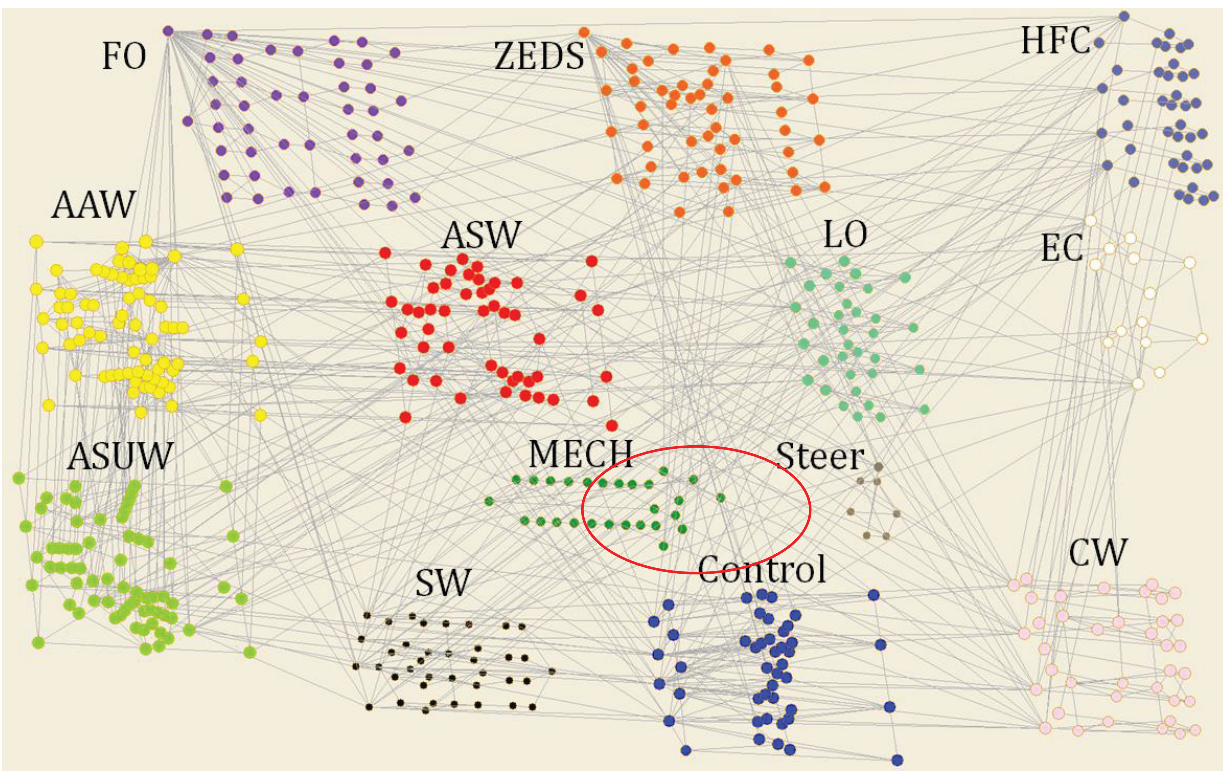

Figure 2-16 - Notional Total-Ship System Architecture

A number of different ship design approaches exist for developing the constraining ship physical architecture: Design Building Blocks (Pawling 2007, Andrews et al. 2012), Bin-Packing (van Oers et al. 2010, van Oers 2011, Duchateau 2016), Intelligent Ship Arrangements (Parsons et al. 2008), Subdivision Block (SDB) Compartment Allocation (Brown and Sajdak 2015, Goodfriend and

Brown 2018) and nodal or network representations (Gillespie et al. 2012, Gillespie et al. 2013, Gillespie and Singer 2013). Some of these approaches work from the inside-out (blocks to hull) and others from the outside- in (hull to blocks), but all use or represent some form of spatial blocks within the ship with network nodes and connecting arcs or edges representing their adjacency. The Subdivision Block (SDB) Compartment Allocation approach is illustrated in Figure 2-17 and a nodal or network approach is illustrated in Figure 2-18.

The SDB approach begins with a preliminary hullform and deckhouse geometry generated with less than a dozen simple design variables (Figure 2-3, Step #5) in the Hullform Exploration as discussed previously. Representative designs are sized to support a particular selection of system options in Step #6. In Step #7, transverse bulkheads and decks are added based on stack-up lengths, floodable length parametrics, average deck height and "style" considerations (McDonald 2009, Andrews 2018). Intersections between transverse bulkheads, decks and the hull are determined and a SDB representation is created as shown in Figure 2-17. External (ghost) blocks are added for locating topside equipment and some blocks are split port and starboard to allow for separate allocations of distributed systems where port and starboard redundancy is important to determining vulnerability.

Once this simple 2.5D geometry is created, compartments and components are allocated to SDBs in Figure 2-3, Step #8. From this point on, a network-approach may be used by representing SDBs using a nodal matrix consistent with Figure 2-17. Logical architecture vital components (VCs) or nodes are mapped to physical architecture SDBs or nodes by first assigning VCs to compartments and then assigning compartments to SDBs based on metrics and priorities assigned to the SDB nodes as shown in Figure 2-19. These metrics may be operability metrics, probabilities of kill given hit, shock factors or other scalar values. Multi-edge paths between pairs of nodes may be identified based on the same or other metrics and these paths used to route distributed system piping, cables and shafting as shown in Figure 2-20. When applied to all subsystems, this completes a simple logical and physical model, the "physical solution", sufficient for architecture flow optimization, preliminary sizing of components, and reliability and vulnerability assessment.

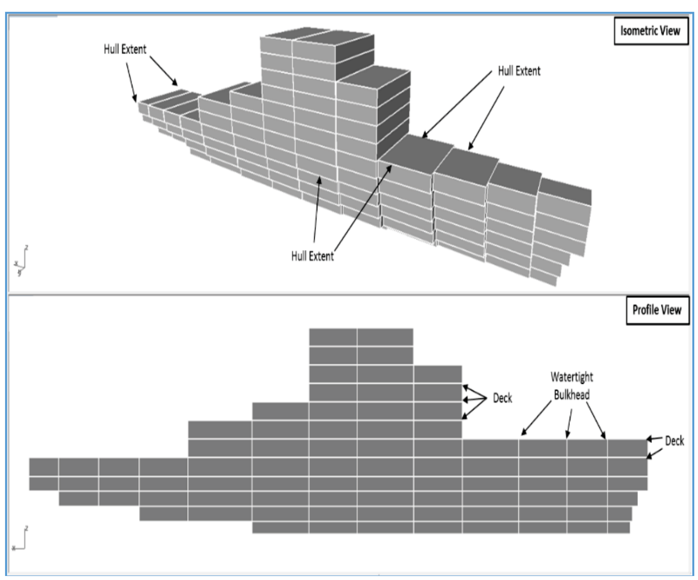

Figure 2-17 - Subdivision Block (SDB) Representation of Physical Architecture

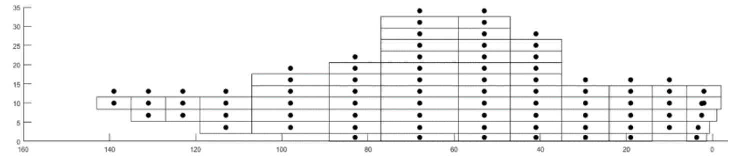

Figure 2-18 - Nodal or Network Representation of Physical Architecture

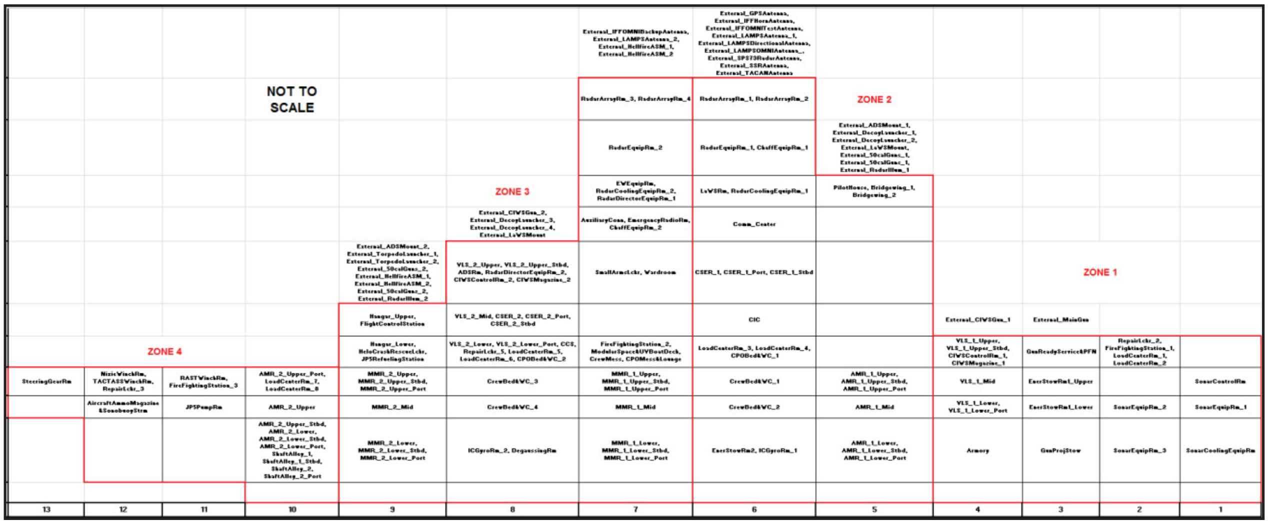

Figure 2-19 - Vital Components (VCs) and Compartments Allocated to Subdivision Blocks (SDBs)

Once the physical, logical and operational architectures have been defined, their interactions or intersections are used to perform simulations, optimizations and analyses, and find physical solutions, physical behavior, functional utilization solutions, and ultimately the system response. For example, operational architecture intersects with physical architecture and results in physical behavior when OpSit scenarios result in weapon hits being applied to the physical architecture as shown in Figure 2-21. Each hit location has a calculated hit probability. A damage ellipsoid that considers the type of weapon and the ship structure is applied for each hit as shown in Figure 2-22. If a damage ellipsoid intersects a SDB, all VCs in that SDB are deactivated. When the full set of hits are evaluated, hit probabilities for each subdivision block may be calculated as shown in Figure 2-23.

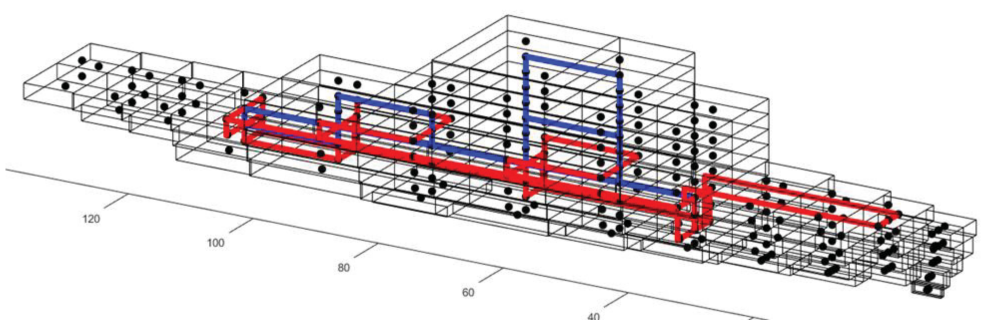

Figure 2-20 - Routing of Distributed Systems (Red = electric, Blue = chilled water)

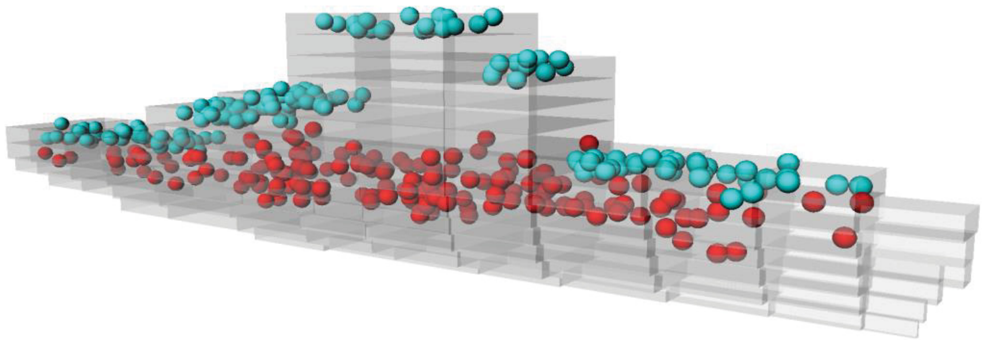

Figure 2-21 - Weapon Hit Locations

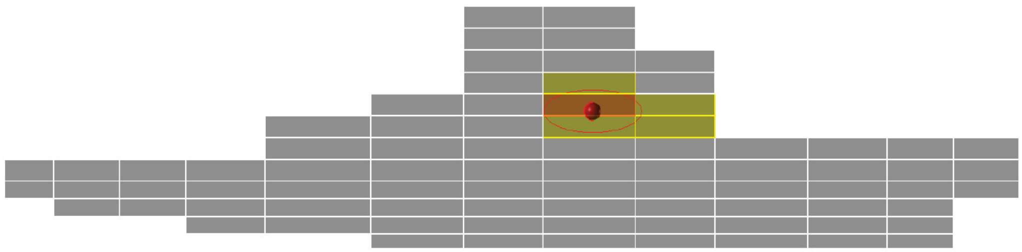

Figure 2-22 - Damage Ellipsoid Intersection with SDBs

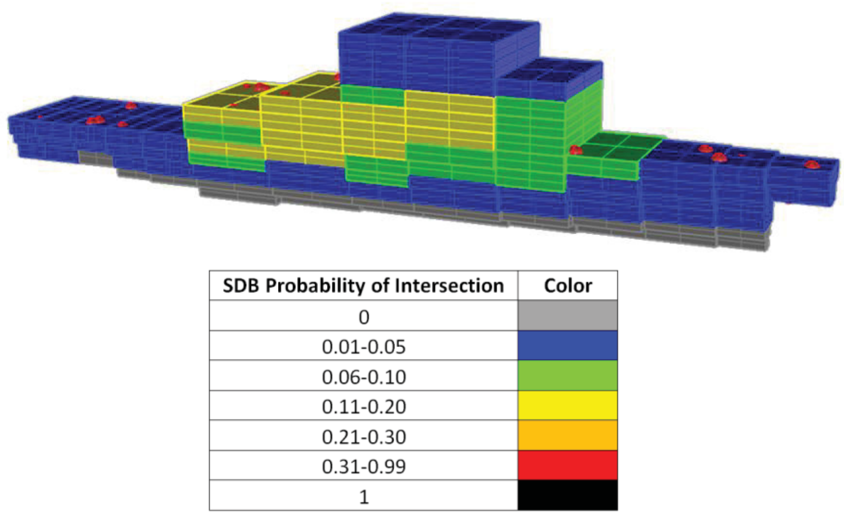

Figure 2-23 - SDB Hit Probabilities

This intersection may be further extended to intersect with logical architecture by applying SDB deactivation to VCs contained in the damaged SDBs. The process to calculate this intersection is shown in Figure 2-24. The impact of VC deactivation on system function and ship capability can be assessed in two ways: 1) using deactivation diagrams generated from the logical architecture as shown in Figure 2-25; and 2) using architecture flow optimization node/arc deactivation. The deactivation diagram method is computationally fast, but only considers whether VCs are active and connected. The AFO approach takes longer, but considers the capacity of components and connections (pipes and cable). We use both methods in our process. Figure 2-3 Step #9 uses an AFO, but instead of considering actual hit damage scenarios, more simply deactivates one SDB at a time and requires the ship to maintain its capability with these losses in addition to normal operational conditions for endurance, sustained speed and battle. These requirements are used to size power and energy components and their connections in Figure 2-3, Step #10. Since the physical size of components (weight, dimensions, space requirements) is directly related to capacity, it is also determined at the functional utilization intersection.

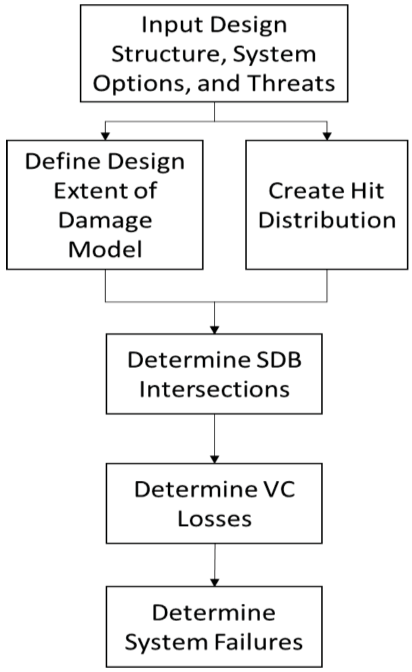

Figure 2-24 - System Damage Response Intersection Process

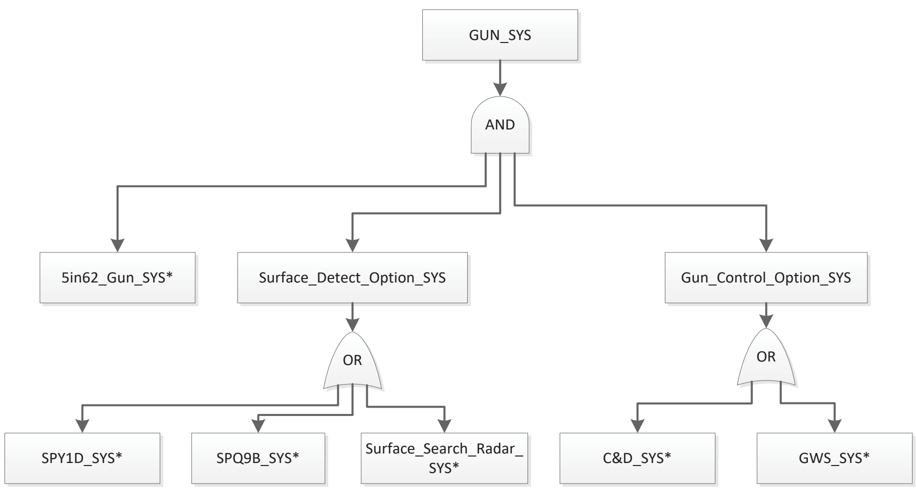

Figure 2-25 - Gun System DBD

Figure 2-3 Step#13 considers only the deactivation of VCs and uses deactivation diagrams to calculate vulnerability and reliability. The vulnerability analysis calculates probabilities of kill given hit, $P_{k/h}$'s, for the various ship combat capabilities and system combinations (Goodfriend and Brown 2018). This data is stored and can be recalled for use in OEMs and to calculate the OMOE during ship synthesis. The reliability analysis calculates system availability and is also used in OEMs and to calculate the OMOE.

Once system components are sized and the architecture optimized in the first CPES Exploration AFO, Step #9, the resulting systems may then be applied in a second CPES quasi-dynamic AFO

(DAFO). Cramer et al. (2013) proposed a linear programming method applied in the time domain where an optimization is performed on the static electric/mechanical/ thermal system at each time step effectively providing a heuristic approximation of an ideal power management system in time. The same linear programming formulation developed in the our AFO can be applied with additional component model characteristics and a power management objective. This DAFO can be used for recoverability assessment and energy storage sizing. This is performed in Figure 2-3, Step #12.

The CPES process, Figure 2-3 Steps #3 through #13, are completed for each combination of CPES DV options (PSYS, AAW, ASW, ASUW) in their representative designs, typically 250-500 combinations. Data from each of these combinations are collected and saved for application in ship synthesis, Step #14. The Ship Synthesis Model (SSM) is applied using a Multi-Objective Genetic Optimization (MOGO) to search the design space, identify layers of non-dominated designs, support design selection and complete the C&RE process shown in Figure 2-2. The SSM uses hullform-related RSMs from the Hullform Exploration, a Manning RSM from the Manning Exploration, and system combination CPES data including vulnerability, availability, recoverability and component sizing weight/space/ power (including energy storage) from the CPES Explorations to assess design feasibility and calculate design objective attributes for cost, effectiveness and risk.

Conclusions and Way Ahead

The network architecture framework presented in this paper promises to be a powerful tool for formulating and analyzing system problems using simple metrics in naval ship concept exploration. This framework is extremely helpful for understanding, decomposing and integrating system of system problems. It enables fast and simple tools for connectivity optimization, component sizing, system vulnerability and recoverability analysis, and energy storage considerations using an architectural flow optimization. It offers great potential for implementation in the US Navy's RSDE/LEAPS suite of tools.

Ongoing and future work using this framework and related tools includes:

- Refinement of Architecture Flow Optimization (AFO) methods for early naval ship distributed system design.
- Improvement of tools for preliminary naval ship arrangements with UNDEX and UNDEX Shock Vulnerability Assessment criteria in addition to AIREX.
- Development of naval ship system deactivation diagrams directly from a network architecture framework for use in vulnerability and reliability analyses.
- Extension of network architecture framework applications in US Navy FOCUS-compliant ship design including the extraction of network architecture from LEAPS data.
- Further refinement and implementation of network architecture framework in total ship synthesis for flexible machinery system sizing and collection of data.
- Development of time-based operational architecture methods and tools in the network architecture framework for naval ship Concept and Requirements Exploration (C&RE) and sizing of energy storage systems. Incorporate energy storage into AFO to manage OpSit stochastic loads over time and run in AFO time-based simulation.
- The use of Operational Effectiveness Models (OEMs) with Operational Architecture for C&RE.

- The use of time-based stochastic loads (from DDS 310-1) and application of load-shedding doctrine consistent with required ship external time-based operational situation task requirements implemented in the operational architecture.

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3. Early-Stage Naval Ship Distributed System Design Using Architecture Flow Optimization

Mark A. Parsons (SM)[1], **Mustafa Y. Kara** (SM)[1], **Kevin M. Robinson** (M)[2], **Nicholas T. Stinson** (AM)[1] **and Alan J. Brown** (FL)[1]
[1]Kevin T. Crofton Dept. of Aerospace and Ocean Engineering, Virginia Tech, Blacksburg, VA
[2]Naval Architecture and Marine Engineering Section, United States Coast Guard Academy, New London, CT

This paper describes the Architecture Flow Optimization (AFO) method, a network-based method for designing and analyzing naval ship Combat, Power, and Energy Systems (CPES). This method is used in an established naval ship Concept and Requirements Exploration (C&RE) process. Both this method and process decompose CPES into three architectures: logical, physical, and operational; describing the system's spatial, functional, and temporal characteristics respectively. AFO incorporates system topologies, input/output energy coefficient vital component models, preliminary arrangements, and (nominal and damaged) steady state operational scenarios into a linear optimization method to minimize the energy flow cost required to satisfy all operational scenarios demands and constraints. AFO results are used to inform system topology design and assess the feasibly and survivability of a representative design in the C&RE process. AFO results may also be used in a physics-based vital component sizing method, a subsequent higher fidelity preliminary arrangement, and survivability/effectiveness metrics in the C&RE process.

KEY WORDS: ship design, naval ship, warship, distributed system, system architecture, survivability

INTRODUCTION AND MOTIVATION

Combat, Power, and Energy Systems (CPES) are fundamental to the mission and design of modern naval surface combatant ships. CPES are distributed systems: mechanical, electrical, thermal, and electronic components distributed throughout a ship and connected to work together. Understanding CPES architecture and design is critical in determining a naval ship's combat effectiveness and survivability (Brown 2019).

These systems, particularly power and energy systems, have been traditionally represented in "one-line diagrams" and "machinery equipment lists". Modern distributed systems are increasingly more interconnected and interdependent than their less capable predecessors. This complexity can make CPES vulnerable to cascading failure and unforeseen behaviors that given current design practices would only become evident when the system is in operation.

Distributed systems are also interdependent with the ship's general arrangement which may be considered a distributed system itself. CPES component physical locations and connectivity within the ship determine critical attributes and functionality of these systems and visa-versa. Understanding relationships between various attributes of these systems in a total system perspective is critical to achieving uninterrupted effective operations, performance, reliability, safety, naval ship survivability and affordability (Brown 2019).

Brefort et al. (2018) confirmed the need to consider these system interdependencies and proposed an architecture framework for ship distributed systems. This framework provides a structured way to decompose the logical, physical, and operational aspects of a distributed system and represent their interdependencies. Figure 3-1 shows this decomposition visually in a Venn diagram. The logical architecture describes the relationship of system components, the physical architecture describes the distributed system spatial arrangement and physical attributes, and the operational architecture describes the temporal behavior characteristics of the ship and systems performing their mission(s) and functions.

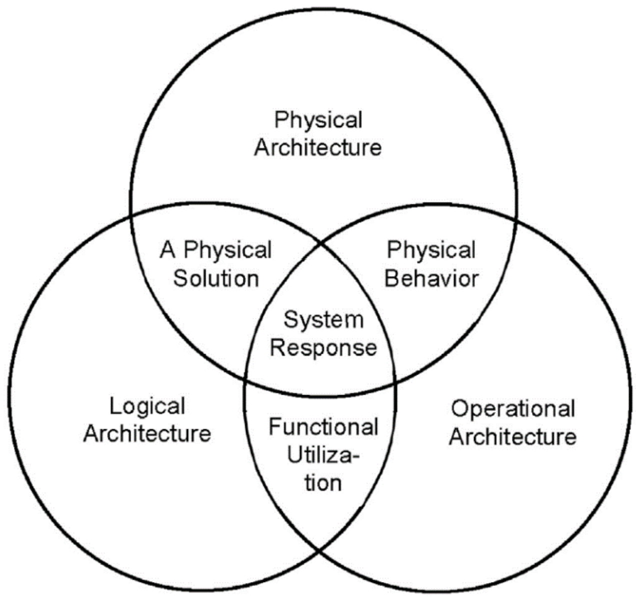

Figure 3-1: Architecture Framework for Ship Distributed Systems (Brefort et al. 2018)

Parsons et al. (2019) describe an application of this distributed system architecture framework to a naval ship Concept and Requirements Exploration (C&RE) process developed, expanded, and applied over two decades at Virginia Tech and MIT (Brown and Thomas 1998, Brown and Salcedo 2003, Stepanchick and Brown 2007, Strock and Brown 2008, Brown and Sajdak 2015, Goodfriend and Brown 2018, Robinson 2018). The C&RE process includes combat vulnerability and survivability assessment; a task usually deferred to preliminary design or later when higher levels of detail are available. If this task is deferred, changes to the distributed systems become difficult and/or costly to make as many important design decisions are made during concept exploration.

An important element of the C&RE Process is the CPES Exploration process, illustrated in Figure 3-2. In this process, an Initial Capabilities Document (ICD) identifies the mission need and capability gaps which are used to guide a technology review to identify CPES technology options consistent with the ship mission and at a stage of development that would make them available in time for use in the ship.

The CPES physical architecture has two important classes of information: (1) the constraining architecture defined by the ship arrangement and relationships with compartments and subdivision; and (2) the physical attributes (weight, dimensions) of components of a given distributed system and their locations relative to each other in the ship. The constraining architecture defines the organization and overall layout of major compartments and thus the possible spatial configurations that a given distributed system can take within and between these spaces. It creates bounds on the possible layout configurations of distributed systems. The process discussed in this paper divides the ship into subdivision blocks (SDBs) bounded by decks and transverse bulkheads within the hull and deckhouse. A preliminary arrangement assigns compartments and their associated logical architecture system components to SDBs, effectively locating components within the ship. Physical architecture is described more completely later in this paper.

CPES components are assigned compartment locations within the hull and deckhouse of a representative design which are subsequently arranged into Subdivision Blocks (SDBs) in the physical architecture. Representative designs include hull, subdivision and preliminary arrangements synthesized for each combination of CPES system options. A single set of midrange hullform DV values except LOA are used for all representative designs. LOA values are calculated (not optimized) as required to support system option weight, space and electric power requirements (Parsons et al. 2019). This provides the necessary input for CPES Exploration #1 which is the primary subject of this paper. Results are saved for each system option combination with their respective representative designs for recall in the final ship synthesis whenever this set of options is selected.

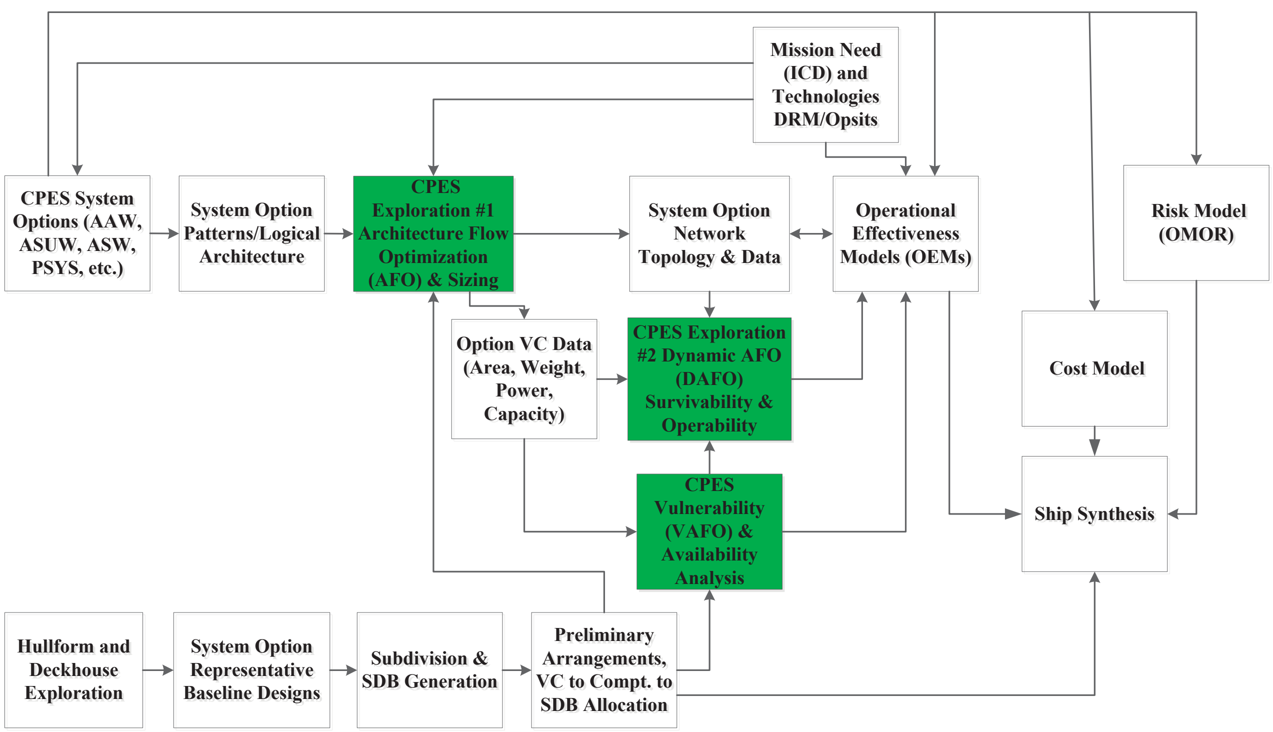

Figure 3-2: CPES Design (Parsons et. al 2019)

An Architecture Flow Optimization (AFO) or energy flow assessment is performed in CPES Exploration #1 for each system option combination in the design space. Following the AFO, CPES components are sized based on their energy flow requirements. In previous versions of this CPES design process, components were sized manually or parametrically. An energy flow optimization provides a more rational and physics-based means of sizing components. These sized components are used in the second CPES Exploration #2 where more complex operational scenarios and damage recoverability are assessed and in a CPES Vulnerability and Availability Analysis (VAFO).

Trapp (2015) introduced the idea of using a network flow optimization to design an Integrated Engineering Plant (IEP) consisting of two interrelated subsystems: electrical distribution and cooling. His approach minimizes the cost of electrical energy and cooling fluid flows in the network with constraints for arc survivability. This linear optimization uses CPLEX Optimization Studio (CPLEX), a commercially available linear optimization program developed by IBM ILOG (IBM 2015).

Robinson (2018) modified Trapp's approach to consider the energy flow in eight plexus (or subsystems) in in a total ship system with a more realistic survivability assessment. These plexes interact through a few common nodes and in particular through the electrical, chilled water, and HVAC subsystems. Ship data, system logical architecture, preliminary arrangements, and operational scenarios necessary for running the optimization are provided in their representative baseline designs and operational architecture.

This paper expands Robinson's (2018) method and further describes the distributed system architecture framework developed by Parsons et al. (2019). Once a system's logical, physical, and operational architecture attributes are defined, an architecture flow optimization (AFO) can be performed. The AFO assembles and intersects these architectures, satisfies all operational requirements, and determines the optimum energy flow through the total system.

The AFO energy flow results are used to modify the system's logical architecture, calculate commodity flows (mechanical, electrical, fluid), size vital components, and ultimately synthesize the total ship design. These results are also very informative for the designer and marine engineer to better understand the energy flow through the various ship systems from both logical and physical perspectives during various operational situations.

LOGICAL ARCHITECTURE

Distributed systems and their components can be characterized by their commodity flow (mechanical or electric power, chilled water, lube oil, seawater, glycol coolant, data, etc.) and their ability to transport, store, or convert energy. The AFO simple energy flow model does not require "through" variables (i.e. current, flow rate, speed) or "cross" variables (i.e. voltage, pressure, torque). The AFO assumes a steady or quasi-steady state and models complex behaviors like pump curves, engine maps, power conversion, or heat exchange using simple energy flow coefficients and conservation of energy for each node. Components are assumed to operate at their nominal design conditions. This simple logical architecture has a sufficient level of detail for component sizing and system refinement in early-stage design.

A plex is created by integrating selected technology components in systems that provide specific capabilities required by the ship. Each plex is restricted to a single commodity flow. As a result, plexes are similar to traditional marine engineering distributed systems (i.e. fuel oil service system, electrical distribution system, chilled water system, AAW system) (Brown 2018). These plexes serve as the fundamental grouping for objects of study in the AFO.

A node is a representation of a single or multiple flow operations (e.g. source, sink, distribution, or conversion). Most nodes model the behavior performed by single component. This behavior may interact with a single or multiple plexes. Nodes representing a single flow operation of the source or sink type may not be associated with a component. These unassociated source/sink nodes represent the ship's interactions with the environment.

Generally, connections between nodes are called edges; they may be directed or undirected. The AFO only uses directed edges (also called arcs) and approximates undirected edges with two opposing arcs. In the AFO, arcs connecting two nodes in a single plex are called explicit arcs and arcs connecting two nodes in different plexes are called implicit arcs. Figure 3-3 shows a notional multiplex network for a Future Surface Combatant (FSC) and shows both explicit and implicit arcs. This network includes the following plexes:

1. Mechanical Propulsion System (MECH)
2. Zonal Electrical Distribution System (ELEC)
3. Machinery Control System (CONT)
4. Chilled Water System (CW)
5. Fuel Oil Service System (FO)
6. Hydrofluorocarbon System (HFC)
7. Lube Oil Service System (LO)
8. Seawater Cooling System (SW)
9. Hydraulic Steering System (STEER)
10. Electronic Cooling System (EC)
11. Glycol Cooling System (GLYCOL)
12. Heating, Ventilation, and Cooling System (HVAC)
13. Anti-Air Warfare System (AAW)
14. Anti-Surface Warfare System (ASUW)
15. Anti-Submarine Warfare System (ASW)

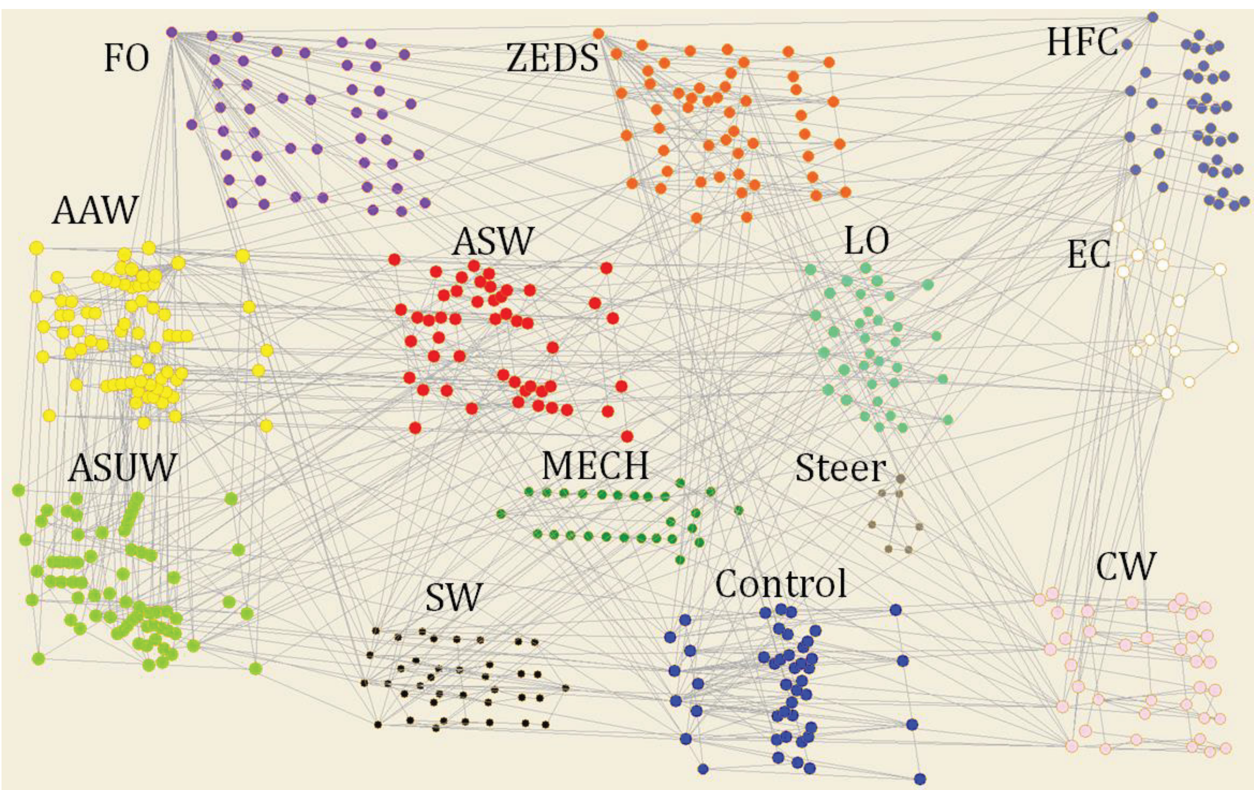

Figure 3-3: Notional Future Surface Combatant Total-Ship Multiplex Logical Architecture

Each node is assigned a unique node number, a compartment, a Machinery Equipment List (MEL) number and any implicit to/from arcs as shown in Figure 3-4. The compartment assignment is used in defining the physical architecture of the system, described in the next section. Explicit arcs are defined as ordered pairs of node numbers. The first node is the tail of the arc and the second node is the head of the arc.

DV	Node	Vertex Label / VC	Compartment	MEL#	VC Dependency	Dependency 1 / Arc From	Dependency 2 / Arc From	Dependency 3 / Arc From	Dependency 4 / Arc To	Dependency 5 / Arc to
PSYS	**2**	**IPS, MVDC**								
*Vertices										
MECH	1	Propulsion_SYS	0	114		PMM1_SYS	PMM2_SYS			
	2	Propeller1_VC	ShaftAlley_1_Stbd	21						
	3	TailShaftAndStrutBearing1_VC	ShaftAlley_1_Stbd	23						
	4	SternTubeAndSeal1_VC	ShaftAlley_1_Stbd	24						
	5	LineShaftAndBearings1A_VC	ShaftAlley_1_Stbd	25					Zone3_Air_Heat_SYS	
	6	LineShaftAndBearings1B_VC	ShaftAlley_1_Stbd	25					Zone3_Air_Heat_SYS	
	7	ThrustBearing1_VC	MMR_2_Lower	26						Zone2_Air_Heat_SYS
	8	PMM1_SYS	MMR_2_Lower	7	PMM1_VC	PMM1_ELEC_SYS	PMM1_LO_SYS	PMM1_CONT_SYS	PMM1_LO_SYS	Zone2_Air_Heat_SYS
	9	PMM1-Coupling_VC	MMR_2_Lower	27						
	10	PMM1-Clutch_VC	MMR_2_Lower	28						
	11	Propeller2_VC	ShaftAlley_2_Port	21						
	12	TailShaftAndStrutBearing2_VC	ShaftAlley_2_Port	23						
	13	SternTubeAndSeal2_VC	ShaftAlley_2_Port	24						
	14	LineShaftAndBearings2A_VC	ShaftAlley_2_Port	25					Zone3_Air_Heat_SYS	
	15	LineShaftAndBearings2B_VC	ShaftAlley_2_Port	25					Zone3_Air_Heat_SYS	
	16	ThrustBearing2_VC	AMR_2_Lower_Port	26						Zone3_Air_Heat_SYS
	17	PMM2_SYS	AMR_2_Lower_Port	7	PMM2_VC	PMM2_LO_SYS	PMM2_ELEC_SYS	PMM2_CONT_SYS	PMM2_LO_SYS	Zone3_Air_Heat_SYS
	18	PMM2-Coupling_VC	AMR_2_Lower_Port	27						
	19	PMM2-Clutch_VC	AMR_2_Lower_Port	28						
ELEC	101	BusNode12_SYS	AMR_1_Lower_Port	1	BusNode12_VC				Zone2_Air_Heat_SYS	
	102	PCM14_SYS	AMR_1_Upper_Port	2	PCM14_VC				Zone1_Air_Heat_SYS	
	103	PCM12_SYS	AMR_1_Lower_Port	2	PCM12_VC				Zone1_Air_Heat_SYS	
	104	LC11_SYS	LoadCenterRm_1	3	LC11_VC				Zone1_Air_Heat_SYS	
	105	SWBD1_SYS	AMR_1_Upper	4	SWBD1_VC	SWBD1_CONT_SYS			Zone2_Air_Heat_SYS	
	106	LC12_SYS	LoadCenterRm_2	3	LC12_VC				Zone1_Air_Heat_SYS	
	107	PCM13_SYS	AMR_1_Upper_Stbd	2	PCM13_VC				Zone1_Air_Heat_SYS	
	108	PCM11_SYS	AMR_1_Lower_Stbd	2	PCM11_VC				Zone1_Air_Heat_SYS	
	109	BusNode11_SYS	AMR_1_Upper_Stbd	1	BusNode11_VC				Zone2_Air_Heat_SYS	
	110	Zone1_ELEC_SYS	0	116		SPGM1_SYS	SPGM2_SYS	PGM1_SYS	PGM2_SYS	
	111	BusNode22_SYS	MMR_1_Lower_Port	1	BusNode22_VC				Zone2_Air_Heat_SYS	

Figure 3-4: Vital Components, Their Compartment Assignments, and Their Implicit Arcs

The baseline attributes of each power and energy node in this multiplex are populated from a MEL based on their MEL number; all components of the same type, with the same MEL number, have the same baseline attributes. The MEL is a complete list of power and energy component types in the multiplex. The component attributes stored in the MEL are baseline weight, volume, area, electric power, and input/output energy coefficients. A similar combat systems equipment list (CSEL) exists for components in the AAW, ASUW, and ASW plexes. The CSEL includes two required electric power values for each component: a battle power and a cruise power (Parsons et al. 2019). Required battle power may be adjusted depending on operational requirements and additional pulse-power loads.

A component's energy coefficients are assigned to the input and output arcs of a component based on simple component models. Figure 3-5 shows the coefficient matrix in the MEL used to model vital components. Each equipment type has input and output coefficients for connections to every plex. Each equipment type has one primary input plex; the corresponding input coefficient is 1. The other input coefficients are assigned values based on the percentage of energy (relative to the primary input) their respective plex sends to that node. Output coefficients are assigned values based on the percentage of total input energy that the nodes send to their respective plex and other plexes. The output coefficients of all equipment types must sum to 1. Each of these coefficients represents the proportion of energy flow to and from the equipment operating at a sized design condition. Coefficients to plexes that an equipment type does not connect to are assigned values of zero. Nonzero coefficients are highlighted in green in Figure 3-5.

		ELEC	ELEC	MECH	MECH	FO	FO	LO	LO	CONT	CONT	SW	SW	CW	CW	HFC	HFC	EC	EC	HVAC	HVAC	Glycol	Glycol	EXTAIR	EXTAIR
VC Type Specification		ELEC	ELEC	MECH	MECH	FO	FO	HeatFlow	HeatFlow	Data	Data	HeatFlow	HeatFlow	HeatFlow	HeatFlow	HeatFlow	HeatFlow	HeatFlow	HeatFlow	HeatFlow	HeatFlow	HeatFlow	HeatFlow	HeatFlow	HeatFlow
MEL #	**VC/SYS**	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output
1	BusNode	1	0.985	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0.015	0	0	0	0
2	PCM	1	0.98	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0.020	0	0	0	0
3	LC	1	0.985	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0.015	0	0	0	0
4	SWBD	1	0.985	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0.015	0	0	0	0
5	SPGM	0	0.478	0	0	1	0	0.01	0.246	1	1	0	0	0	0	0	0	0	0	0	0.021	0	0	0	0.255
6	PGM	0	0.438	0	0	1	0	0.01	0.019	1	1	0	0	0	0	0	0	0	0	0	0.021	0	0	0	0.522
7	PMM	1	0	0	0.97	0	0	0	0.01	1	1	0	0	0	0	0	0	0	0	0	0.020	0	0	0	0
8	FO_ServTank	0	0	0	0	source	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	0	0	0	0
9	FO_ServPump	0.03	0	0	0	1	0.99	0	0	1	1	0	0	0	0	0	0	0	0	0	0.010	0	0	0	0
10	FO_Heater	0	0	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0.000	0	0	0	0
11	FO_Strainer	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	0	0	0	0
12	FO_FilterSep	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	0	0	0	0
13	FO_ServiceMain	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	0	0	0	0
14	FO_StorTk	0	0	0	0	source	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	0	0	0	0
15	LO_Cooler	0	0	0	0	0	0	1	0.01	0	0	0.01	0.99	0	0	0	0	0	0	0	0.000	0	0	0	0
16	LO_SumpTank	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0.000	0	0	0	0
17	LO_MotorDrivenPump	0.03	0	0	0	0	0	1	0.99	1	1	0	0	0	0	0	0	0	0	0	0.010	0	0	0	0
18	LO_DuplexFilter	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0.000	0	0	0	0
19	LO_SyntheticCooler	1	0.01	1	0.01	0	0	0.01	0.99	0	0	0	0	0	0	0	0	0	0	0	0.010	0	0	0	0
20	PropellerCRP	0	0	1	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0.000	0	0	0	0
21	PropellerFP	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	0	0	0	0
22	IPS_POD	1	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0.000	0	0	0	0
23	TailShaftAndStrutBearing	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	0	0	0	0
24	SternTubeAndSeal	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000	0	0	0	0

Figure 3-5: MEL Equipment Input and Output Energy Coefficient Matrix

Figures 3-6 and 3-7 show a Power Generation Module (PGM) gas turbine generator set as an example component model. The primary energy input for a PGM is the chemical energy of fuel from the FO plex; the arc from FO plex to the PGM is assigned a coefficient of 1. A small secondary energy input comes from the LO plex. Fuel energy released in the combustor results in four output energy flows. Only 43.8% of the total input energy to the PGM is ultimately converted to output electrical power. 52.2% is lost in the engine exhaust and module air-cooling. This energy goes up the stack to the outside air heat sink. 1.9% is removed by the engine synthetic LO system. The remaining 2.1% goes directly into the machinery room air as heat. Implicit arcs to and from the CONT plex contain data not energy, therefore they are not included in the energy flow calculations.

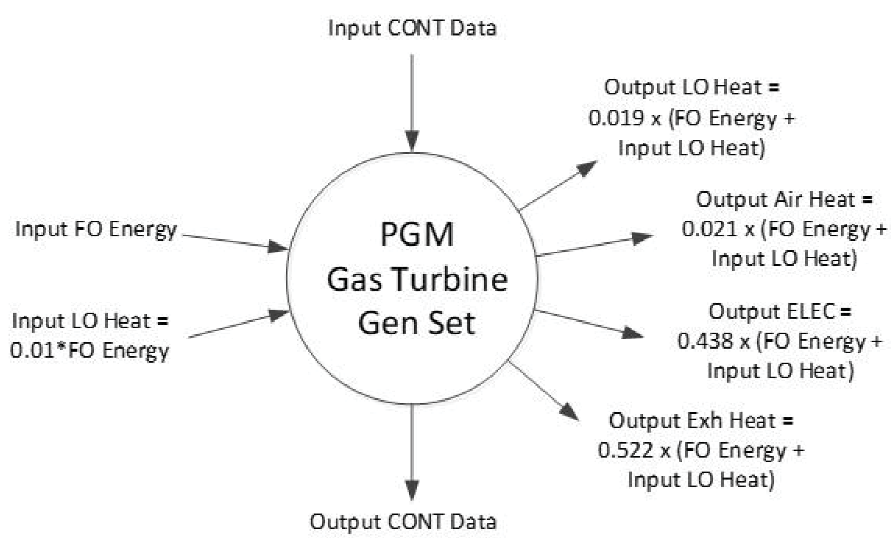

Figure 3-6: Nominal Power Generation Module (Gas Turbine and Generator Set Combination) Nodal Input and Output Coefficients

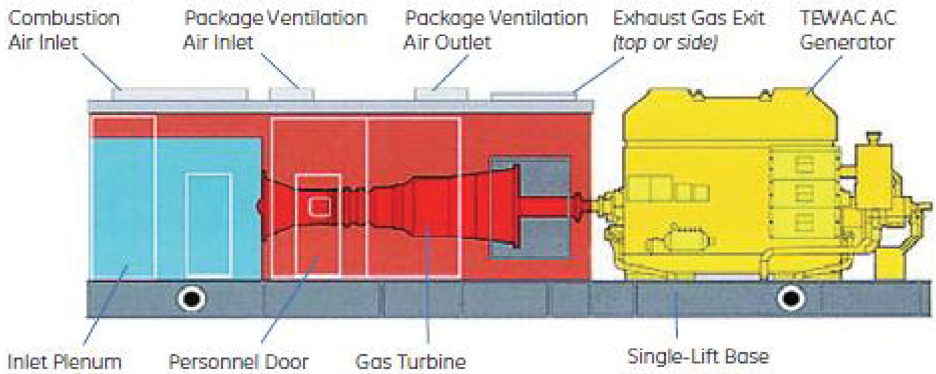

Figure 3-7: PGM - Gas Turbine Generator Set (Doerry & Amy 2016)

Since the AFO must model commodities moving through the total system carrying energy, but only energy flow is considered explicitly, a trace energy flow is used to represent commodity flow on the cold (commodity return) side of the plexes. For example, the Zone 3 loop in the CW plex in Figure 3-9: energy enters the loop at the zonal heat sources (Zone3_HVAC _CW_SYS, EC_HeatExch2_CW_SYS, and Glycol_HeatExch3 _CW_SYS), passes through the chilled water return pipe (CW_Return3_VC), and exits the plex at the chilled water coolers (CW_Cooler_3A_SYS and CW_Cooler_3B_SYS). Without a trace flow, no energy would pass through the chilled water pumps (CW_Pump3A_SYS and CW_Pump3B_SYS) or the chilled water supply pipe (CW_Supply3_VC). A CW 1% input flow to the zonal HVAC heat source pulls a trace flow of CW through the supply path of the loop. These trace flows are scaled back up in the SSM before commodity flow is calculated and component sizing occurs. Trace Flows are implemented in the cooling fluid plexes (CW, HFC, EC, Glycol, LO, and SW).

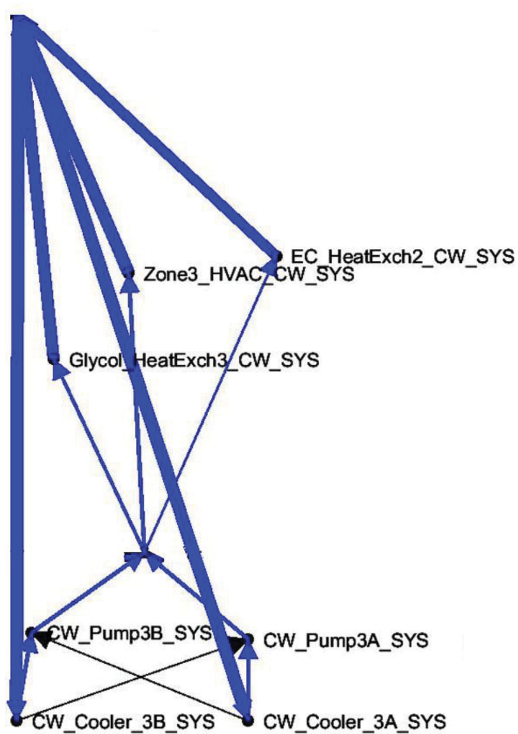

Figure 3-8: Zone 3 CW Loop

Conservation of energy is enforced at all nodes in the multiplex except nodes identified as sources or sinks. The source nodes are: FO_SOURCE (FO plex), ExtAir_SOURCE (HVAC plex), and SW_SOURCE (SW plex). The sink nodes are Propulsion_SYS (MECH plex), ExtAir_SINK (HVAC plex), and SW_SINK (SW plex). These nodes act as interfaces to the environment, providing commodities (air and saltwater) and accepting waste heat carried by commodities (exhaust and warm saltwater). The FO_SOURCE node receives fuel from the ship's fuel oil storage tanks and the Propulsion_SYS node transfers energy to the ocean through the propellers as the ship moves through the water.

PHYSICAL ARCHITECTURE AND PHYSICAL SOLUTION

The AFO uses a simplified 2.5D physical architecture presented in Parsons et al. (2019) where hullform and deckhouse are split by decks and transverse bulkheads into Subdivision Blocks (SDBs). Deck spacing and transverse bulkhead locations are based on stack-up lengths, floodable length parametrics, averaged deck height and other "stylistic" design considerations (McDonald 2009, Andrews 2018). Most SDBs are also split into two additional port and starboard SDBs superimposed on the full block that extend transversely to the centerline to contain components that are purposefully separated port and starboard to reduce system vulnerability. This port/starboard allocation represents the 0.5D portion of the 2.5D physical architecture.

The VCs of logical architecture plexes are assigned to compartments which in turn are allocated to SDBs based on operability, probability of kill given hit, shock factors, and/or other scalar metrics (Parsons et al. 2019). Some VCs have port/starboard redundancy. These VCs are assigned to the corresponding port/starboard SDB of their compartment's assigned SDB. This more accurately models space allocation and component vulnerability.

VCs are only assigned to SDBs. They are not actually arranged with unique x, y, and z coordinates. They are temporarily located at the center of their respective SDBs, see Figure 3-9, which is sufficient to implement the damage algorithms used in early-stage design.

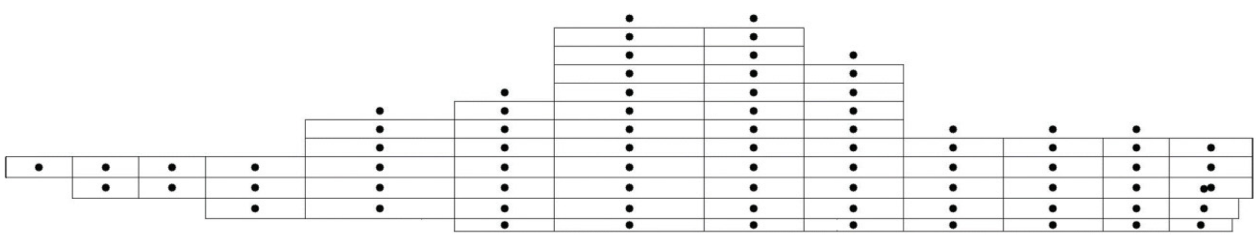

Figure 3-9: AFO's Nodal Description of SDBs (Physical Architecture)

Figure 3-10 shows the same SBDs in a perspective view where the port and starboard SDB nodes are visible. This figure is an example of a physical solution (the shared region of the logical and physical architectures in Figure 3-1) and shows two plexes: the zonal electrical distribution (ELEC) plex in red and the chilled water (CW) plex in blue.

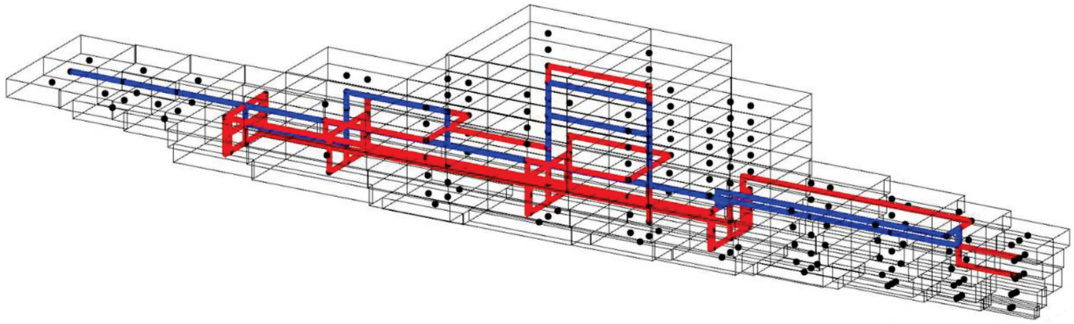

Figure 3-10: ELEC and CW plexes (red and blue respectively) Physical Solution

If two VCs connected by an arc are located in different SDBs, then the arcs are visible in the physical solution. The current routing of these arcs is accomplished by a simple algorithm modeling the forward/aft, transverse, and vertical distances between VCs as straight paths while remaining within the hullform and deckhouse. These straight path distances serve as the arc length used in the next section. Arcs that start and end in same SDB use a standard minimum arc length dependent on the plex. As stated previously, these plexes do not explicitly include distribution components such as wires, pipes, or shafts. As a result, arcs act as distribution components in the physical solution.

The physical solution is created by applying this mapping to all plexes of the ship. The physical solution (including logical and physical architecture) and the operational architecture (described in the next section) are the necessary and sufficient input information to complete an AFO and a preliminary vulnerability analysis.

OPERATIONAL ARCHITECURE CONSTRAINTS AND LINEAR OPTIMIZATION

The operational architecture is applied to the AFO as linear constraints that vary depending on the operational scenario. There are two primary types of scenarios in the CPES Exploration #1 (AFO): undamaged (sustained speed, endurance speed, and battle) and S-1 damaged. A damaged scenario in CPES Exploration #1 selects single SDBs, one at a time, and sets the input and output energy of all components in that SDB to zero, effectively deactivating it (S-1). The final AFO solution that satisfies all scenarios is called the aggregate solution (Robinson 2018). Actual damage scenarios that may include multiple SDBs are used in a separate CPES Vulnerability AFO (VAFO) after the original AFO is completed and all components have been sized.

Doctrinal considerations are also enforced using constraints. The energy flows of all components of the same type in a zone are set equal to each other (e.g. the output energy flow of pumps 3A and 3B in the chilled water plex are set equal to each other). This ensures all collocated redundant components have the same energy flow and are sized the same. This is done by grouping the input/output explicit arcs of components of the same type in the same zone. These "arc groups" are used in equality constraints for each group. This constraint is not enforced in ELEC plex in damaged scenarios or the MECH plex in any scenario. There are three exceptions to this equal flow doctrinal constraint: (1) the ELEC plex in damaged scenarios, (2) the CW, SW, EC, and Glycol plexes in the endurance scenario (where one pump/cooler/sea chest per zone is sufficient), and (3) the MECH plex in all scenarios. Propulsion requirements in the MECH plex are handled separately.

The energy flow into the Propulsion_SYS sink node is a major pull on the system. Each scenario's Propulsion_SYS load is constrained to equal one of four power levels specified by the SSM: sustained speed power, endurance speed power, battle speed power, and one-half endurance speed power. The first three power levels directly correspond to the first three (undamaged) scenarios. The fourth, one-half endurance speed power, is used in the S-1 damaged scenarios. Combat system components are set to their standby connected load in the sustained and endurance speed conditions. They are set to battle connected load in the battle and damaged conditions, unless the component is in a damaged SDBs.

Theses operational and doctrinal constraints must be added to the AFO or the optimization will minimize energy flow cost by setting the flow in all arcs equal to zero. An arc with zero flow can be removed from the network and has no fixed or variable flow cost. The AFO result with zero flow in all arcs represents the null case solution.

The rest of this section outlines the linear optimization's mathematical formulation and the implementation of the operational constraints. This formulation is adapted from the approaches developed by Robinson (2018) and Trapp (2015). In this formulation, a parameter with a single subscript (e.g. A_b) is a nodal parameter and a parameter with two subscripts (e.g. $A_{b,c}$) is an arc parameter. The following parameters are used in the formulation:

- N is the set of nodes.
- n is a specified node within N.
- m is the node at the tail of arc (m, n) which is the primary input to node n.
- o is the node at the head of arc (n, o) which is the primary output from node n.
- i and j are indexed nodes within N.
- P is the set of plexes (multiplex).
- p(n) is the plex of node n.
- A is the set of arcs.
- (i, j) is an indexed arc within A from node i to node j.
- S is the set of scenarios.
- s is an indexed scenario within S.
- e_n^s is the quantity of energy demanded by node n in scenario s.
- $x_{i,j}$ is the aggregate energy flow through arc (i, j).
- $x_{i,j}^s$ is the energy flow through arc (i, j) in scenario s.
- $C_n^{p(i)}$ is the coefficient of arcs to node n from the nodes in the p plex.
- $C_n^{p(j)}$ is the coefficient of arcs from node n to the nodes in the p plex.
- $b_{i,j}^s$ is a binary value associated with whether the flow through arc (i, j) is on or off for damage or flow control in scenario s.
- $\Pi_{i,j}$ is the fixed cost of arc (i, j). Fixed arc costs vary with the distributed commodity, the physical location of the arc, and the crossing of bulkheads/decks. Fixed cost of arcs connecting different zones in fluid plexes are increased compared to other arcs in the same plex.
- $B_{i,j}$ is the binary value associated with whether the arc is used or not.
- $\pi_{i,j}$ is the cost per unit energy flow of arc (i, j). This cost varies with the type of arc and its physical length.

The following two sets are also commonly used. The first set is the list of all arcs in E whose endpoint is node n. The second set is the list of all arcs in E whose starting point is node n.

$$(i,n) \in A = (i,j) \in A \quad \forall\, j = n$$

$$(n,j) \in A = (i,j) \in A \quad \forall\, i = n$$

The linear optimization minimizes the objective function – the cost of the aggregate network is the sum of the arc fixed costs and arc variable flow costs. The fixed cost represents the engineering and instillation costs of the arc. The variable cost scales linearly with the aggregate energy flow (i.e. larger energy flows require more materials in their connections):

$$\sum\nolimits_{(\boldsymbol{i},\boldsymbol{j})\in \boldsymbol{A}} (\boldsymbol{\Pi}_{\boldsymbol{i},\boldsymbol{j}}\ \boldsymbol{B}_{\boldsymbol{i},\boldsymbol{j}} + \boldsymbol{\pi}_{\boldsymbol{i},\boldsymbol{j}}\ \boldsymbol{x}_{\boldsymbol{i},\boldsymbol{j}}) \tag{1}$$

Subject to:

The directed arc constraint – all arc flows are zero or positive:

$$\boldsymbol{x}^{\boldsymbol{s}}_{\boldsymbol{i},\boldsymbol{j}} \geq \boldsymbol{0} \tag{2}$$

The source node constraint – a specified source, n, generates all of the energy as demanded by its outgoing arcs:

$$\boldsymbol{e}^{\boldsymbol{s}}_{\boldsymbol{n}} \geq \sum\nolimits_{(\boldsymbol{n},\boldsymbol{j})\in \boldsymbol{A}} \boldsymbol{x}^{\boldsymbol{s}}_{\boldsymbol{i},\boldsymbol{j}} \tag{3}$$

The sink node constraint – a specified sink, n, consumes all of the energy supplied by its incoming arcs:

$$\boldsymbol{e}^{\boldsymbol{s}}_{\boldsymbol{n}} \geq \sum\nolimits_{(\boldsymbol{i},\boldsymbol{n})\in \boldsymbol{A}} \boldsymbol{x}^{\boldsymbol{s}}_{\boldsymbol{i},\boldsymbol{j}} \tag{4}$$

Only one of the following four constraints is applied to an individual arc flow in a scenario.

The scenario arc flow control constraint – a specified scenario arc flow is set to zero if the scenario arc deactivation binary variable is set to zero:

$$\boldsymbol{x}^{\boldsymbol{s}}_{\boldsymbol{i},\boldsymbol{n}} = \begin{cases} \boldsymbol{0} & \boldsymbol{if\ b^{s}_{i,n} = 0} \\ \boldsymbol{x}^{\boldsymbol{s}}_{\boldsymbol{i},\boldsymbol{n}} & \boldsymbol{if\ b^{s}_{i,n} = 1} \end{cases} \quad \boldsymbol{and}\ \ \boldsymbol{x}^{\boldsymbol{s}}_{\boldsymbol{n},\boldsymbol{j}} = \begin{cases} \boldsymbol{0} & \boldsymbol{if\ b^{s}_{n,j} = 0} \\ \boldsymbol{x}^{\boldsymbol{s}}_{\boldsymbol{n},\boldsymbol{j}} & \boldsymbol{if\ b^{s}_{n,j} = 1} \end{cases} \tag{5}$$

The scenario arc deactivation binary variable is set to 0 (for flow control or damage modeling) or 1 (available) depending on an arc’s state in a scenario:

$$\boldsymbol{b}^{\boldsymbol{s}}_{\boldsymbol{i},\boldsymbol{j}} = \begin{cases} \boldsymbol{0},\ \boldsymbol{if\ the\ edge\ is\ deactivated} \\ \boldsymbol{1},\ \boldsymbol{if\ the\ edge\ available} \end{cases} \tag{6}$$

The scenario known arc flow constraint – a specified scenario arc flow is set to a known value. This constraint is used for the known combat system components’ electrical loads or required propulsion power:

$$\boldsymbol{x^s_{m,n} = e^s_n} \tag{7}$$

$$\boldsymbol{x^s_{n,o} = e^s_n} \tag{8}$$

The scenario incoming arc flow constraint – a non-primary incoming arc flow is the product of the primary incoming arc flow, (m,n), and the incoming coefficient of node n for the corresponding plex the arc originates from:

$$\boldsymbol{x^s_{i,n} = C^{p(i)}_n\left(x^s_{m,n}\right)} \tag{9}$$

The scenario outgoing arc flow constraint – an outgoing arc flow is the product of the sum of the incoming arc flows, $(i, n) \in A$, and the coefficient of node n for the corresponding plex the arc terminates in:

$$\boldsymbol{x^s_{n,j} = C^{p(j)}_n \sum\nolimits_{(i,n)\in A} x^s_{i,j}} \tag{10}$$

The scenario continuity constraint – the sum of incoming arc flows equals the sum of the outgoing arc flows minus the nodal energy demand:

$$\boldsymbol{\sum\nolimits_{(i,n)\in A} x^s_{i,j} - \sum\nolimits_{(n,j)\in A} x^s_{i,j} - e^s_n = 0} \tag{11}$$

The aggregate arc flow constraint – the aggregate arc flow (used in the objective function) is the largest scenario arc flow of that arc. This ensures that this arc has a sufficient capacity for any scenario:

$$\boldsymbol{x_{i,j} = \max_{s\in S}\left(x^s_{i,j}\right)} \tag{12}$$

The binary aggregate arc constraint – fixed costs of unused aggregate arcs are set to zero. A zero signifies an arc that can be removed from the optimized network:

$$\boldsymbol{B_{i,j} = \begin{cases} 0, & if\ x_{i,j} = 0 \\ 1, & if\ x_{i,j} > 0 \end{cases}} \tag{13}$$

EXAMPLE NETWORK FLOW OPTIMIZATION

Before presenting the results of a total ship AFO, it is useful to clarify the methodology with a simple example. Trapp (2015) presents a similar example using his network flow optimization approach.

This example has six nodes linked together by directed arcs and models the flow of a single commodity as shown in Figure 3-11. Nodes 1 and 5 are sources producing 5 and 10 units of the commodity. Nodes 2 and 6 demand 5 and 10 units of the commodity respectively. Arcs are identified by their start and endpoints in Table 3-1. Each arc has a direction, flow cost per unit flow, and an upper capacity limit.

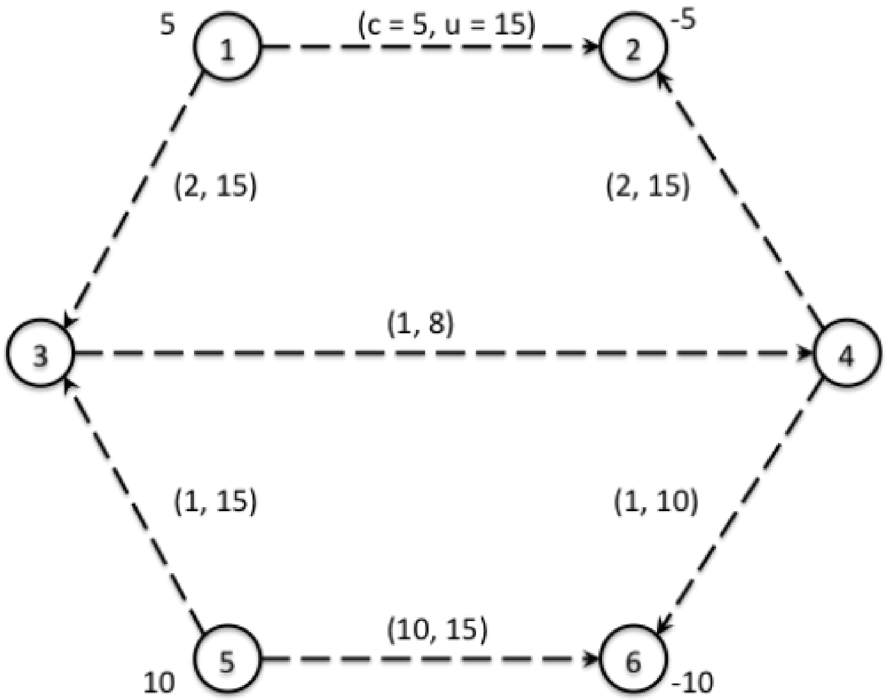

Figure 3-11: Example Network Flow Optimization Example (Trapp 2015)

Figure 3-12 and Table 3-2 show the results of the optimization. 5 units flow directly from node 1 to node 2. Node 5 sends 8 units through the arc (3,4) due to the high cost of arc (5,6). However, 2 units are sent through arc (5,6) due to arc (3,4)'s upper capacity of 8 units. The optimization effectively removes redundant arcs (1,3) and (4,2) from the network.

Table 3-1: Example Network Flow Optimization Parameters (Trapp 2015)

Edge (i,j)	Cost c_{ij}	Capacity u_{ij}
(1,2)	5	15
(1,3)	2	15
(3,4)	1	8
(4,2)	2	15
(4,6)	1	10
(5,3)	1	15
(5,6)	10	15

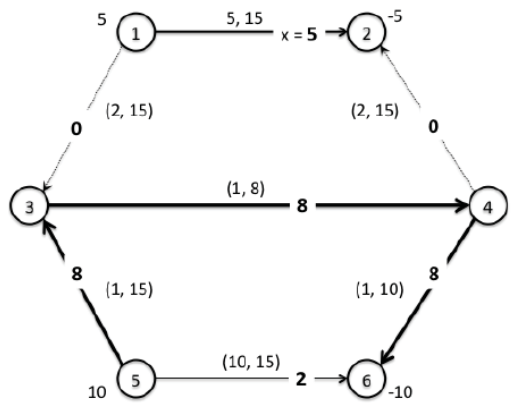

Figure 3-12: Example Network Flow Optimization Solution (Trapp 2015)

Table 3-2: Example Network Flow Optimization Solution Parameters (Trapp 2015)

Edge	Cost	Capacity	Flow
(1,2)	5	15	5
(1,3)	2	15	0
(3,4)	1	8	8
(4,2)	2	15	0
(4,6)	1	10	8
(5,3)	1	15	8
(5,6)	10	15	2

AFO SYSTEM RESPONSE

System Response describes a system's behavior considering the logical, operational, and physical architectures and is represented by overlapping region of all three circles in Figure 3-1. This section presents selected results from the AFO. The figures in this section show the endurance scenario and aggregate system responses of the major energy plexes (MECH, ELEC, CW, FO, LO, and SW). In general, sustained and battle scenarios system responses are the same as the endurance system response, but with larger energy flows due to the use of stored energy for pulse power loads. The energy flows of the figures in this section are plotted on a natural logarithmic scale; small perceived changes in the plots may represent orders of magnitude difference. Figures showing the battle scenario and Main Machinery Room 2 (MMR 2) Lower damaged scenario of specific plexes are provided as selected figures to show unique system responses. Again, the aggregate system response is the minimum energy flow that will satisfy all operational scenarios. Black arcs in these figures represent arcs with no energy flow in any scenario. These black arcs are candidates for removal in the final system.

The plexes/system responses shown here are for a notional Future Surface Combatant with an Integrated Power System (IPS). Power Generation Modules are located in the ELEC plex with Propulsion Motor Modules (PMMs) in the MECH plex. Plexes are generally divided into four zones numbered from forward to aft (right to left in most of the figures in this section).

Figures 3-13 through 3-15 show the MECH plex's system responses. Figure 3-13 shows how the mechanical power for propulsion is split evenly between the port and starboard shafts in the endurance scenario. Figure 3-14 shows how the starboard shaft is deactivated when the starboard propulsion motor module (located in MMR 2 Lower) is deactivated. Figure 3-15 shows the aggregate system response, which is governed by the sustained speed scenario (the scenario with the largest load at the Propulsion_SYS sink node).

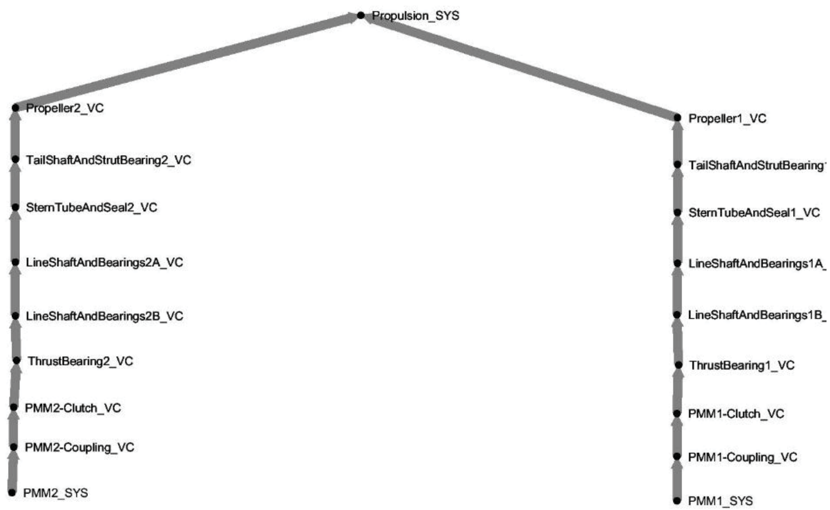

Figure 3-13: MECH Plex Endurance System Response

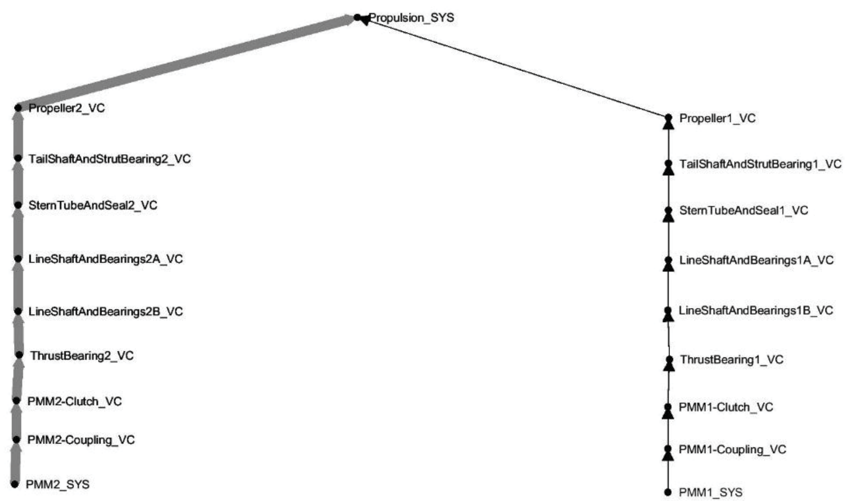

Figure 3-14: MECH Plex Damaged MMR2 Lower System Response

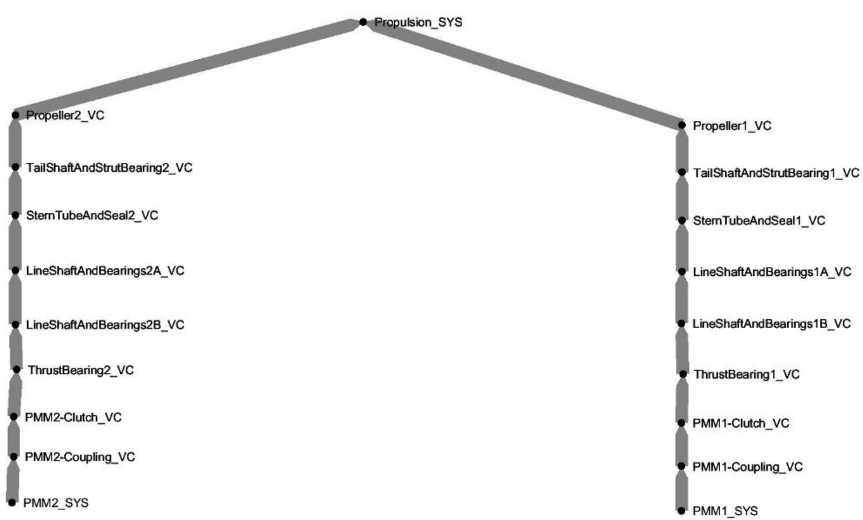

Figure 3-15: MECH Plex Aggregate System Response

Figures 3-16 through 3-19 show the ELEC plex system responses. In an IPS ship, power is generated by Power Generation Modules (PGMs) and Secondary Power Generation Modules (SPGMs), sent to the port and starboard buses (represented by Bus Nodes), distributed forward and aft in the ship as required, and sent back into power conversion modules (PCMs) and load centers (LCs). Figure 3-16 shows that both PGMs are turned off (secured) in the endurance scenario. The ship is required to achieve endurance speed using only the secondary power generation modules SPGMs. Figure 3-16 also shows a small stored energy subnetwork in Zones 1, 2, and 3. This subnetwork is black (deactivated), as it is only used to provide power to high power CPES components in battle and damaged scenarios. The energy magazines are modeled as fully charged at the start of a battle scenario power and will only provide power for a limited duration of time. This is the most that can be modeled in a static analysis. Out future DAFO will be able to more correctly model energy storage and pulse power applications. Figure 3-17 shows the battle system response. PGMs, SPGMs, and stored energy magazines are all active. Nearly all arcs are used in this system response. Figure 3-18 shows the Damaged MMR 2 Lower system response. PGM 2 is in the MMR 2 Lower SDB and is deactivated in this figure. Figure 3-19 shows the aggregate ELEC plex system response, which is primarily governed by the battle scenario. This system response will satisfy the demands shown in Figures 3-16 through 3-18.

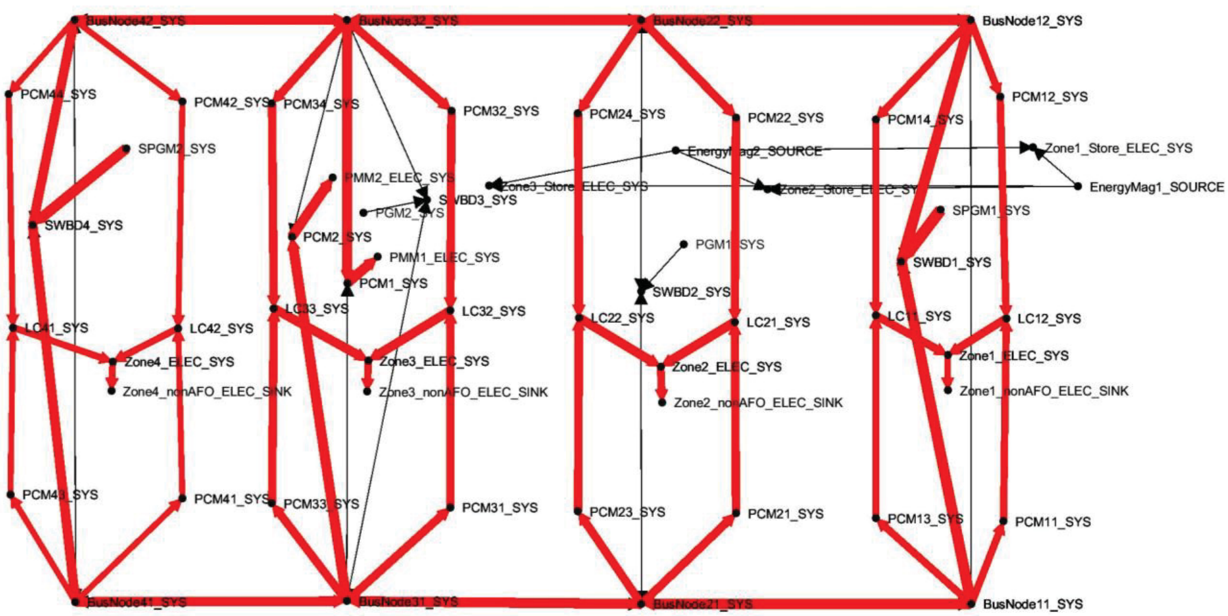

Figure 3-16: ELEC Plex Endurance System Response

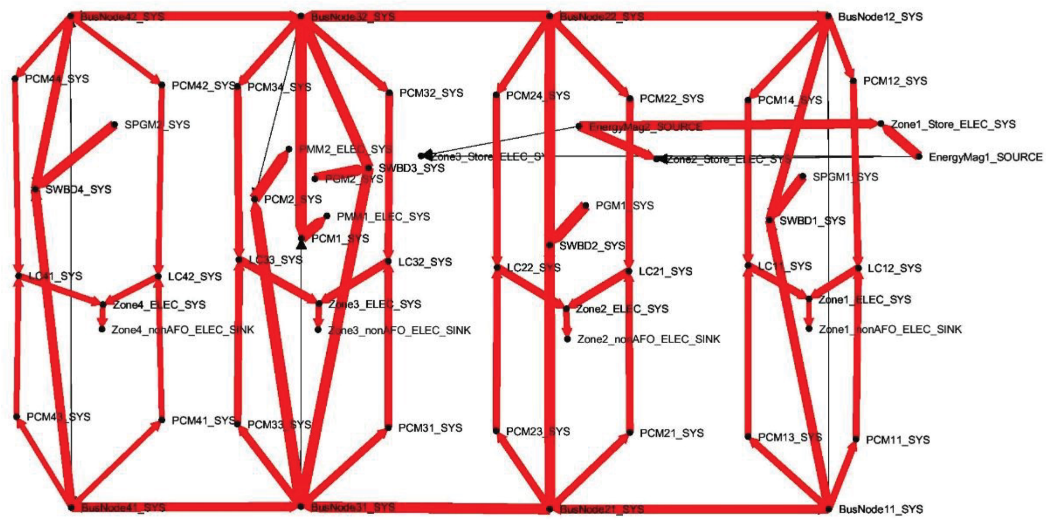

Figure 3-17: ELEC Plex Battle System Response

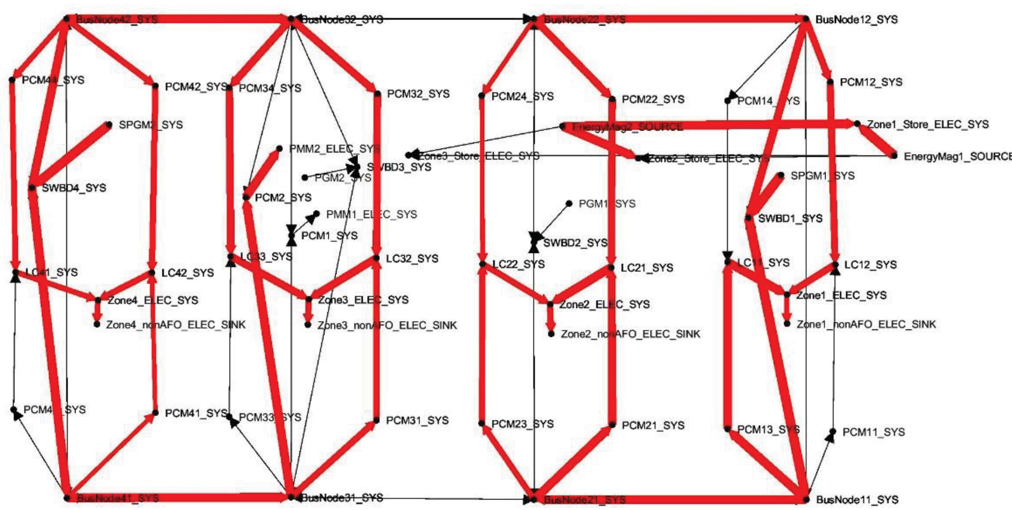

Figure 3-18: ELEC Plex Damaged MMR2 Lower System Response

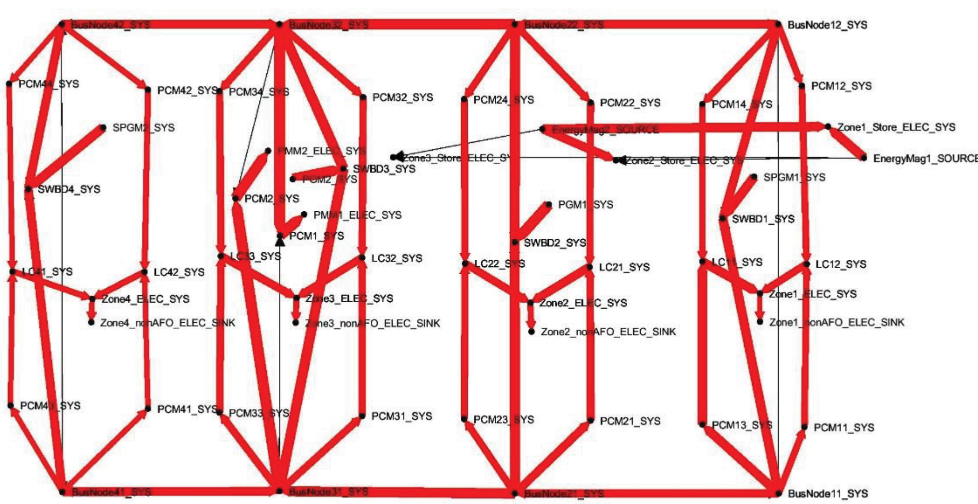

Figure 3-19: ELEC Plex Aggregate System Response

Figures 3-20 through 3-23 show the CW plex system responses. This is the first plex that models a physical commodity (chilled water) carrying (heat) energy. Trace flows are required in this and other plexes with thermal fluid commodities. The Chilled Water Coolers (CW_Coolers_#_SYS) have an energy flow limit of 1500 tons of refrigeration (or 5275 kW). Each zone has two coolers for a total of 3000 tons per zone and 12000 tons overall. The limit was originally 1000 tons per unit with only one unit in each of Zones 1 and 4, but this total cooling was not sufficient for managing the large pulse power loads, particularly due to the rail gun so capacities were increased. Figure 3-20 shows the endurance system response where only one cooler and pump are used in each zone; this is an example of the second exception to the equal flow doctrinal contestant: components of the same type in the same zone to have the same flow. The cooling required in zones 1 and 2 in this scenario is under the 3000-ton limit, and cross connects at the supply and return nodes are not used in these zones. Figure 3-21 shows the battle system response. Required cooling in Zone 2 exceeds the 3000-ton limit primarily due to the heat from the glycol heat exchanger in Zone 2. This heat exchanger is the primary means of cooling the railgun in the battle scenario. Since the cooling limit is exceeded, supplemental cooling is provided by the coolers in Zone 1 through the supply and return zonal cross connecting arcs. Figure 3-22 shows the damaged MMR 2 Lower system response. The CW coolers in Zone 3 are connected to the saltwater HFC condensers in the SW plex. These components are all in the MMR 2 Lower SDB and are deactivated in this scenario which requires using the cross-connect with Zone 4 for CW. The EC and Glycol plexes are realigned to limit the energy flow sent to CW Zone 3 (compare the energy flows of the EC and Glycol heat exchanger nodes in Figures 3-21 and 3-22). Figure 3-23 shows the aggregate system response. This system response is heavily influenced by the cooler 1500-ton limit and the damage scenarios.

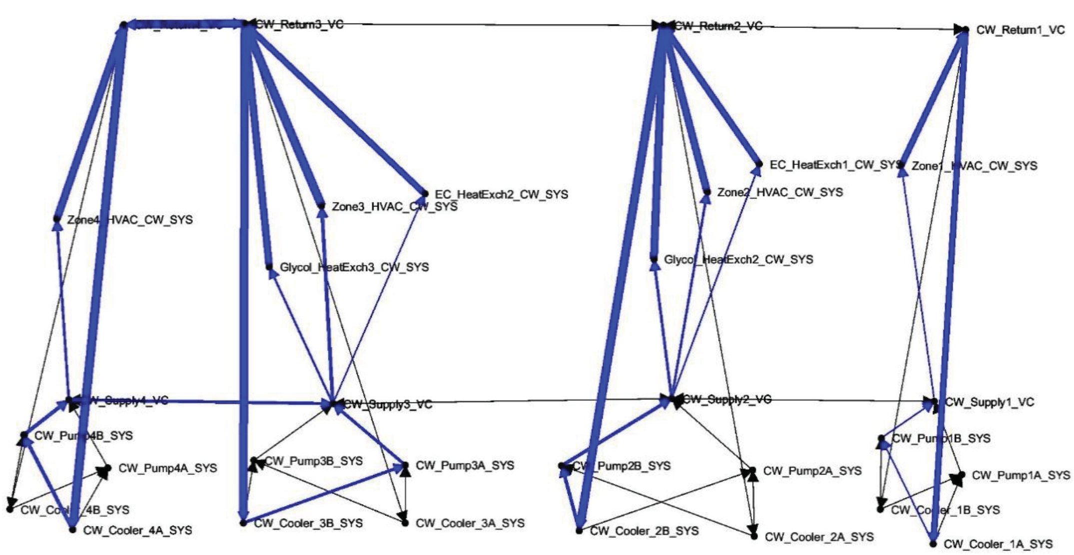

Figure 3-20: CW Plex Endurance System Response

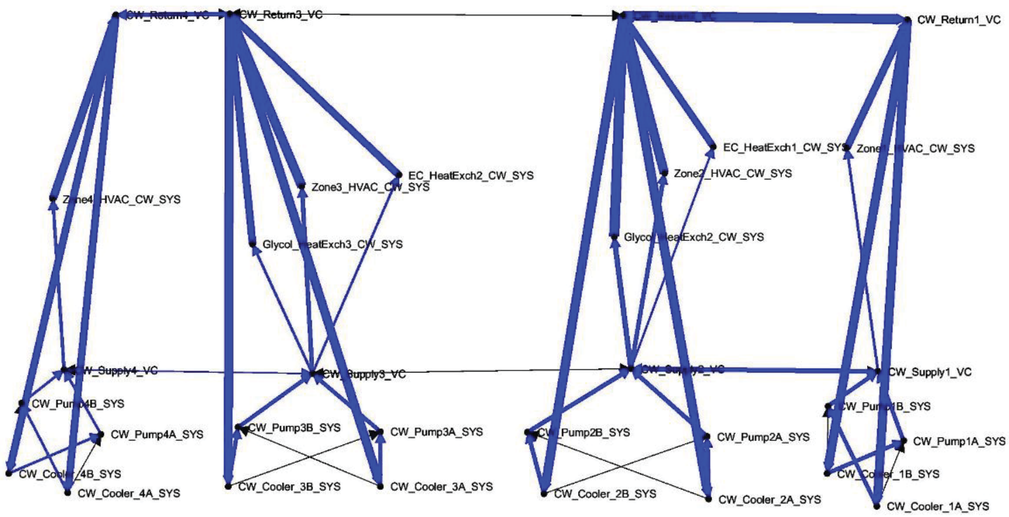

Figure 3-21: CW Plex Battle System Response

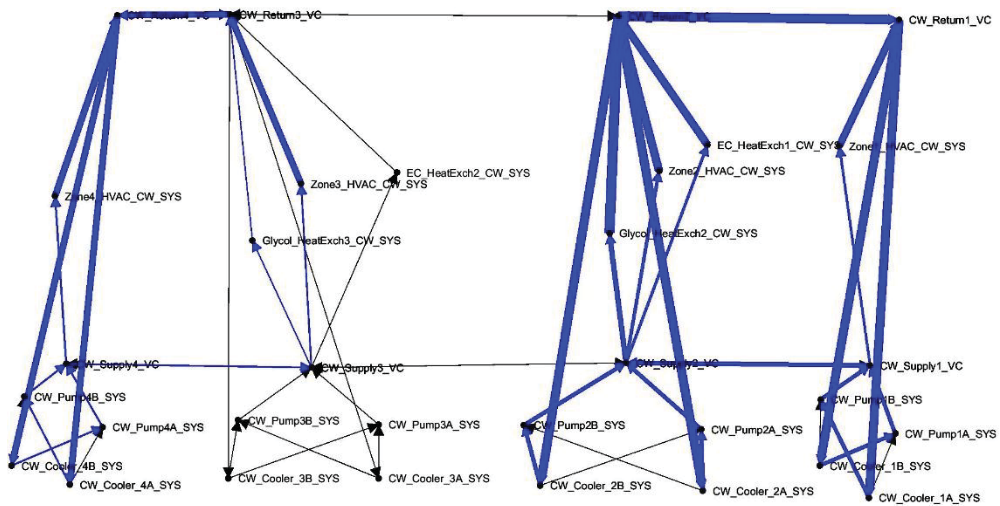

Figure 3-22: CW Plex Damaged MMR2 Lower System Response

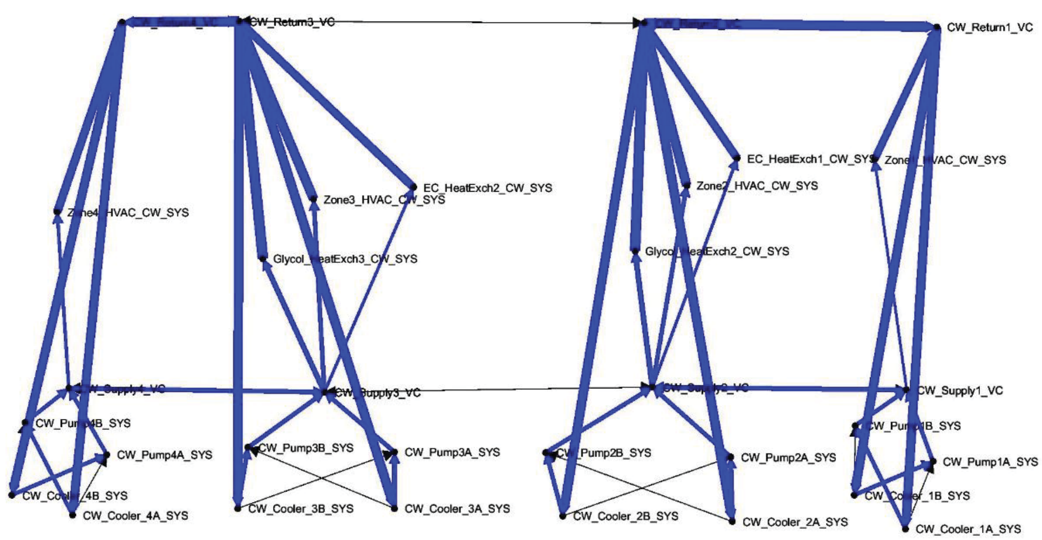

Figure 3-23: CW Plex Aggregate System Response

Figures 3-24 through 3-27 show the FO plex system responses. Figure 3-24 shows the endurance system response. As noted in the ELEC system responses, the PGMs are deactivated and only the SPGMs are active. Figure 3-25 shows the battle system response where the PGMs and SPGMs active (also seen in the ELEC plex battle system response). Note the thickness of the arcs in Zones 2 and 3 compared to Zones 1 and 4 in Figure 3-25. The PGMs are gas turbines while the SPGMs are diesel engines. The PGMs have a higher fuel consumption and a higher power output. This is represented by the thicker arc flows. Figure 3-26 shows the MMR 2 Lower Damaged system response. All of the Zone 3 components are located in MMR 2 Lower and are deactivated in this system response. It is noteworthy to see the ship can maintain sufficient power in this scenario with only the SPGMs. Figure 3-27 shows the aggregate system response, which is primarily driven by battle scenario (a near sustained speed propulsion requirement and high power loads of combat systems).

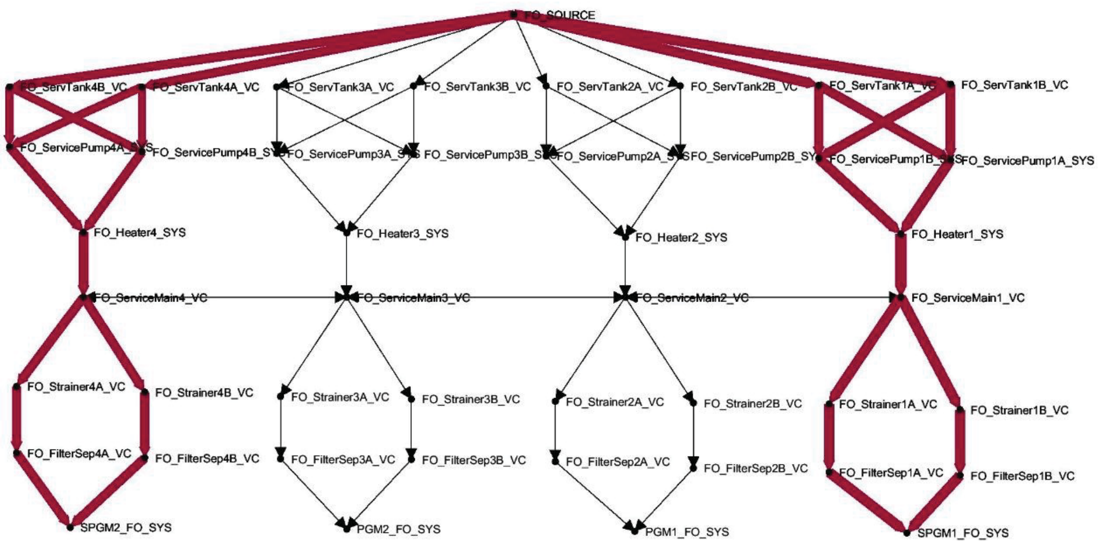

Figure 3-24: FO Plex Endurance System Response

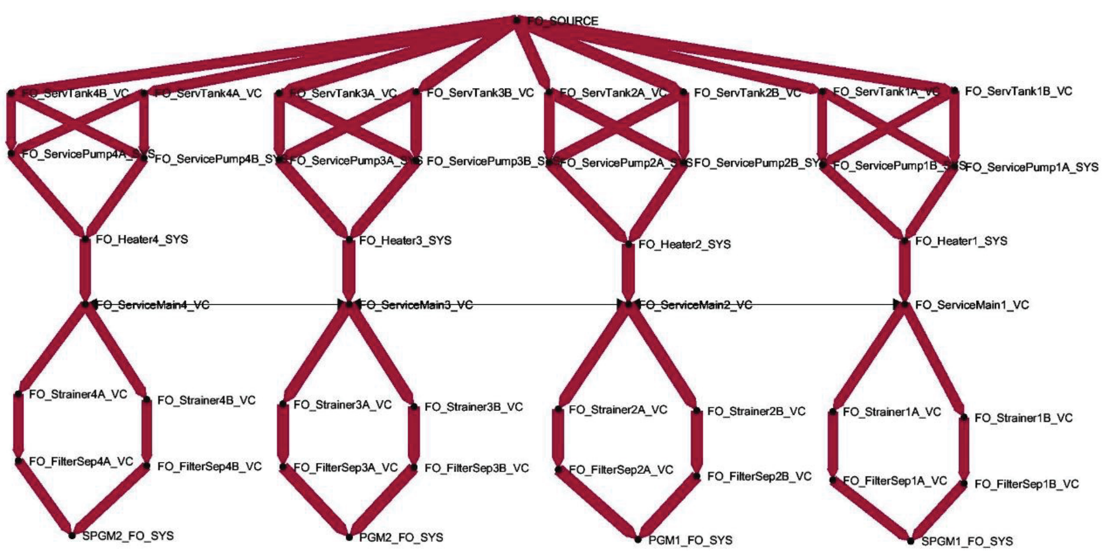

Figure 3-25: FO Plex Battle System Response

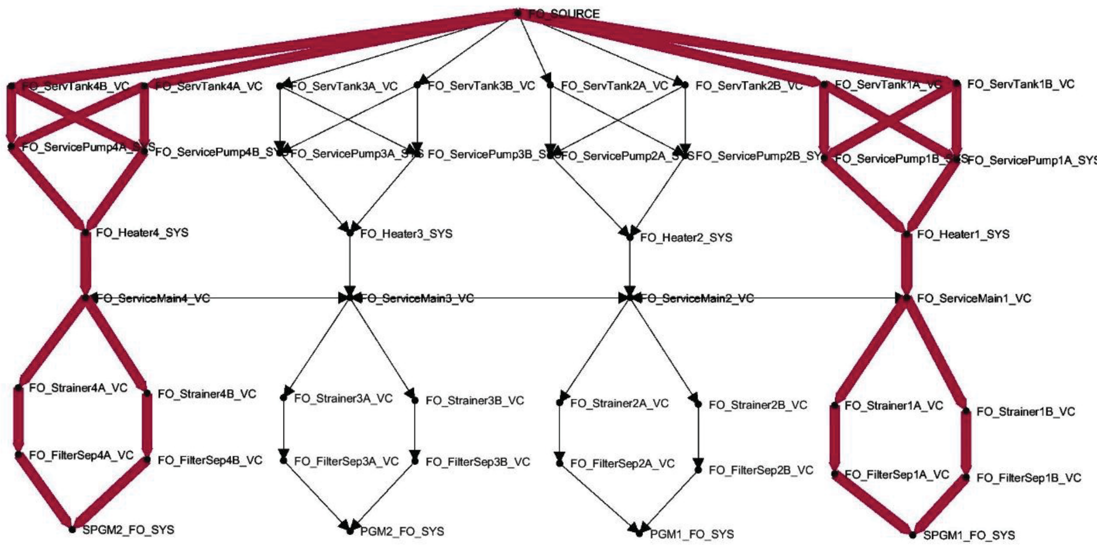

Figure 3-26: FO Plex Damaged MMR2 Lower System Response

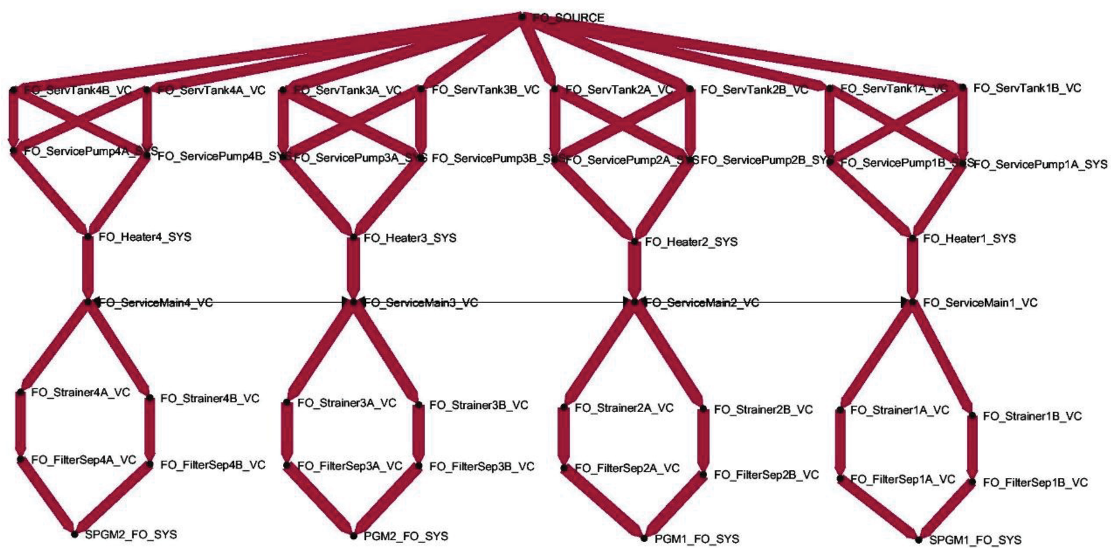

Figure 3-27: FO Plex Aggregate System Response

Figures 3-28 through 3-31 show the LO plex system responses. The LO plex provides cooling to PGMs, SPGMs, and PMMs. Figure 3-28 shows the endurance system response. Unlike the FO endurance system response, Figure 3-24, Zone 3 is still active due the presence of the PMM in Zone 3/MMR 2. Figure 3-29 shows the Damaged MMR 2 Lower system response; all Zone 3 components (including PMM1_LO_SYS) are located in MMR 2 Lower and deactivated. Therefore, propulsion requirements must be solely provided by PMM2. This is also seen in the MECH and ELEC Damaged MMR 2 Lower system response (Figures 3-14 and 3-18). Figure 3-30 shows the aggregate system response, which is primarily governed by a combination of the sustained speed and battle system responses.

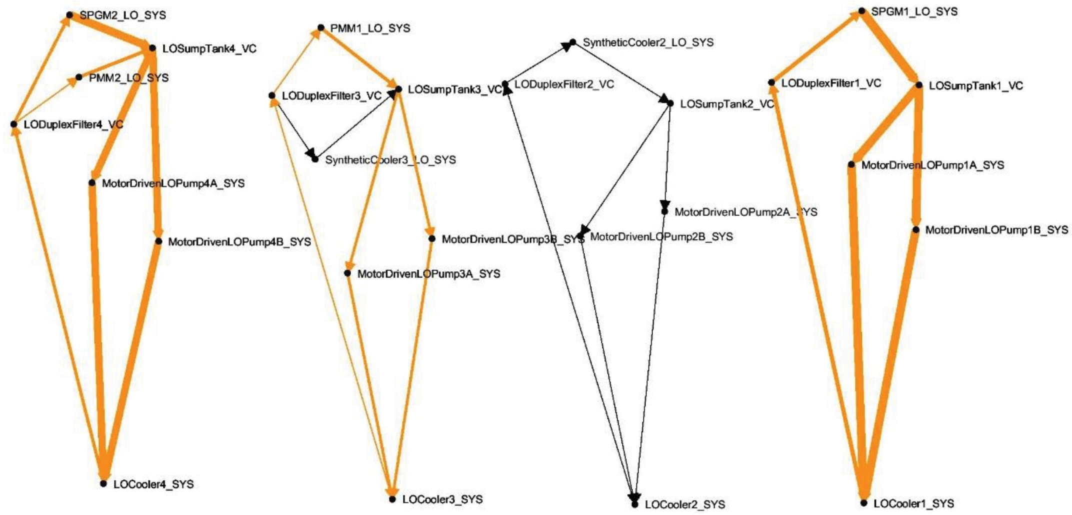

Figure 3-28: LO Plex Endurance System Response

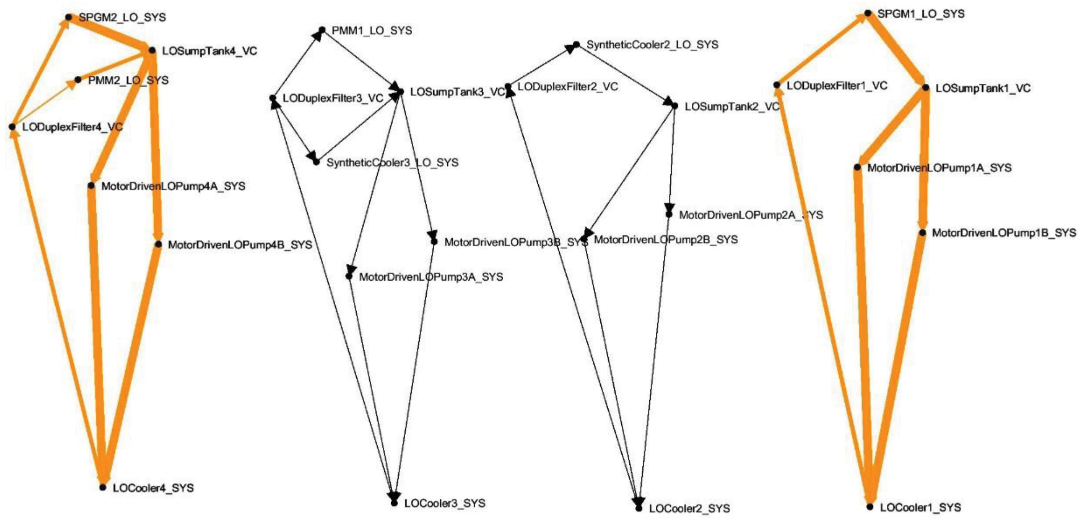

Figure 3-29: LO Plex Damaged MMR2 Lower System Response

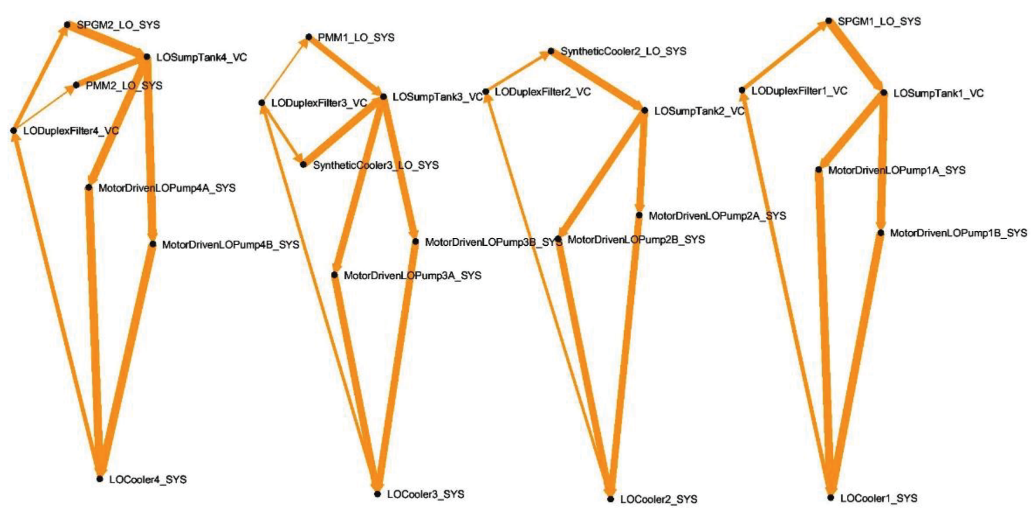

Figure 3-30: LO Plex Aggregate System Response

Figures 3-31 through 3-33 show the SW plex system responses. The SW plex is an open system, the SW_SOURCE and SW_SINK nodes represent a connection from the ship to the ocean. Trace flows are required to model the salt water moving from the source, through the pumps, to the HFC condensers and LO Coolers. Trends seen in the CW and HFC plexes' system response also appear in the SW system responses. Figure 3-31 shows the endurance system response where only one sea chest and pump are used in zones 2 and 3; this is another example of the second exception to the equal flow doctrinal contestant. Figure 3-32 shows the Damaged MMR 2 Lower system response. All Zone 3 components are located in MMR 2 Lower and therefore deactivated in this scenario. Figure 3-33 shows the aggregate system response, which is governed by the battle scenario.

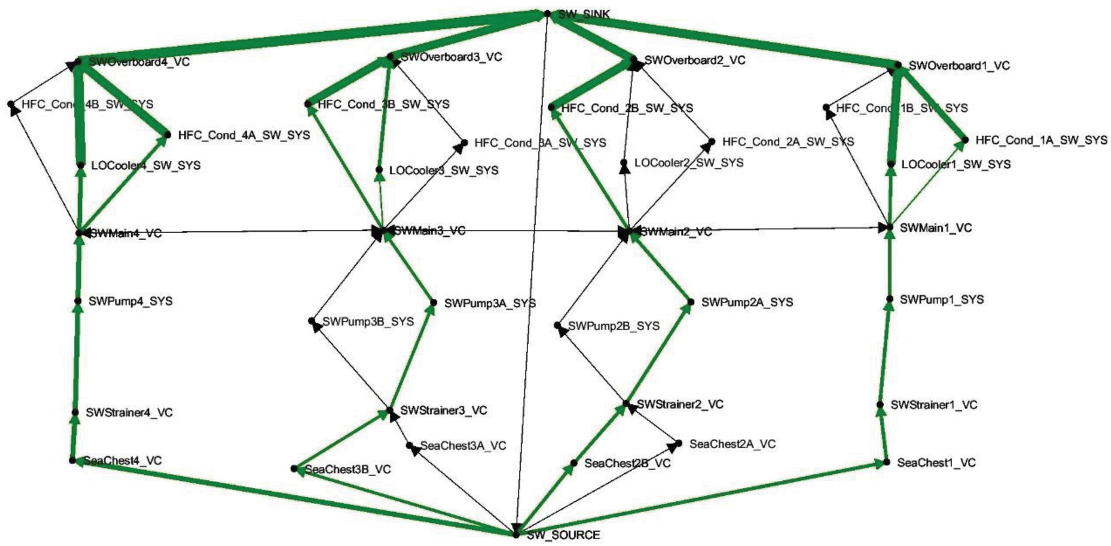

Figure 3-31: SW Plex Endurance System Response

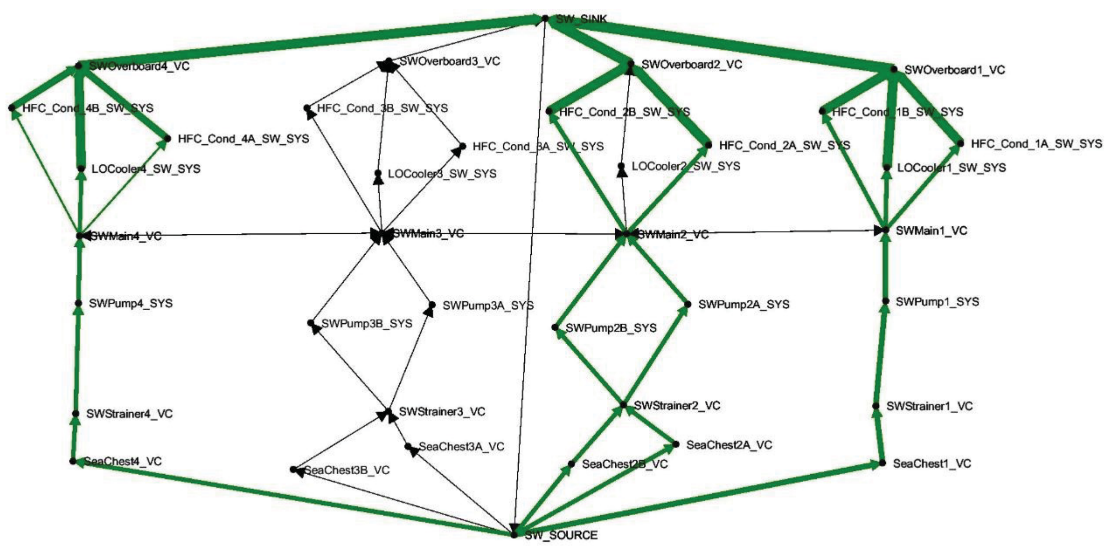

Figure 3-32: SW Plex Damaged MMR2 Lower System Response

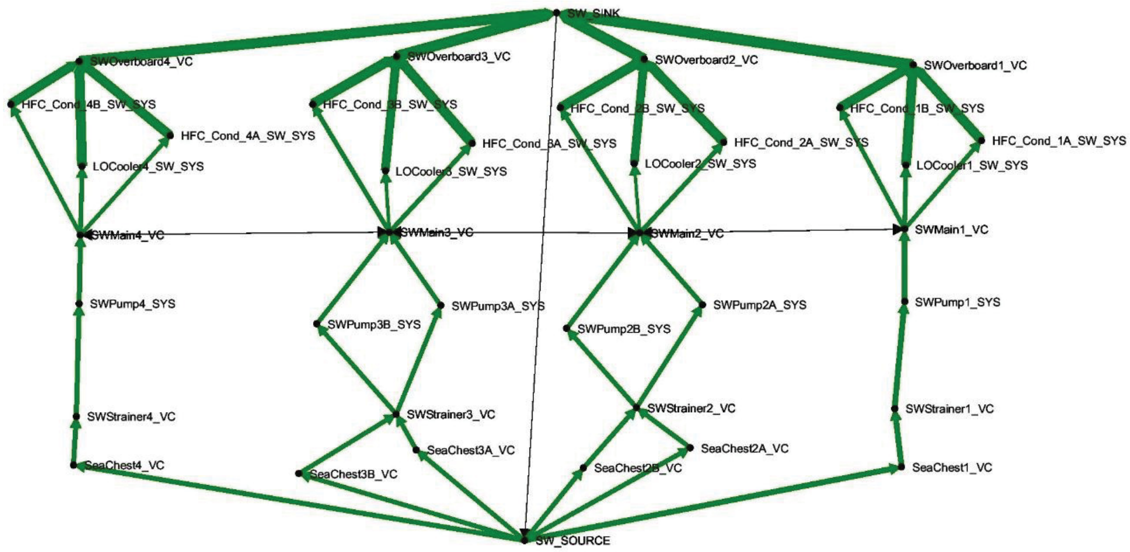

Figure 3-33: SW Plex Aggregate System Response

CONCLUSIONS AND FUTURE WORK

This paper presents a methodology and analysis tool to assess ship system feasibility and vulnerability using simplified preliminary arrangements, operational scenarios, and energy flow models in a Concept and Requirements Exploration (C&RE). An Architecture Flow Optimization (AFO) methodology is described and applied to a future surface combatant design in the context of a new distributed system Architecture Framework. A number of simplifying approaches are applied including: 1) the use of subdivision blocks (SDBs) vice curvilinear geometry to define the physical architecture; 2) the assignment of vital components (VCs) to compartments and compartments to SDBs rather than using x, y, z coordinates for VCs; 3) the use of simplified energy flow component models; 4) the use of simplified steady or quasi-steady state operational scenarios. An important question with these simplifications is their ability to provide and support sufficiently accurate and detailed analysis for concept exploration decisions. As a result of this research, we have tentatively concluded that these simplifications provide sufficient information in naval ship C&RE. Furthermore, the AFO provides a useful tool to help naval ship designers understand the energy flow, size components and assess feasibility and survivability in early-stage naval ship design.

Future work to be performed with this method includes the following:

- Vulnerability metric refinement using thermal signatures from AFO energy flow results
- Pulsed power load analysis using a Dynamic Architecture Flow Optimization (DAFO)
- Overall design vulnerability assessment using a Vulnerability Architecture Flow Optimization (VAFO)
- Cascading and secondary damage analysis using a DAFO
- Damaged ship/system recoverability analysis using a DAFO
- Further definition and refinement of the Operational Architecture with required capability interfaces to the logical architecture and application in the DAFO.

ACKNOWLEDGEMENTS

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4. Naval Ship Distributed System Design and Total Ship Synthesis Using Network Architecture Framework

Nicholas T. Stinson[1] (AM), **Mustafa Y. Kara**[1] (SM), **Mark A. Parsons**[1] (SM), **Dr. Alan J. Brown**[1] (FL)
[1]Kevin T. Crofton Dept. of Aerospace and Ocean Engineering, Virginia Tech, Blacksburg, VA

This paper describes an adaptable component level machinery system weight and size estimation tool used in the context of a distributed system architecture framework and ship concept design. The system architecture framework decomposes the system of systems into three intersecting architectures: physical, logical, and operational to describe the spatial and functional relationships of the system together with their temporal behavior characteristics. Following an Architecture Flow Optimization (AFO), or energy flow analysis based on this framework, vital components are sized based on their energy flow requirements for application in a ship synthesis model (SSM). Previously, components were sized manually or parametrically. This was not workable for assessing many designs in concept exploration and outdated parametric models based on historical data were not sufficiently applicable to new ship designs. The new methodology presented in this paper uses the energy flow analysis, baseline component data, and physical limitations to individually calculate sizes and weights for each vital component in a ship power and energy system. The methodology allows for new technologies to be quickly and accurately implemented to assess their overall impact on the design. The optimized flow analysis combined with the component level data creates a higher fidelity design that can be analyzed to assess the impact of various systems and operational cases on the overall design. This paper describes the SSM, discusses the AFO's contribution, and provides background on the component sizing methodology including the underlying theory, baseline data, energy conversion, and physical assumptions.

INTRODUCTION

Brown and Sajdak (2015) present a naval ship Concept and Requirements Exploration (C&RE) process that was developed, expanded and applied over two decades at Virginia Tech and MIT (Brown and Thomas 1998, Brown and Salcedo 2003, Stepanchick and Brown 2007, Strock and Brown 2008). Recent work in a Naval International Cooperative Program (NICOP) has explored the use of networks to provide an alternative approach and different paradigms for preliminary arrangements, architecture, and for considering survivability in early design decisions (Brefort et al. 2018). This network approach has proven to be exceptionally capable and flexible for the C&RE application. As a result, the C&RE process has been reworked to apply this approach and its associated framework to various C&RE process steps including ship synthesis and vital component sizing.

The architecture framework decomposes the total system architecture into three views: physical, logical, and operational as shown in Figure 4-1. This representation describes the spatial and functional relationships of the system together with their temporal behavior characteristics. This approach is featured in *Marine Engineering* (2019). Brefort et al. (2018) provides a more comprehensive architectural framework description.

Integral with the C&RE process is its Ship Synthesis Model (SSM) which is responsible for: synthesizing the total ship system of systems; assessing its weight, space, power balance and feasibility; assessing its operational effectiveness, cost and risk; and incorporating the results of external domain explorations for hullform, manning, reliability, combat vulnerability, combat recoverability and combat, power and energy system (CPES) definition. In our prior synthesis model, parametric equations based on prior ship data were used to calculate most of these characteristics. This parametric approach is not sufficiently applicable or flexible for thinking outside the box in new designs. A more physics-based, design-specific approach is required. In the updated tools, the network architecture framework facilitates useful applications such as Architecture Flow Optimization (AFO). An AFO begins with a system logical architecture, applies and enforces steady-state or quasi-steady-state operational constraints and performs a linear programming optimization. The objective function in this optimization minimizes the flow cost of the network. This cost has two components: a fixed cost (representing the engineering and installation costs of connecting components) and a variable cost (which linearly increases with flow). Parsons et al. (2019 a&b) and Brown (2019) provide a complete description of the AFO linear optimization formulation and the operational constraints. The AFO is used for architecture optimization, CPES Vital Component (VC) sizing and system feasibility assessment. Properly sized VC data is then used in the SSM. The application and integration of AFO sizing output into the SSM is described in this paper.

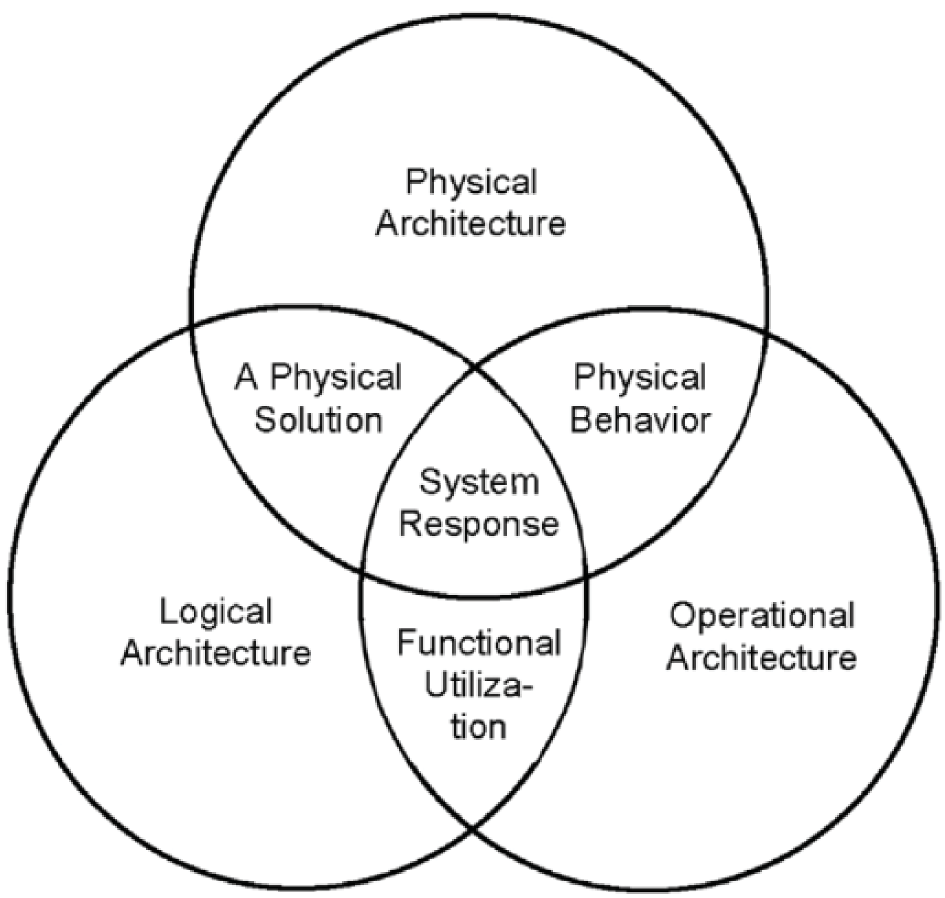

Figure 4-1: Representation of an Architectural Framework for Ship Distributed Systems (Brefort et al., 2018)

CONCEPT & REQUIREMENTS EXPLORATION (C&RE)

A notional naval ship Concept and Requirements Exploration (C&RE) process is illustrated in Figure 4-2. It begins with a statement of mission need in an Initial Capabilities Document (ICD). The content of the ICD is refined and expanded to better understand the ship's Concept of Operations (CONOPS), operational situations (OpSits), tasks required by the mission, and operational capabilities required to perform the mission (ROCs). This is important for specifying the system operational architecture and calculating an Overall Measure of Effectiveness (OMOE) later in the process. Next, a thorough collection and review of applicable technologies and a comparative naval architecture study of recent ships with similar missions are performed. This includes combat, propulsion, power and distributed system technologies with their logical architectures. From these studies, designers begin to define the ship design space and a very preliminary Initial Baseline Design.

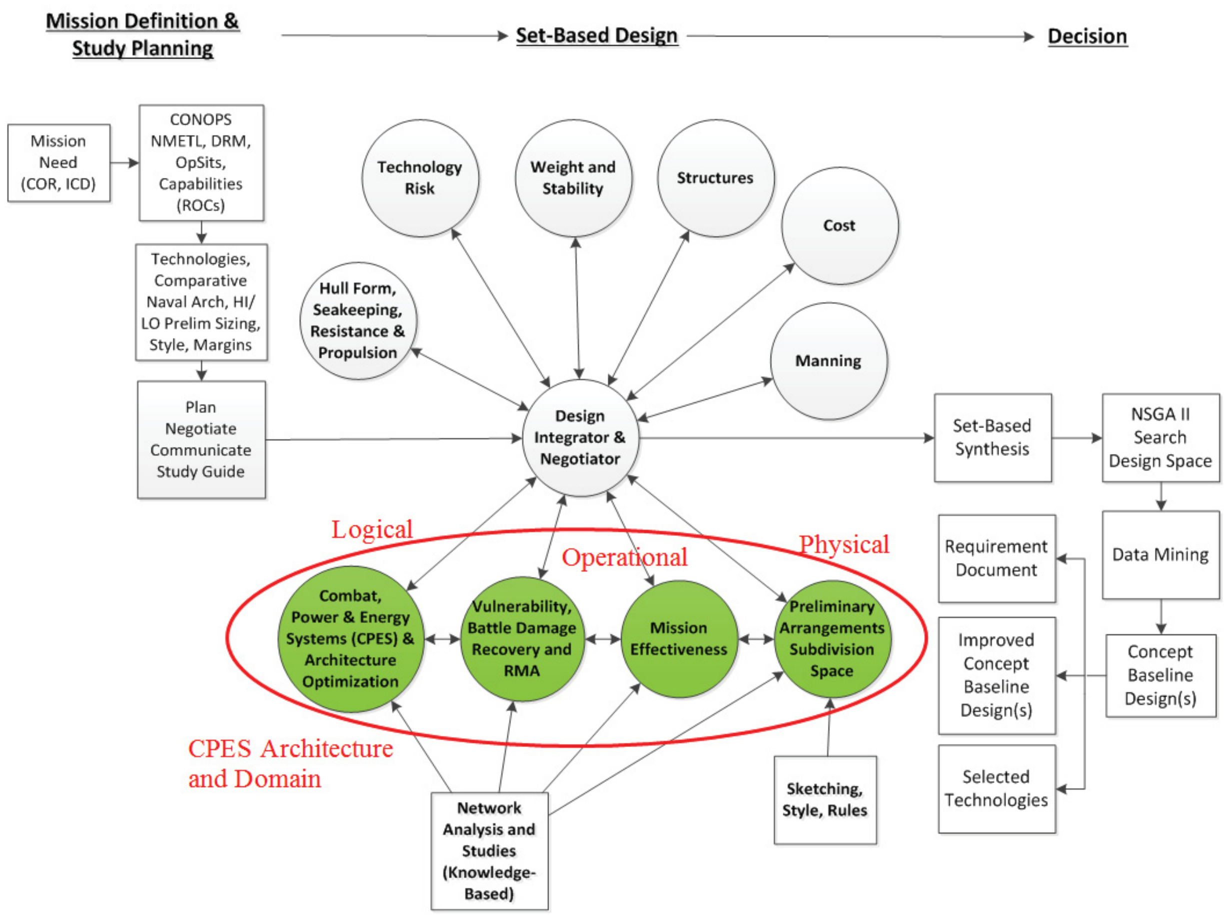

Figure 4-2: Naval Ship Concept & Requirements Exploration (C&RE) Process with CPES Architecture and Set-Based Domain

Next comes domain-specific concept explorations in at least six important domains: hullform and deckhouse geometry, combat power and energy systems including propulsion and other distributed systems, mission systems, preliminary arrangements, manning and automation, survivability (for naval ships) and reliability/maintainability and availability (RM&A). These explorations are typically accomplished simultaneously by multiple domain experts with interaction through a design manager or system integrator to coordinate the feasible design space definition and any product interdependency assumptions. Important products of these explorations include the collection and analysis of data for each discipline using a design of experiments (DOE) approach, the identification of important design variables and parameters, the definition and refinement of the design space for each discipline, and response surface models (RSMs) approximating the relationship between input design variables and response characteristics for use later in a design-specific synthesis model. Generic parametric equations and a generic synthesis model based on limited data from past ship designs are not sufficiently applicable or flexible for thinking outside the box in new designs. A more physics-based, design-specific approach is required. This is the primary reason for these explorations.

CPES exploration, preliminary arrangements, survivability and RM&A are closely coupled and computationally extensive so they are explored using representative designs. Representative designs including hull, subdivision, preliminary arrangements are synthesized for each combination of CPES system options. A single set of midrange hullform DV values except for LOA are used for all representative designs. Representative LOA values are calculated (not optimized) as required to support system option weight, space and electric power requirements using the less definitive parametric approach. Vital Component (VC) sizing data, vulnerability probabilities, reliability and architecture data are saved for each system option combination in their respective representative designs for recall in the final ship synthesis whenever this set of options comes up. The CPES process is illustrated in Figure 4-3.

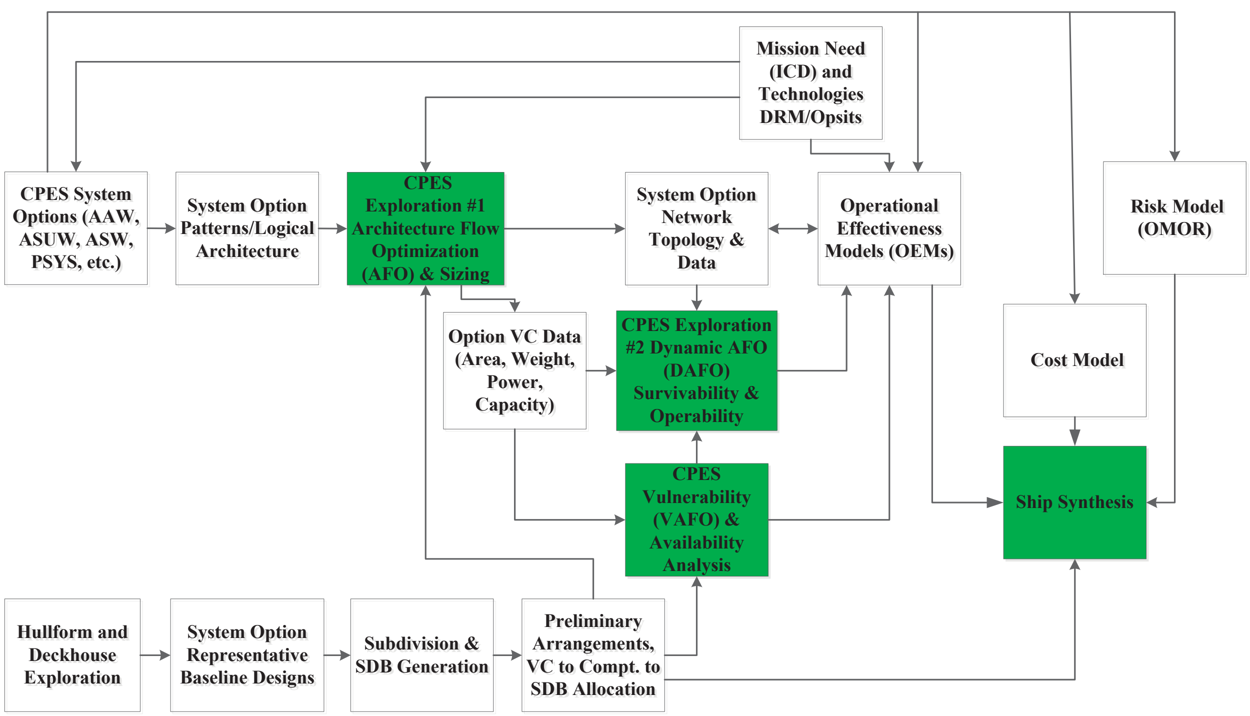

Figure 4-3: CPES Design Process Using Figure 4-1 Architectural Framework

Once these individual explorations are complete, a set-based integration approach may be used to reduce the large integrated design space for ship synthesis. This approach may include searching for non-dominated (Pareto) designs using a Multi-Objective Genetic Optimization (MOGO) with dominance and feasibility layers, and targeted higher fidelity simulations (Brown et al. 2017). This process is intended to delay decision-making, control convergence until later in the design process, and enable parallel domain solutions. Instead of working towards feasible Pareto-optimal solutions, it works to identify and remove clearly infeasible and badly dominated solutions. High-fidelity physics simulations may be introduced early through variable-fidelity response surfaces to minimize the risk of removing domain solutions that could later prove to be feasible and non-dominated.

The Ship Synthesis Model (SSM) contains the tools necessary to generate and evaluate a ship design based on an input set of design variables, design parameters and related data collected in the various explorations as RSMs or discrete data files. The SSM focuses on the ship balance, feasibility, and overall analysis. It has the capability to analyze a single ship or to run in a Multi-Objective Genetic Optimization (MOGO) and evaluate an array of ships searching for non-dominated designs within the designated bounds of the design variables and parameters. The SSM is used at two separate times in the C&RE process. Referring to Figure 4-3, it is first used in the CPES exploration to create and analyze representative designs for each combination of system DV options. This use includes preliminary ship LOA sizing, subdivision, arrangement, AFO component sizing, reliability assessment and survivability assessment. It is also used in the final synthesis and MOGO where the collected representative design data are applied. To accomplish this, the SSM operates in 3 modes: 1) parametric – this may be used to run the MOGO without the CPES exploration and AFO; 2) parametric for preliminary sizing, arrangement and AFO assessment of representative designs; and 3) post-AFO for final synthesis and MOGO with CPES exploration and AFO data.

SHIP SYNTHESIS MODEL (SSM)

The SSM is implemented using Model Center (Phoenix Integration 2017) and Excel software in an Exploration and Ship Synthesis Model (E&SSM) as shown in Figure 4-4. Different regions and modules in this model are used to perform various steps in the C&RE. The left-hand red box in Figure 4-4 represents the SSM. It includes: input modules for design variables (DVs) and design parameters (DPs); response surface models (RSMs) for rapidly calculating hullform hydrostatics, seakeeping, endurance resistance and propulsion, sustained speed, battle speed and manning data; a simple output summary module; a multi-objective genetic optimization (MOGO) module; and three instances of the Excel-based SSM worksheet calculations. RSMs are developed based on physics-based modeling using Design of Experiments (DOEs) performed in various domain explorations to efficiently develop response data sets for fitting response surfaces. Modules for these explorations are shown in the right-hand red box. In order to consider integrated power system (IPS) applications, available electric power for propulsion must be calculated after all other electric loads have been determined. Then RSMs calculate sustained and battle speed before completing the SSM effectiveness assessment. Model Center provides the ability to run a Design of Experiments (DOE), create Response Surface Models (RSMs), and run tools like the Darwin optimizer for a MOGO to generate non-dominated frontier(s) of design alternatives. The E&SSM also contains the Preliminary Arrangements Module (PAM), a third instance of the Excel SSM module which provides the framework for the physical architecture.

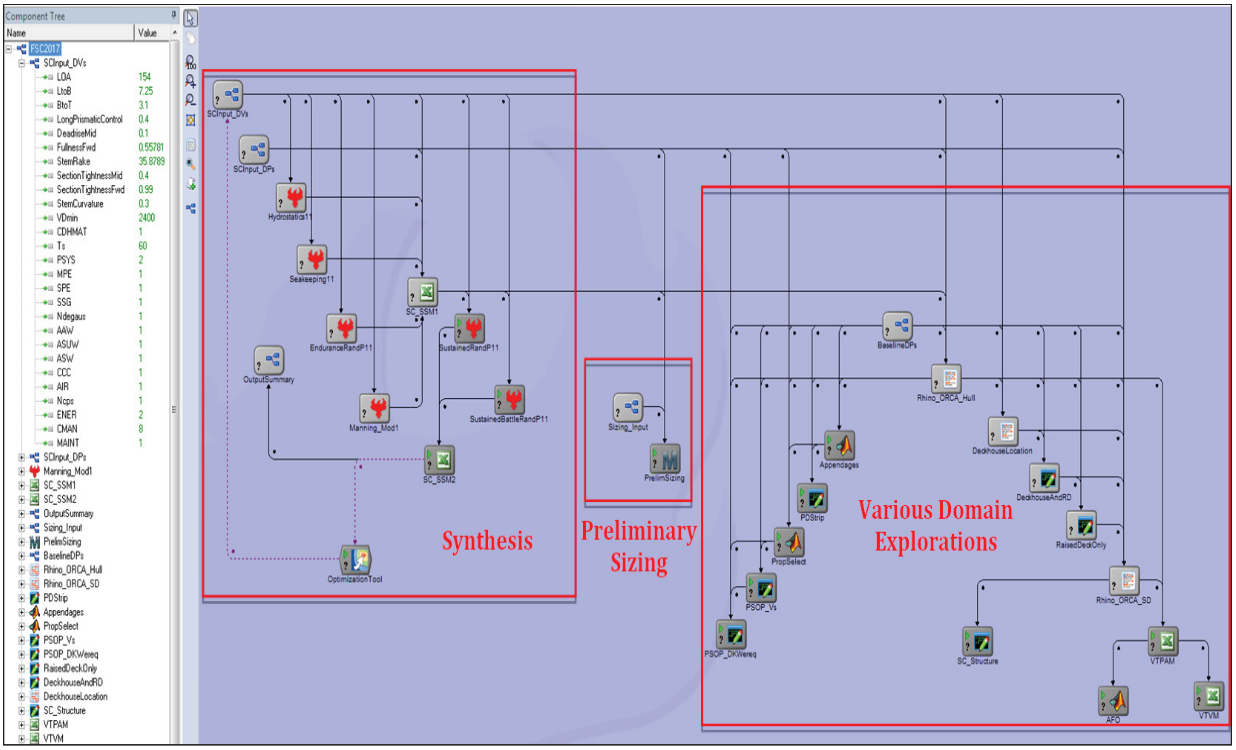

Figure 4-4: Exploration and Ship Synthesis Model (E&SSM) in Model Center (MC) (Parsons et al 2019a)

The Excel SSM module performs a number of calculations organized into worksheets as shown in Table 4-1. The "DVs&DPs" worksheet for a notional surface combatant is open in Table 4-1. The first eight DVs apply to hullform design. The parameters used for hullform design are specific to the use of the Orca3D Hull Design Assistant (Orca3D 2019). Each parameter controls a factor influencing hull shape. The Hull Design Assistant generates a 3D hullform for each new design and allows the exploration to automate the hull design process. The hull DVs are followed by various system option DVs. These include manning and maintenance factors. The system option DVs are listed in Table 4-1 for power and energy system architecture options, main machinery and combat systems. The combat systems impact the AFO sizing significantly in terms of electric power requirements, cooling and zonal architecture. They must be incorporated at this early stage. Design parameters (DPs) are constant for all designs. Combat systems DVs typically considered for a surface combatant (SC) exploration are grouped by warfare area: anti-air warfare, electronic warfare, and guided missile launching systems (AAW/SEW/GMLS); anti-surface warfare and naval surface fire support (ASUW/NSFS); anti-submarine warfare and mine countermeasures (ASW/MCM); command, control, communications, computers and intelligence (CCC or C4I); and aircraft which for a SC typically would include helos and UAVs (AIR). Each option has a predetermined list of major vital components and architectures which are chosen based on the required mission capabilities of the ship. The options progress from a goal targeted area as option 1 to the minimum required level as the final option. Options in-between offer intermediate capabilities. The PSYS option allows for a choice of main propulsion and power architecture (IPS, HED, CODAG, COGAG, number of shafts) and main propulsion engines and secondary engines or power generation modules, chosen from a list of Navy-qualified designs. This yields 1,296 unique combat system combinations with 8 different propulsion systems (10,368 total system combinations). The DVs&DPs worksheet also contains basic data for electric component power and gravimetric densities that can be adjusted based on current technology or technology goals (PMS 320, 2013). A baseline ship with the input values listed in the left column is presented in this paper as a representative design, but design space values would vary within the listed ranges in the fourth column and through all system combinations. The MOGO searches the full design space to assess feasibility, effectiveness, cost and risk before eliminating (badly) dominated designs.

Table 4-1: Notional Surface Combatant SSM Worksheets and Design Space

Input Value	DV	Design Variables	Values	Description
135.10	1	Length on Deck (LOA)	150 to 175m	
7.49	2	LtoB Ratio	7 to 7.65	
3.03	3	BtoT Ratio	3.25to3.6	
0.400	4	Long'l Prismatic Control	0.1 to .4	
0.393	5	Deadrise Mid	.1-.4	
0.300	6	Fullenss Fwd	.3 to .6	
42.031	7	Stem Rake	35-45 deg	
0.420	8	Section Tightness Mid	.4 to .99	
3000	9	Minimum Volume of Deckhouse (VD)	2000-5000 m3	
7.00	10	Manning and Automation Factor (CMAN)	0.5-1.0	
2	11	Maintenance	1to3	Maintenance Plan
1	12	Degaussing (DEGAUS)	0,1	0=none, 1=yes
1	13	CPS	0,1,2	0=none, 1=partial, 2=full
60	14	Provisions Duration (Ts)	30-60 days	
8	**15**	Propulsion System (PSYS) - Architecture	1	IPS,2 pods, 2xGTPGM,2xDSPGM, MVDC
			2	IPS,2 FPP, 2 shafts, 2xPMM,2xGTPGM,2xDSPGM, MVDC
			3	COGAG, DDG-51, LVAC
			4	HED, 2 CRP, 2 shafts, 2xGTMPE,2xDSPGM,2xSPMM,2xSSG, MVAC
			5	CODAG,2 CRP, 2 shafts, 2xGTMPE, 2DSPE,4xSSG,CODAG
			6	IPS,2 FPP, 2 shafts, 2xPMM,1xGTPGM,2xDSPGM, MVDC
			7	HED, 2 CRP, 2 shafts, 1xGTMPE,2xDSPGM,2xSPMM,2xSSG, MVAC
			8	CODAG,2 CRP, 2 shafts, 1xGTMPE, 2DSPE,4xSSG,CODAG
1	**16**	MPE/PGM Main Propulsion Engine or PGM	1	MT30
			2	LM2500+
4	**17**	SPE Secondary Engine or SPGM	1	MTU 20V 8000 M91L (10MW)
			2	20PA6B STC (8.1 MW)
			3	16PA6B STC (6.48 MW)
			4	CAT 280V16 (5.06 MW)
3	**18**	Ship Service Generator	1	Allison 501K34 SSGTG
			2	CAT 280V12 SSDG
			3	CAT 280V8 SSDG
5	**19**	AAW,SEW,GMLS	Option 1	AMDR-S/X 37 RMA /4 faces,AEGIS BMD (ACB), MK41 VLS - 32 and 64 CELL,IFF,2xCIWS,2xAIEWS,8xMK53 SRBOC&NULKA,2xLaWS
			Option 2	AMDR-S 37 RMA /4 faces,2xSPG-62,AN/SPQ-9B,AEGIS BMD (ACB), 2xMK41 VLS - 32 CELL,IFF,2xCIWS,2xSLQ32,8xMK53 SRBOC&NULKA,2xLaWS
			Option 3	SPY-3 /4 faces,2xSPG-62,AN/SPQ-9B,AEGIS BMD (ACB), 2xMK41 VLS - 32 CELL,IFF,2xCIWS,2xSLQ32,8xMK53 SRBOC&NULKA,2xLaWS
			Option 4	AMDR-S/X - 9 RMA/4 faces, AEGIS CS, MK41 VLS - 2x32 CELL ea, IFF,2xCIWS,2xAIEWS,8xMK53 SRBOC&NULKA,1xLaWS
			Option 5	AMDR-S 9 RMA /3 faces,2xSPG-62,AN/SPQ-9B,AEGIS CS, 2xMK41 VLS - 24 CELL ea, IFF,2xCIWS,2xSLQ32,8xMK53 SRBOC&NULKA
			Option 6	AMDR-S 9 RMAs 1 rotating face,2xSPG-62,AN/SPQ-9B,AEGIS CS, 2xMK41 VLS - 16 CELL ea, IFF,2xCIWS,2xSLQ32,8xMK53 SRBOC&NULKA
6	**20**	ASUW/NSFS	Option 1	Rail Gun, SPS-73, IRST, 50 cal machine guns, ADS, VLS Hellfire missiles,LaWS,2xCIWS
			Option 2	5in/62 Gun, SPS-73, IRST, 50 cal machine guns, ADS, VLS Hellfire missiles,LaWS,2xCIWS
			Option 3	5in/62 Gun, SPS-73, IRST, 50 cal machine guns, VLS Hellfire missiles,2xCIWS
			Option 4	5in/62 Gun, SPS-73, IRST, 50 cal machine guns, ADS, VLS Hellfire missiles
			Option 5	76mm Gun, SPS-73, IRST, 50 cal machine guns, ADS, VLS Hellfire missiles
			Option 6	57mm Gun, SPS-73, IRST, 50 cal machine guns, VLS Hellfire missiles
6	**21**	ASW/MCM	Option 1	5M Dual Band Sonar,ASWCS,ASWTCS,NIXIE,TRIPWIRE, 2xLAMPS and Hangar,SVTT,ASROC,TACTAS,SSDT,CATT/TWS
			Option 2	5M SQS-53D Sonar,ASWCS,ASWTCS,NIXIE,TRIPWIRE, 1xLAMPS and Hangar,SVTT,ASROC,TACTAS,SSDT,CATT/TWS
			Option 3	SQS-53D Sonar,ASWCS,ASWTCS,NIXIE,TRIPWIRE, 1xLAMPS and Hangar,SVTT,ASROC,TACTAS
			Option 4	SPS 56 Sonar,ASWCS,ASWTCS,NIXIE,TRIPWIRE, SVTT,ASROC,TACTAS,SSDT,CATT/TWS
			Option 5	no hull sonar, ASWCS,ASWTCS,NIXIE,TRIPWIRE, 1xLAMPS and Hangar,SVTT,ASROC,TACTAS,SSDT,CATT/TWS
			Option 6	NO HULL Sonar,ASWCS,ASWTCS,NIXIE,TRIPWIRE, 1xLAMPS and Hangar,SVTT,ASROC,TACTAS
1	**22**	CCC	Option 1	ExComm Level A, Cooperative Engagement Capability (CEC) and Link 11, Navigation System, TSCE, InTop,MK 37 Tomahawk Weapon System (TWS)
			Option 2	ExComm Level B, Cooperative Engagement Capability (CEC) and Link 11, Navigation System, TSCE, MK 37 Tomahawk Weapon System (TWS)
2	**23**	**AIR**	Option 1	Embarked 2xLAMPS w/ Hangar, 2 x UAV
			Option 2	Embarked 1xLAMPS w/ Hangar, 2 x UAV
			Option 3	2 x UAV w/ Hangar

DVs&DPs | Links | Combat | CSEL | AAW | ASW | ASUW | FM | PSYS | MEL | EPLA | Engines | Machinery | SpaceA | Electric | Weight | Tankage | Cost | Feasibility | RiskRegister&OMOR | OMOE

Other SSM worksheets (from left to right in Table 4-1) perform the following functions:

- **Links** – This worksheet stores input data from Model Center including RSM calculation output to be used by other SSM worksheets.
- **Combat** – This worksheet sums selected combat system option vital component characteristics (from AAW, ASUW, ASW worksheets) for weight, space and electric power in SWBS and SSCS groups to be used by the SSM and PAM. Option components are specified in combat system component vectors and their data is stored in the Combat System Equipment List (CSEL). The Combat Macro located on this sheet uses the network architecture created by the component vectors to calculate the component characteristics mentioned above.
- **CSEL** – The combat system equipment list contains the following data for each combat system vital component specified by the combat system architectures: CSEL number, SSCS, SWBS, area, weight, dimensions, cruise electric power required, battle electric power required, arrangement requirements, system and subsystem categories, and cooling type/system. This list is used to populate data for the combat systems macro and subsequently provides coefficients used in the network architecture that sizes the weapons systems on the ship from the preliminary DVs & DPs.
- **AAW** – This worksheet contains the AAW system option architecture: vital component (VC) vertices and arcs, VC compartments, system plex external dependencies such as cooling and

power, assigned subdivision block (SDB) boundaries, VC CSEL component number, and data copied from the CSEL: VC SWBS, SSCS, electric loads, VCG, weight, dimensions, and arc energy flow coefficients (discussed later with PSYS). The data is stored separately for each option and accessed with the Combat Systems macro to create the overall combat network architecture.

- **ASW –** Similar to AAW, but for ASW system architecture.
- **ASUW –** Similar to AAW, but for ASUW system architecture.
- **PSYS –** This worksheet is central to power and energy system architecture optimization, energy flow and sizing. It will be discussed in detail below.
- **MEL –**The machinery equipment list (MEL) contains the following data for each PSYS vital component type specified by the PSYS architectures: MEL number, SSCS, SWBS, VC baseline component weight, dimensions, commodity baseline capacity, commodity flow units, system or plex, arc energy flow coefficients, arc energy trace scaling factor and arc commodity conversion factor (discussed later with PSYS). A further discussion and sample of the MEL is provided later in this paper.
- **EPLA –** The Electric Power Load Analysis worksheet summarizes electric loads stored and calculated in other worksheets, particularly the Electric worksheet, categorized by SWBS group. This data can be calculated using parametric equations (as for the representative designs) or post-AFO based on the optimized energy flow. It is separated into battle loads, sustained speed loads, cruise/endurance loads, anchor, in port, emergency, and connected loads for all the SWBS group calculations. This data is used in determining the overall electric load of the ship.
- **Engines –** This worksheet contains basic power (MCR), size and weight information for engines currently in use and qualified by the US Navy. This data is pulled into the MEL as required for the chosen engine/PGM DV options. Different PSYS options can choose different engines.
- **Machinery –** This worksheet calculates and sums SWBS 200, 300, and 500 weights, CG, and electric loads. It also calculates main machinery room volume. This data can be calculated using parametric equations and engine/PGM data (as for the representative designs) or post-AFO based on the optimized energy flow. When flagged, the Machinery worksheet will utilize the AFO arc flow results and scaled component data from PSYS and provide a higher fidelity estimate of overall ship weight, space, electric and thermal loads that is more physics-based, consistent with new technology and balanced by zone. The AFO results on this worksheet are discussed later.
- **Electric** – This worksheet calculates manning, electric loads, and auxiliary machinery room volume. It receives inputs from the SSM and uses a series of parametric equations to systematically calculate various loads for multiple SWBS groups and compartments. The data for SWBS groups outside of 200, 300, and 500 is still used by the current version of the SSM. These electric loads are also refined post-AFO.
- **SpaceA –** This worksheet calculates space available: hull, deckhouse and total ship volume and area; total machinery room volume; and hull cubic number for use in other parametrics. The inputs to this worksheet come mostly from the Links and DVs&DPs worksheets, and the outputs are a preliminary space estimate, pre-AFO.
- **Weight –** This worksheet calculates and sums single digit SWBS weights with center of gravity using weight inputs from Combat and Machinery. This data can be calculated using parametric equations (as for the representative designs) or post-AFO based on the optimized

energy flow. When flagged, the Weight worksheet will utilize AFO arc flow results and scaled component data from PSYS and provide a higher fidelity estimate of overall ship weight that is more physics-based, consistent with new technology and balanced by zone. The results calculated on this worksheet are discussed further later.

- **Tankage –** This worksheet calculates fuel weight, fuel tankage volume, other tankage volume, other liquid weights and endurance range based on US Navy Design Data Sheet DDS 200-1. Inputs are from the SSM and outputs are calculated using a set of parametrics and factors to estimate tankage capacities and weights along with areas and volumes required for this capacity based on factors such as deck height and the principal dimensions of the ship.
- **Cost –** This worksheet calculates lead and follow-ship acquisition costs and overall life cycle cost using weight-based parametrics modified for producibility and complexity. The inputs are single digit SWBS group weights along with a series of complexity and producibility factors. Cost is first calculated using single digit SWBS weights and then a series of factors are applied to calculate total costs for the lead, follow, and overall life cycle of the ship.
- **Feasibility –** This worksheet calculates overall design feasibility considering available versus required stability, space, electric power, speed and endurance range.
- **Risk Register & OMOR –** This worksheet calculates an Overall Measure of Risk for a given design based on a risk register with probabilities and consequences for adverse events determined by technology selection by DVs. (Mierzwicki 2003, Mierzwicki and Brown 2004). The risk is related to the selected options for combat systems and power systems and a predetermined set of coefficients for each of these systems based on previous research to determine their level of risk.
- **OMOE –** This worksheet calculates an Overall Measure of Effectiveness for a specific design using calculated and expert opinion option-based measures and values of performance (MOPs and VOPs) assembled into a single effectiveness metric using an OMOE/MOP hierarchy with weights calculated using the analytical hierarchy process (AHP) (Demko 2005). The calculation procedure is similar to the OMOR in that the chosen options for weapon and power systems directly determine the effectiveness of the ship in various load conditions.

ARCHITECTURE FLOW OPTIMIZATION (AFO)

Robinson (2018) presents a naval ship distributed system analysis approach using an Architecture Flow Optimization (AFO) and consistent with the system architecture framework (Brown 2019) described above. This process uses linear equations and a linear programming optimization to calculate the flow of energy in ship power and energy systems for multiple scenarios including: sustained speed; endurance speed; battle; and damage (Parsons (2019b). The AFO uses a series of flow coefficients to specify the energy flow in vital components and connections by establishing sources, sinks, and simplified component flow models. Figure 4-5 illustrates the total ship architecture with nodes identified in their respective subsystems or plexes. The PSYS worksheet is the primary interface with the AFO process. It contains the data for architecture, vital components (nodes) and arcs necessary to run the AFO. It also contains the coefficients for each VC. The final aggregate energy flows for all explicit arcs in the PSYS plexes (which are linearly optimized in kW) are returned from the AFO to the SSM PSYS worksheet.

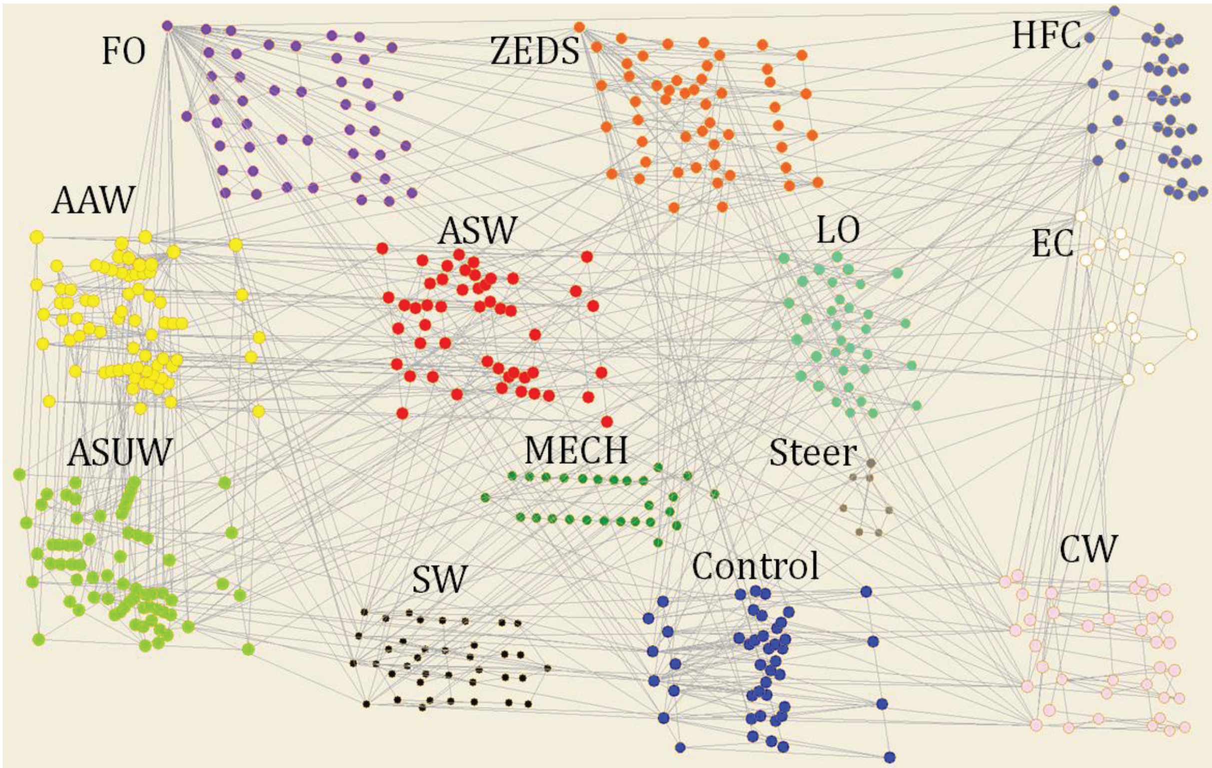

Figure 4-5: Notional Ship System Architecture (Parsons et al. 2019a)

SSM VITAL COMPONENT SIZING AND APPLICATION (PSYS, MEL, Machinery and Weight Modules)

Before VCs can be sized for their required commodity flow capacity, the final aggregate energy flows for all explicit arcs returned from the AFO must be converted to aggregate commodity flows. Table 4-2 shows the results of this calculation in the PSYS worksheet. First, the total arc energy flow into each VC node is summed. Next, trace flows must be scaled up to equivalent energy flow values that can be used to calculate commodity flow. This is discussed below. Then the energy flows into each VC are converted to required commodity flows and finally rounded up to VC required commodity flow capacity.

Table 4-2: PSYS Required Commodity Flow Capacity Calculations

DV	Node	Vertex Label / VC	Aggregate Arc Energy and Commodity Flow for Commodity Capacity							
			Flow to Node #	Total Aggregate Arc energy flow (kW) from AFO arcs below	Arc energy scaling factor (1 or 100, actual or trace)	Adjusted Arc energy flow	Related Commodity Flow Units	Commodity Flow Factor	Aggregate Required Commodity Flow	Standard Required Commodity Capacity
PSYS	2	IPS, MVDC								
*Vertices										
MECH	1	Propulsion_SYS	1	69981.1	1	69981	kW	1	69981.1	69990
	2	Propeller1_VC	2	34990.5	1	34991	kW	1	34990.5	35000
	3	TailShaftAndStrutBearing1_VC	3	34990.5	1	34991	kW	1	34990.5	35000
	4	SternTubeAndSeal1_VC	4	34990.5	1	34991	kW	1	34990.5	35000
	5	LineShaftAndBearings1A_VC	5	35166.4	1	35166	kW	1	35166.4	35170
	6	LineShaftAndBearings1B_VC	6	35343.1	1	35343	kW	1	35343.1	35350
	7	ThrustBearing1_VC	7	35520.7	1	35521	kW	1	35520.7	35530
	8	PMM1_SYS	8	35520.7	1	35521	kW	1	35520.7	35530
	9	PMM1-Coupling_VC	9	35520.7	1	35521	kW	1	35520.7	35530
	10	PMM1-Clutch_VC	10	35520.7	1	35521	kW	1	35520.7	35530
	11	Propeller2_VC	11	34990.5	1	34991	kW	1	34990.5	35000
	12	TailShaftAndStrutBearing2_VC	12	34990.5	1	34991	kW	1	34990.5	35000
	13	SternTubeAndSeal2_VC	13	34990.5	1	34991	kW	1	34990.5	35000
	14	LineShaftAndBearings2A_VC	14	35166.4	1	35166	kW	1	35166.4	35170
	15	LineShaftAndBearings2B_VC	15	35343.1	1	35343	kW	1	35343.1	35350
	16	ThrustBearing2_VC	16	35520.7	1	35521	kW	1	35520.7	35530
	17	PMM2_SYS	17	35520.7	1	35521	kW	1	35520.7	35530
	18	PMM2-Coupling_VC	18	35520.7	1	35521	kW	1	35520.7	35530
	19	PMM2-Clutch_VC	19	35520.7	1	35521	kW	1	35520.7	35530
CW	301	CW_Supply1_VC	301	71.1	100	7105	m3/hr	0.062	440.5	450
	302	CW_Supply2_VC	302	141.2	100	14116	m3/hr	0.062	875.2	880
	303	CW_Supply3_VC	303	141.0	100	14103	m3/hr	0.062	874.4	880
	304	CW_Supply4_VC	304	71.1	100	7106	m3/hr	0.062	440.5	450
	305	CW_Return1_VC	305	10584.4	1	10584	m3/hr	0.062	656.2	660
	306	CW_Return2_VC	306	18437.4	1	18437	m3/hr	0.062	1143.1	1150
	307	CW_Return3_VC	307	19245.9	1	19246	m3/hr	0.062	1193.2	1200
	308	CW_Return4_VC	308	10718.6	1	10719	m3/hr	0.062	664.6	670
	309	CW_Cooler_1A_SYS	309	3517.0	1	3517	m3/hr	0.062	218.1	220
	310	CW_Cooler_2A_SYS	310	3517.0	1	3517	m3/hr	0.062	218.1	220
	311	CW_Cooler_3A_SYS	311	3517.0	1	3517	m3/hr	0.062	218.1	220
	312	CW_Cooler_4A_SYS	312	3517.0	1	3517	m3/hr	0.062	218.1	220
	313	CW_Pump1A_SYS	313	35.5	100	3553	m3/hr	0.062	220.3	230
	314	CW_Pump2A_SYS	314	35.5	100	3553	m3/hr	0.062	220.3	230
	315	CW_Pump3A_SYS	315	35.5	100	3553	m3/hr	0.062	220.3	230
	316	CW_Pump4A_SYS	316	35.5	100	3553	m3/hr	0.062	220.3	230
	317	CW_Pump1B_SYS	317	35.5	100	3553	m3/hr	0.062	220.3	230
	318	CW_Pump2B_SYS	318	35.5	100	3553	m3/hr	0.062	220.3	230
	319	CW_Pump3B_SYS	319	35.5	100	3553	m3/hr	0.062	220.3	230
	320	CW_Pump4B_SYS	320	35.5	100	3553	m3/hr	0.062	220.3	230
	321	CW_Cooler_2B_SYS	321	3517.0	1	3517	m3/hr	0.062	218.1	220
	322	CW_Cooler_3B_SYS	322	3517.0	1	3517	m3/hr	0.062	218.1	220
	323	EC_HeatExch1_CW_SYS	323	9.3	1	9	m3/hr	0.062	0.6	10
	324	EC_HeatExch2_CW_SYS	324	9.3	1	9	m3/hr	0.062	0.6	10
	325	Zone1_HVAC_CW_SYS	325	35.5	1	36	m3/hr	0.062	2.2	10
	326	Zone2_HVAC_CW_SYS	326	43.7	1	44	m3/hr	0.062	2.7	10
	327	Zone3_HVAC_CW_SYS	327	51.8	1	52	m3/hr	0.062	3.2	10
	328	Zone4_HVAC_CW_SYS	328	36.9	1	37	m3/hr	0.062	2.3	10
	329	Glycol_HeatExch2_CW_SYS	329	131.4	1	131	m3/hr	0.062	8.1	10
	330	Glycol_HeatExch3_CW_SYS	330	131.4	1	131	m3/hr	0.062	8.1	10
	331	CW_Cooler_1B_SYS	309	3517.0	1	3517	m3/hr	0.062	218.1	220
	332	CW_Cooler_4B_SYS	332	3517.0	1	3517	m3/hr	0.062	218.1	220

Trace Flows

Since the AFO must model commodities moving through the total system carrying energy, but only energy flow is considered explicitly, a trace energy flow is used to represent commodity flow on the cold (commodity return) side of the plexes. For example, energy enters at the zonal heat sources, passes through the hot side of the CW system and exits at the chilled water coolers. Without a trace flow, no energy would pass through the chilled water pumps or the chilled water supplies on the cold side of the system after the chilled water coolers. Requiring a CW 1% input flow to the zonal heat source pulls a trace flow of CW through the cold side of the loop. These trace flows are scaled back up (x100) in the SSM (PSYS) before commodity flow is calculated and component sizing occurs. Trace Flows are implemented in the cooling fluid plexes (CW, HFC, EC, Glycol, LO, and SW), but not in MECH and ELEC plexes, as shown in Table 4-2.

Commodity Flow Conversion in PSYS

Next, PSYS converts the AFO aggregate energy flow to commodity flows in plexes where the energy flow is not already its commodity. For electrical and mechanical systems this is still in kW, but for systems such as chilled water, lube oil, seawater and fuel, the flow in kW is converted to a necessary volume of fluid commodity flow in m3/hr. The equation below uses the commodity conversion factor ($\rho c_p \Delta T$) to calculate commodity flow, where $\dot{V}$ is the commodity volume flow rate, $\dot{q}$ is the energy (heat) flow rate from the AFO, c_p is the commodity specific heat, ΔT is the normal temperature difference between hot and cold sides, and ρ is the commodity density. Parameter values for all commodities are summarized in Table 4-3.

$$\dot{V} = \frac{\dot{q}}{\rho c_p \Delta T}$$

Table 4-3: Fluid Commodity and Flow Conversion Data (Marine Engineering 2019)

Fluid	Density (kg/m^3)	Specific heat (kJ/kgK)	ΔT Normal Operating Temp Range (˚F)	ΔT Normal Operating Temp Range (°K)	Commodity Flow Units	Commodity Flow/kW Factor
Chilled water(CW)	1000	4.19	25	13.89	m3/hr	0.062
Deionized water (EC)	1000	4.20	5	2.78	m3/hr	0.309
Seawater	1025	3.93	18	10.00	m3/hr	0.089
Glycol mix	1111	2.50	30	16.67	m3/hr	0.078
Lube oil	880	2.00	20	11.11	m3/hr	0.184

Machinery Equipment List and Baseline VC Data

As described above, the machinery equipment list (MEL) contains the following data for each PSYS vital component type specified by the PSYS architectures: MEL number, SSCS, SWBS, VC baseline component weight, dimensions, commodity baseline capacity, commodity flow units, system or plex, arc energy flow coefficients, arc energy trace scaling factor and arc commodity conversion factor. A list of VC baseline component weight, dimensions and commodity baseline capacity was developed for all VC types. Each of these components was individually researched and given a standard value that is typical for a destroyer-size ship (either as an overall component or as a component power density). These values are listed in Table 4-4. This standard data can be updated as new technology emerges with improved capacities and allows the SSM to adapt to future technology. The standard machinery equipment list can also grow to include components from different classes of ships and will depend on the program inputs to determine which base components to use for scaling in weight, size, and electric load estimations.

Components (such as in a standard AC plant) are listed as separate components for purposes of the AFO, but the weight and sizing are based on an integrated plant which is more representative of current ship practice and the way technology is packaged. Thus some components show zeroes for weights and flow. Other components such as switchboards and PCMs may seem quite small, but that is because they are based on power and weight densities from a recent technology study (NAVSEA PMS 320, 2013). These densities are based on an average of actual and goal values and can be adjusted to fit the current state of technology when running the ship synthesis. Other components such as supplies and returns are sized based on arc lengths and appear as zeroes.

Table 4-4: Machinery Equipment List (MEL)

VC Type Specification						Baseline VC Type Data (from TAKE MEL and Engines)					
MEL #	VC/SYS	Description	Subsystem & Medium	SWBS	SSCS	WT(MT)	L (m)	B (m)	H (m)	Baseline Capacity	Capacity Units
1	BusNode	BusNode	ELEC	324	43323	0.83	0.32	1.25	2.50	2500.00	kW
2	PCM	power conversion module	ELEC	314	43324	0.64	0.32	1.25	2.50	350.00	kW
3	LC	load center	ELEC	324	43324	0.83	0.32	1.25	2.50	2500.00	kW
4	SWBD	switchboard	ELEC	324	4152	0.83	0.32	1.25	2.50	2500.00	kW
5	SPGM	secondary power generation module	ELEC	235	416	79.35	11.2658	2.04	3.73	9700	kW
6	PGM	power generation module	ELEC	235	416	41.85	12.852	3.84	3.78	34920	kW
7	PMM	propulsion motor module	MECH	235	415	1.00	1.23	0.90	0.90	200.00	kW
8	FO_ServTank	fuel oil (DFM) service tank	FO	261	435	0.0	0.0	0.0	0.0	0.0	m3
9	FO_ServPump	fuel oil service pump	FO	261	435	0.1	0.9	0.4	0.5	7.4	m3/hr
10	FO_Heater	fuel oil heater	FO	261	435	0.7	1.3	0.7	1.5	14.8	m3/hr
11	FO_Strainer	fuel oil strainer	FO	261	435	0.1	0.356	0.610	0.686	7.4	m3/hr
12	FO_FilterSep	fuel oil filter seperator	FO	261	435	0.15	0.36	0.61	0.69	7.40	m3/hr
13	FO_ServiceMain	fuel oil service main piping/valves/maniforlds	FO	261	435	0.00	0	0.00	0	0	m3/hr
14	FO_StorTk	fuel oil (DFM) storage tank	FO	261	3911	0.00	0	0.00	0	0	m3
15	LO_Cooler	lube oil cooler	LO	262	41	0.907	2.362	0.457	1.067	90	m3/hr
16	LO_SumpTank	lube oil sump/tank	LO	262	41	0.00	0	0.00	0	0.00	m3/hr
17	LO_MotorDrivenPump	motor driven lube oil pump	LO	262	41	0.1	0.762	0.762	2.413	270	m3/hr
18	LO_DuplexFilter	lube oil duplex filter	LO	262	41	0.2	2.485	0.910	1.623	280	m3/hr
19	LO_SyntheticCooler	synthetic lube oil cooler for GT	LO	262	41	0.907	2.362	0.457	1.067	90	m3/hr
20	PropellerCRP	controled reversible pitch propeller	MECH	245	42	0.00	0	0.00	0	0	kW
21	PropellerFP	fixed pitch propeller	MECH	245	42	29.50	3.00	6.50	6.50	23500.00	kW
22	IPS_POD	electric propulsion pod	MECH	245	42	155.00	10	5	5	40000	kW
23	TailShaftAndStrutBearing	tail shaft and strut bearing	MECH	244	42	1.73	1.62	0.86	0.86	23500.00	kW
24	SternTubeAndSeal	stern tube and seal	MECH	244	42	0.60	0.35	1.32	1.32	23500.00	kW
25	LineShaftAndBearing	line shaft bearing	MECH	244	42	2.40	1.09	1.37	1.35	23500.00	kW
26	ThrustBearing	thrust bearing	MECH	244	42	14.70	1.25	1.76	1.76	40000	kW
27	PMM_Coupling	propulsion motor module coupling	MECH	242	42	3.06	1.5	1	1	40000	kW
28	PMM_Clutch	propulsion motor module clutch	MECH	242	42	3.00	1.5	1.5	1.5	40000	kW
29	ReductionGear_Dbl	main double reduction gear	MECH	241	42	56.30	2.9	4.42	3.39	40000	kW
30	MPE	main propulsion engine	MECH	234	41	27.90	9.18	3.84	3.78	36000	kW
31	MPE_Coupling	main propulsion engine coupling	MECH	242	42	1.00	0.7	0.5	0.5	20000	kW
32	MPE_Clutch	main propulsion engine clutch	MECH	242	42	1.50	1	1	1	20000	kW
33	SPE	secondary propulsion engine	MECH	233	41	52.90	8.047	2.04	3.73	10000	kW
34	SPE_Coupling	secondary propulsion engine coupling	MECH	242	42	0.75	0.5	0.3	0.3	10000	kW
35	SPE_Clutch	secondary propulsion engine clutch	MECH	242	42	0.80	0.5	0.5	0.5	10000	kW
36	IEC	integrated electronic controls	CONT	252	4144	1.00	1	1	2	1	1
37	SCU	shaft control unit	CONT	252	4144	0.17	0.7	1	1.4	1	1
38	PACC	propulsion/auxiliary control console	CONT	252	4144	1.00	0.7	1	1.4	1	1
39	EPCC	electric plant control console	CONT	252	4144	0.17	0.7	1	1.4	1	1
40	DCC	damage control console	CONT	252	4144	0.17	0.7	1	1.4	1	1
41	EOOWC	engineering officer of the watch console	CONT	252	4144	0.41	0.92	0.92	0.92	1	1
42	RSC	repair station concole	CONT	252	4144	0.17	0.7	1	1.4	1	1
43	DMS_CCS	data multiplex system control station	CONT	252	4144	0.17	0.7	1	1.4	1	1
44	PH_DISP	pilot house display	CONT	252	4144	0.41	0.915	0.195	0.915	1	1
45	CIC_DISP	CIC display	CONT	252	4144	0.17	0.7	1	1.4	1	1
46	SCC	ship control console	CONT	252	311	3.05	7.00	1.22	2.13	1	1
47	THROTTLE_CP	throttle control panel	CONT	252	4144	0.17	0.7	1	1.4	1	1
48	RPM_DP	rpm display panel	CONT	252	4144	0.17	0.7	1	1.4	1	1
49	WASH_CP	washdown and countermeasures control panel	CONT	252	4144	0.17	0.7	1	1.4	1	1
50	DMS_Node	data multiplex system node	CONT	252	311	0.20	1	1	2	1	1
51	AIEC	auxiliary integrated engineering console	CONT	252	4144	0.17	0.7	1	1.4	1	1
52	SeaChest	sea chest	SW	256	325	0.00	0	0.00	0	0	m3/hr
53	SW_Strainer	salt water strainer	SW	256	325	6.58	2.44	1.83	3.56	1199.00	m3/hr
54	SW_ServPump	salt water service pump	SW	256	325	2.29	1.14	1.14	2.78	1200.00	m3/hr
55	SW_Overboard	salt water overboard discharge	SW	256	325	0.00	0	0.00	0	0	m3/hr
56	SW_ServMain	salt water main piping/valves	SW	256	325	0.00	0	0.00	0	0	m3/hr
57	SW_Source	salt water source	SW	256	325	0.00	0	0.00	0	0	m3/hr
58	CW_Supply	chilled water supply main piping/valves/expansionta	CW	514	432	0.00	0	0.00	0	0	m3/hr
59	CW_Return	chilled water return main piping/vales	CW	514	432	0.00	0	0.00	0	0	m3/hr
60	CW_Cooler	chilled water / HFC cooler or evaporator	CW	514	432	0.00	0.00	0.00	0.00	0.00	m3/hr
61	CW_Pump	chilled water pump	CW	514	432	0.38	1.32	0.38	0.51	128.00	m3/hr
62	HVAC_Heat_SYS	HVAC_SYS	HVAC	512	432	0.00	0	0.00	0	0	tonAC
63	HFC_Cond	hydrofluorocarbon SW condenser	HFC	514	432	0.00	0	0	0	0	tonAC
64	HFC_Cmprsr	hydrofluorocarbon compressor	HFC	514	432	12.05	4.27	2	2.57	1365	tonAC
65	HFC_TXV	hydrofluorocarbonthermal expansion valve	HFC	514	432	0.00	0	0	0	0	tonAC
66	HFC_RCVR	hydrofluorocarbon receiver	HFC	514	432	0.00	0.00	0.00	0.00	0	tonAC
67	EC_Demineral	electronic cooling water demineralizer	EC	532	432	0.20	1.00	1.00	1.00	100	m3/hr
68	EC_ExpandTank	electronic cooling water expansion tank	EC	532	432	0.35	2.00	1.00	1.00	2	m3
69	EC_CircPump	electronic cooling water circulating pump	EC	532	432	0.30	1.00	0.30	0.50	100	m3/hr
71	EC_HeatExch	electronic cooling water/chilled water heat exchang	EC	532	432	1.63	1.55	1.37	2.51	45	m3/hr
72	FireMain	fire and flushing main piping/valves	FF	521	325	0.00	0.00	0.00	0.00	0	0
73	FM_Strainer	firemain stariner	FF	521	325	1.13	1.02	1.20	1.20	500	m3/hr
74	FirePump	electric fire pump	FF	521	325	1.46	2.49	0.71	0.86	454	m3/hr
75	AFFF	aquius film forming foam station	FF	555	325	1.50	2.19	1.07	1.75	227	m3/hr
76	MagazineSprinkling	magazine sprinkling system	FF	555	325	0.00	0.00	0.00	0.00	0	0
77	WashdownCountermeasure	washdown system	FF	555	325	0.00	0.00	0.00	0.00	0	0
78	HoseReelService	fire hose reel system	FF	555	325	0.00	0.00	0.00	0.00	0	0
79	EMRG PFN	electro-magnetic rail gun PFN	ELEC	333	43323	0.00	0.00	0.00	0.00	27200	kW
80	ENERSTOR	energy storage / battery	ELEC	313	433	7.62	2.54	2.14	1.98	710	kW
81	SSG	ship service generator	ELEC	311	433	3.22	6.75	1.89	2.58	3362	kW
82	ReductionGear_Single	main single reduction gear	MECH	241	42	56.30	2.9	4.42	3.39	40000	kW
83	EM_MK2	energy magazine	ELEC	333	433	7.62	2.54	2.14	1.98	710	kW
84	ReductionGear_Cross	main cross reduction gear	MECH	241	42	56.30	2.9	4.42	3.39	40000	kW
85	FW_Distiller	Fresh Water Distiller, Reverse Osmosis	FW	531	432	2.72	3.266	1.83	1.893	65	m3/hr
86	FW_BromineFeed	Brominator	FW	533	432	0.01	0.965	0.203	0.406	2	m3/hr
87	FW_Pump	Motor Driven Fresh Water Pump	FW	533	432	0.19	0.787	0.559	0.356	23	m3/hr
88	FW_Tank	fresh water tank	FW	533	432	0.00	0	0.00	0	0	0
89	FW_Accum	fresh water accumulator	FW	533	432	0.20	1	1	2	2	m3
90	FW_Loads	ship fresh water distributiion system	FW	533	432	0.00	0	0.00	0	0	0
91	HPAC	high pressure air compressor, 3000psi	AIR	551	435	1.10	1.5	1.5	1.5	2	m3/min
92	LPAC	low pressure air compressor, 125psi	AIR	551	435	1.00	1.346	1.067	1.829	5	m3/min
93	StartAC	starting air compressor	AIR	551	435	0.57	1.334	0.841	0.836	5	m3/min
94	HPSep	high pressure air moisture separator	AIR	551	435	0.68	1.83	0.91	1.52	10	m3/min
95	HPFilter	high pressure air filter	AIR	551	435	0.77	0.132	0.285	0.285	50	m3/min
96	HPFlask	high pressure air flask	AIR	551	435	1.18	3.175	1.07	1.07	4	m3
97	HPDryer	high pressure air dryer	AIR	551	435	0.26	0.61	0.864	1.473	20	m3/min
98	HPtoLP_Red	HP to LP air reducer	AIR	551	435	0.01	0.438	0.438	0.5	20	m3/min
99	LPDehyd	high pressure air dehydrator	AIR	551	435	0.05	0.4	0.4	1	20	m3/min
100	LPFlask	low pressure air flask	AIR	551	435	1.18	3.175	1.07	1.07	3	m3
101	HPDryer	high pressure air dryer	AIR	551	435	0.26	0.61	0.864	1.473	20	m3/min
102	StartFlask	starting air flask	AIR	551	435	1.18	3.175	1.07	1.07	4	m3
103	AIR_HP_Main	HP air piping, reducers and valves	AIR	551	435	0.00	0	0.00	0	0	0
104	AIR_LP_Main	LP air piping, reducers and valves	AIR	551	435	0.00	0	0.00	0	0	0
105	STEER_Ram	steering hydraulic ram	STEER	561	311	5.00	1.2	8.5	1.5	0	0
109	Glycol_ExpandTank	electronic cooling water expansion tank	Glycol	532	432	0.00	0.00	0.00	0.00	0.00	m3
110	Glycol_CircPump	electronic cooling water circulating pump	Glycol	532	432	0.00	0.00	0.00	0.00	0.00	m3/hr
111	Glycol_HeatExch	electronic cooling water/chilled water heat exchang	Glycol	532	432	1.63	1.55	1.37	2.51	45.42	m3/hr

Table 4-5: PSYS Required Adjusted VC Data Calculations

DV	Node	Vertex Label / VC	Adjusted VC Design Data (adjusted for Standard Required Capacity)									Aggregate Arc Energy and Commodity Flow for Commodity Capacity							
			Baseline VC Commodity Capacity	WT(MT)	VCG(m)	L (m)	B (m)	H (m)	Required Area	Required Volume	VC Standard Required Commodity Capacity	Flow to Node #	Total Aggregate Arc energy flow (kW) from AFO arcs below	Arc energy scaling factor (1 or 100, actual or trace)	Adjusted Arc energy flow	Related Commodity Flow Units	Commodity Flow Factor	Aggregate Required Commodity Flow	Standard Required Commodity Capacity
PSYS	2	IPS, MVDC																	
*Vertices																			
MECH	1	Propulsion_SYS	0	0.0	3.31	0.0	0.0	0.0	0.0	0.0	69990	1	69981.1	1	69981	kW	1	69981.1	69990
	2	Propeller1_VC	23500	43.9	3.31	3.4	7.4	7.4	25.4	188.8	35000	2	34990.5	1	34991	kW	1	34990.5	35000
	3	TailShaftAndStrutBearing1_VC	23500	2.6	3.31	1.9	1.0	1.0	1.8	1.8	35000	3	34990.5	1	34991	kW	1	34990.5	35000
	4	SternTubeAndSeal1_VC	23500	0.9	3.31	0.4	1.5	1.5	0.6	0.9	35000	4	34990.5	1	34991	kW	1	34990.5	35000
	5	LineShaftAndBearings1A_VC	23500	3.6	3.31	1.2	1.6	1.5	2.0	3.0	35170	5	35166.4	1	35166	kW	1	35166.4	35170
	6	LineShaftAndBearings1B_VC	23500	3.6	3.31	1.3	1.6	1.6	2.0	3.0	35350	6	35343.1	1	35343	kW	1	35343.1	35350
	7	ThrustBearing1_VC	40000	13.1	3.31	1.2	1.7	1.7	2.0	3.4	35530	7	35520.7	1	35521	kW	1	35520.7	35530
	8	PMM1_SYS	200	177.7	3.31	6.9	5.1	5.1	35.1	177.7	35530	8	35520.7	1	35521	kW	1	35520.7	35530
	9	PMM1-Coupling_VC	40000	2.7	3.31	1.4	1.0	1.0	1.4	1.3	35530	9	35520.7	1	35521	kW	1	35520.7	35530
	10	PMM1-Clutch_VC	40000	2.7	3.31	1.4	1.4	1.4	2.1	3.0	35530	10	35520.7	1	35521	kW	1	35520.7	35530
	11	Propeller2_VC	23500	43.9	3.31	3.4	7.4	7.4	25.4	188.8	35000	11	34990.5	1	34991	kW	1	34990.5	35000
	12	TailShaftAndStrutBearing2_VC	23500	2.6	3.31	1.9	1.0	1.0	1.8	1.8	35000	12	34990.5	1	34991	kW	1	34990.5	35000
	13	SternTubeAndSeal2_VC	23500	0.9	3.31	0.4	1.5	1.5	0.6	0.9	35000	13	34990.5	1	34991	kW	1	34990.5	35000
	14	LineShaftAndBearings2A_VC	23500	3.6	3.31	1.2	1.6	1.5	2.0	3.0	35170	14	35166.4	1	35166	kW	1	35166.4	35170
	15	LineShaftAndBearings2B_VC	23500	3.6	3.31	1.3	1.6	1.6	2.0	3.0	35350	15	35343.1	1	35343	kW	1	35343.1	35350
	16	ThrustBearing2_VC	40000	13.1	3.31	1.2	1.7	1.7	2.0	3.4	35530	16	35520.7	1	35521	kW	1	35520.7	35530
	17	PMM2_SYS	200	177.7	3.31	6.9	5.1	5.1	35.1	177.7	35530	17	35520.7	1	35521	kW	1	35520.7	35530
	18	PMM2-Coupling_VC	40000	2.7	3.31	1.4	1.0	1.0	1.4	1.3	35530	18	35520.7	1	35521	kW	1	35520.7	35530
	19	PMM2-Clutch_VC	40000	2.7	3.31	1.4	1.4	1.4	2.1	3.0	35530	19	35520.7	1	35521	kW	1	35520.7	35530
CW	301	CW_Supply1_VC	0.0	0.0	8.52	0.0	0.0	0.0	0.0	0.0	450.00	301	71.1	100	7105	m3/hr	0.062	440.5	450
	302	CW_Supply2_VC	0.0	0.0	8.52	0.0	0.0	0.0	0.0	0.0	880.00	302	141.2	100	14116	m3/hr	0.062	875.2	880
	303	CW_Supply3_VC	0.0	0.0	8.52	0.0	0.0	0.0	0.0	0.0	880.00	303	141.0	100	14103	m3/hr	0.062	874.4	880
	304	CW_Supply4_VC	0.0	0.0	5.92	0.0	0.0	0.0	0.0	0.0	450.00	304	71.1	100	7106	m3/hr	0.062	440.5	450
	305	CW_Return1_VC	0.0	0.0	8.52	0.0	0.0	0.0	0.0	0.0	660.00	305	10584.4	1	10584	m3/hr	0.062	656.2	660
	306	CW_Return2_VC	0.0	0.0	8.52	0.0	0.0	0.0	0.0	0.0	1150.00	306	18437.4	1	18437	m3/hr	0.062	1143.1	1150
	307	CW_Return3_VC	0.0	0.0	8.52	0.0	0.0	0.0	0.0	0.0	1200.00	307	19245.9	1	19246	m3/hr	0.062	1193.2	1200
	308	CW_Return4_VC	0.0	0.0	5.92	0.0	0.0	0.0	0.0	0.0	670.00	308	10718.6	1	10719	m3/hr	0.062	664.6	670
	309	CW_Cooler_1A_SYS	0.0	0.0	8.52	0.0	0.0	0.0	0.0	0.0	220.00	309	3517.0	1	3517	m3/hr	0.062	218.1	220
	310	CW_Cooler_2A_SYS	0.0	0.0	8.52	0.0	0.0	0.0	0.0	0.0	220.00	310	3517.0	1	3517	m3/hr	0.062	218.1	220
	311	CW_Cooler_3A_SYS	0.0	0.0	8.52	0.0	0.0	0.0	0.0	0.0	220.00	311	3517.0	1	3517	m3/hr	0.062	218.1	220
	312	CW_Cooler_4A_SYS	0.0	0.0	5.92	0.0	0.0	0.0	0.0	0.0	220.00	312	3517.0	1	3517	m3/hr	0.062	218.1	220
	313	CW_Pump1A_SYS	128.0	0.7	8.52	1.6	0.5	0.6	0.7	0.5	230.00	313	35.5	100	3553	m3/hr	0.062	220.3	230
	314	CW_Pump2A_SYS	128.0	0.7	8.52	1.6	0.5	0.6	0.7	0.5	230.00	314	35.5	100	3553	m3/hr	0.062	220.3	230
	315	CW_Pump3A_SYS	128.0	0.7	8.52	1.6	0.5	0.6	0.7	0.5	230.00	315	35.5	100	3553	m3/hr	0.062	220.3	230
	316	CW_Pump4A_SYS	128.0	0.7	5.92	1.6	0.5	0.6	0.7	0.5	230.00	316	35.5	100	3553	m3/hr	0.062	220.3	230
	317	CW_Pump1B_SYS	128.0	0.7	8.52	1.6	0.5	0.6	0.7	0.5	230.00	317	35.5	100	3553	m3/hr	0.062	220.3	230
	318	CW_Pump2B_SYS	128.0	0.7	8.52	1.6	0.5	0.6	0.7	0.5	230.00	318	35.5	100	3553	m3/hr	0.062	220.3	230
	319	CW_Pump3B_SYS	128.0	0.7	8.52	1.6	0.5	0.6	0.7	0.5	230.00	319	35.5	100	3553	m3/hr	0.062	220.3	230
	320	CW_Pump4B_SYS	128.0	0.7	5.92	1.6	0.5	0.6	0.7	0.5	230.00	320	35.5	100	3553	m3/hr	0.062	220.3	230
	321	CW_Cooler_2B_SYS	0.0	0.0	8.52	0.0	0.0	0.0	0.0	0.0	220.00	321	3517.0	1	3517	m3/hr	0.062	218.1	220
	322	CW_Cooler_3B_SYS	0.0	0.0	8.52	0.0	0.0	0.0	0.0	0.0	220.00	322	3517.0	1	3517	m3/hr	0.062	218.1	220
	323	EC_HeatExch1_CW_SYS	0.0	0.0	17.33	0.0	0.0	0.0	0.0	0.0	0.00	323	9.3	1	9	m3/hr	0.062	0.6	10
	324	EC_HeatExch2_CW_SYS	0.0	0.0	14.33	0.0	0.0	0.0	0.0	0.0	0.00	324	9.3	1	9	m3/hr	0.062	0.6	10
	325	Zone1_HVAC_CW_SYS	0.0	0.0	11.33	0.0	0.0	0.0	0.0	0.0	0.00	325	35.5	1	36	m3/hr	0.062	2.2	10
	326	Zone2_HVAC_CW_SYS	0.0	0.0	17.33	0.0	0.0	0.0	0.0	0.0	0.00	326	43.7	1	44	m3/hr	0.062	2.7	10
	327	Zone3_HVAC_CW_SYS	0.0	0.0	14.33	0.0	0.0	0.0	0.0	0.0	0.00	327	51.8	1	52	m3/hr	0.062	3.2	10
	328	Zone4_HVAC_CW_SYS	0.0	0.0	8.52	0.0	0.0	0.0	0.0	0.0	0.00	328	36.9	1	37	m3/hr	0.062	2.3	10
	329	Glycol_HeatExch2_CW_SYS	0.0	0.0	23.33	0.0	0.0	0.0	0.0	0.0	0.00	329	131.4	1	131	m3/hr	0.062	8.1	10
	330	Glycol_HeatExch3_CW_SYS	0.0	0.0	23.33	0.0	0.0	0.0	0.0	0.0	0.00	330	131.4	1	131	m3/hr	0.062	8.1	10
	331	CW_Cooler_1B_SYS	0.0	0.0	8.52	0.0	0.0	0.0	0.0	0.0	220.00	309	3517.0	1	3517	m3/hr	0.062	218.1	220
	332	CW_Cooler_4B_SYS	0.0	0.0	5.92	0.0	0.0	0.0	0.0	0.0	220.00	332	3517.0	1	3517	m3/hr	0.062	218.1	220

Component Scaling

The PSYS worksheet shown in Table 4-5 imports the associated baseline component data from the MEL and required commodity flows from the AFO to individually size each vital component. This yields a higher fidelity estimate of space, power and weight than previously possible with parametric equations only.

Scaling component dimensions requires an understanding of each individual component and how their shape generally changes with increased capacity. Many components scale in all three directions while others have a set width and height and scale lengthwise only. The control system (CONT) data is not currently scaled. MPEs and SPEs in the MECH system are given their baseline value by default (determined based on DV values and available engine data).

Scaling components continuously as opposed to discreetly based on a component database has been researched previously (Stapersma 2015, Hu 2016). Stapersma's approach focuses on first principles by determining the power required for a machine, sizing a primary element based on this given power, and following that element down the chain to secondary elements and overall machine size. This robust approach yields accurate results but is dependent on establishing a database of components and individual equations consistent with the physics for each component. Stapersma presents a series of plots showing the relations of specific components' core lengths to overall lengths (Figure 4-6). The core length in this example is linearly related to the power input. The graph shows a linear trend between the core length to the overall component length. Thus a linear trend between power (or commodity flow) and overall size can be inferred.

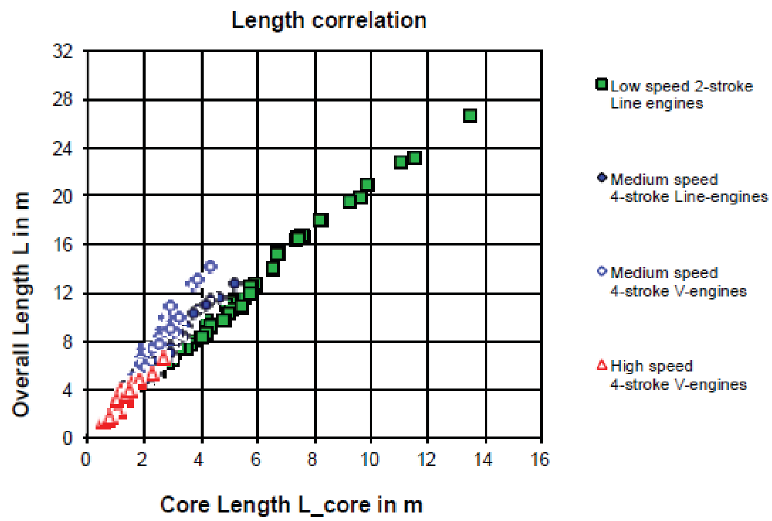

Figure 4-6: Correlation of core length to overall length (Stapersma, 2015)

Hu expands on this research by analyzing a wider set of components with larger ranges of power and commodity flows. With this larger data set, the linearity of flow to size over the entire range becomes more of an exponential trend as seen in Figure 4-7 and Figure 4-8. Locally, however, for a given flow capacity the trend remains linear up to a range of approximately ±25%. Thus, if the initial baseline data is reasonably close to the component to be sized, a linear trend is acceptable in determining volumes and weights based on a commodity flow comparison. Currently, a linear relationship of sizing with commodity flow is assumed in our models.

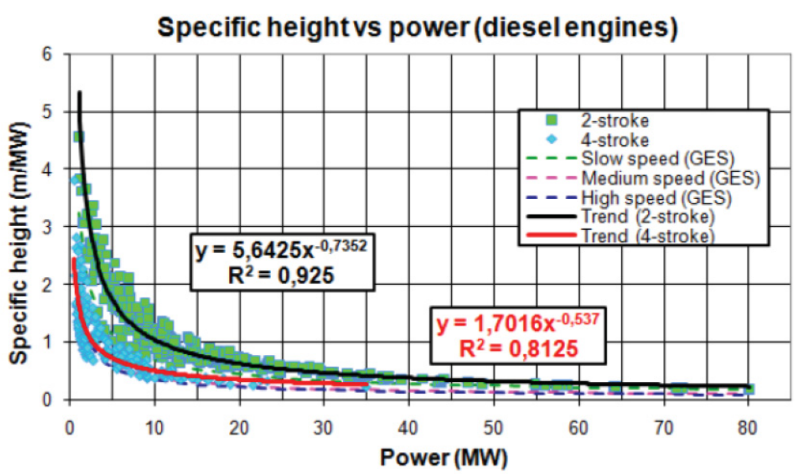

Figure 4-7: Height vs power in diesel engines (Hu 2016)

The next question, once these preliminary observations have been made, is how to use this linear scaling. This is largely influenced by the type of component that is being scaled. For VCs such as MPEs, SPEs, PGMs, and SPGMs the Navy's accepted component list dictates specific models with known sizes that can be chosen from the MEL. In all other cases, baseline component volume and weight are scaled linearly with the ratio of aggregate to baseline commodity flow capacity. Component dimensions are scaled by either scaling all three baseline dimensions with the cube root of the flow capacity ratio, or by retaining the baseline depth and height and scaling only the baseline length linearly with the flow capacity ratio. Bus nodes, power conversion modules, switchboards, and other components that are typically in a deck height enclosure are scaled in only length, holding height and depth constant. The remaining components are scaled in all three dimensions with care taken to ensure that the components do not exceed a specified deck height. Weights for all VCs are scaled as a gravimetric density factor based on the ratio of aggregate to baseline commodity flow. Figure 4-9 summarizes the logic process used to scale components.

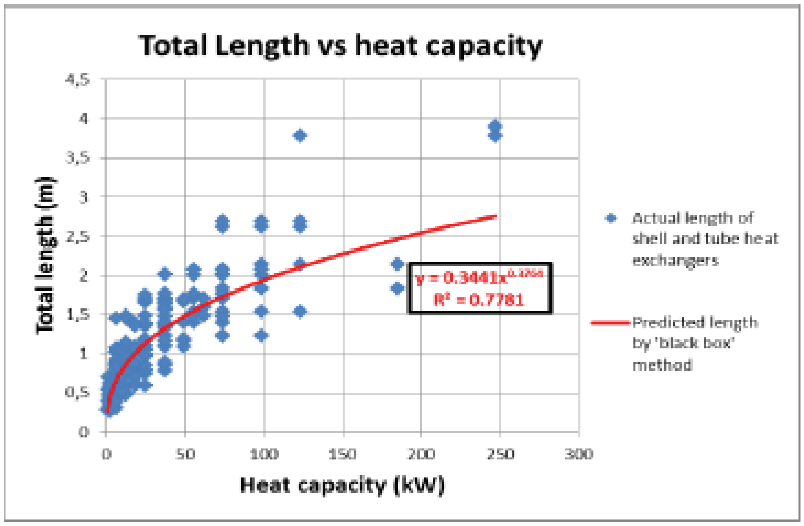

Figure 4-8: Length vs heat capacity in shell and tube heat exchangers (Hu 2016)

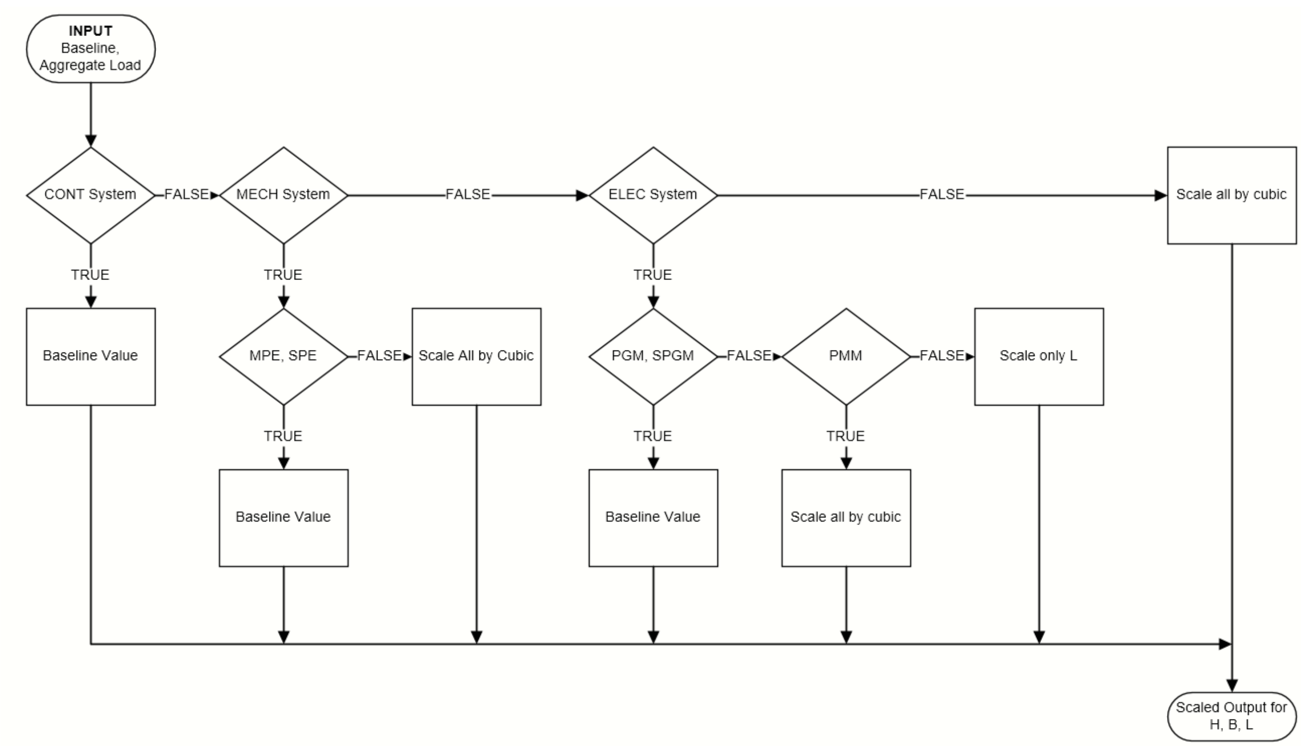

Figure 4-9: Scaling Method Flowchart

The following geometric relationships were used to determine the individual dimensional scaling factor based on the ratio of capacities. For volumetric scaling the ratio of volumes (V) is calculated by direct correlation to the required and baseline commodity flow capacities (E).

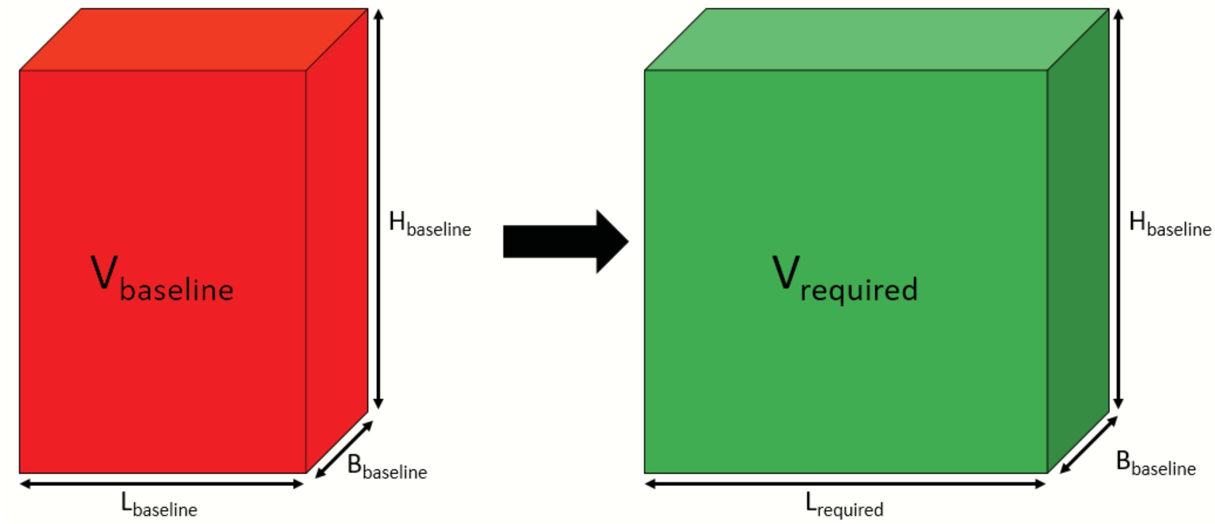

Figure 4-10: Unidirectional component scaling

$$V_{baseline} = L_{baseline} \cdot B_{baseline} \cdot H_{baseline}$$

$$V_{required} = L_{required} \cdot B_{required} \cdot H_{required} = (L_{baseline} \cdot x) \cdot (B_{baseline} \cdot x) \cdot (H_{baseline} \cdot x)$$

$$R_V = \frac{E_{required}}{E_{baseline}} = \frac{V_{required}}{V_{baseline}} = \frac{(L_{baseline} \cdot x) \cdot (B_{baseline} \cdot x) \cdot (H_{baseline} \cdot x)}{L_{baseline} \cdot B_{baseline} \cdot H_{baseline}} = \mathrm{x}^3$$

$$\therefore x = \sqrt[3]{R_V}$$

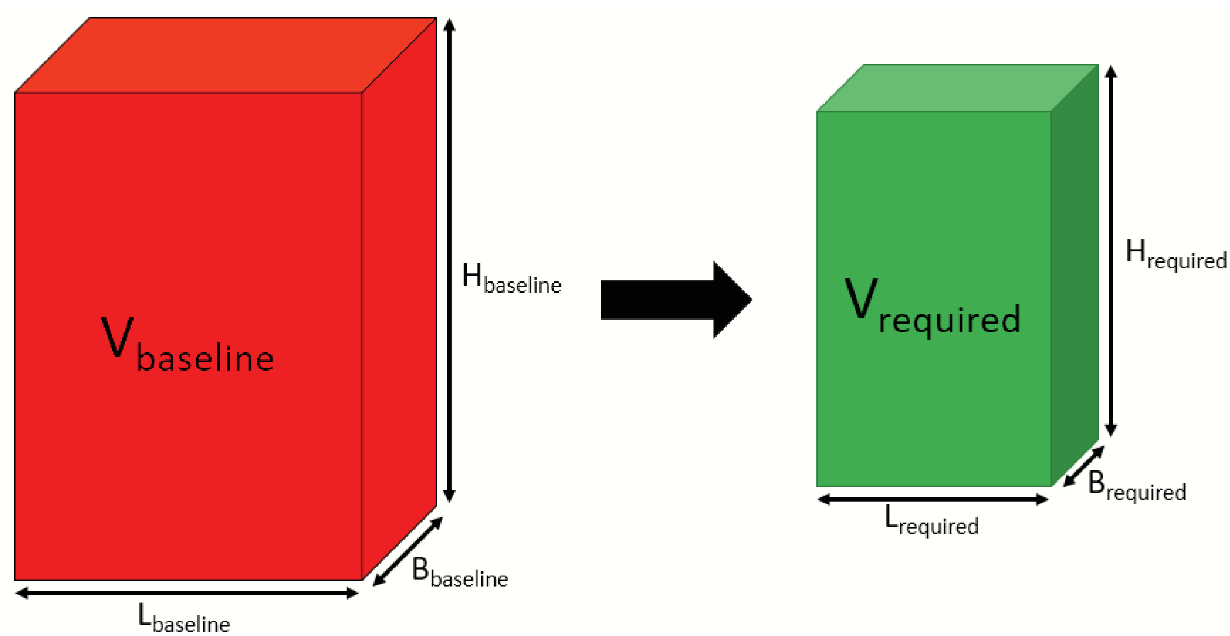

Figure 4-11: Volumetric component scaling

PSYS Worksheet

The PSYS worksheet contains the calculation steps described above. It includes a series of power system (PSYS) architecture options and under each option all vital components used in each option are listed followed by a list of arcs connecting these vital components. The AFO optimizes the energy flow in the selected system option as discussed previously. During optimization, the AFO also determines the maximum energy flow over all scenarios for each arc, what we call the aggregate flows. After the AFO performs its calculations, the arc aggregate flows are written back to the PSYS worksheet.

Machinery Worksheet

The Machinery worksheet and machinery macro sums the SWBS 200, 300 and 500 space, power and weight for application to the total ship in the post-AFO SSM and MOGO. The macro was developed to calculate the machinery equipment weights, centers of gravity, space requirements, volume requirements, and electric loads in battle, sustained, and cruise conditions up to a three-digit SWBS number. Individual components are scaled based on aggregate required commodity capacity compared to the baseline capacity and baseline component dimensions. These individual components values are then used to calculate the characteristics listed above for each individual SWBS group. This information is then returned to the SSM where it is used to generate an overall estimate of machinery weight, space and electric loads, optimized for the selected system options.

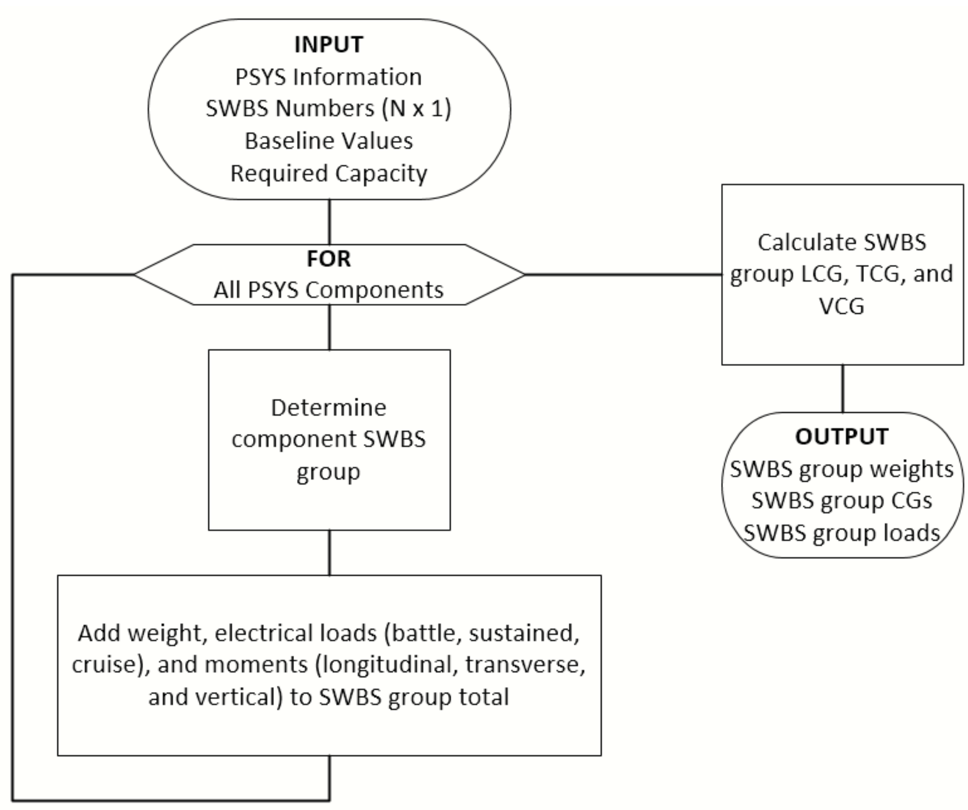

Figure 4-12: Macro general flowchart

This macro and associated component sizing replaces the empirical equations used previously to estimate total machinery weight based on a few basic ship and system parameters. The previous method was highly dependent on historical data and estimates that could potentially be conservative for future technologies. Using a macro based on individual component dimensions and weights makes the machinery weight dependent on a machinery equipment list of actual baseline components, which can be updated or altered on a component level as new technologies emerge. Thus, this approach is more adaptable for future use and for multiple ship types and sizes. Figure 4-12 shows the logic behind the macro. It essentially acts as a summing algorithm for weights, space and electric power based on SWBS groups and also calculates LCG, TCG, and VCG data for the entire set of components in their individual physical architecture locations.

Sample results from the Machinery Macro are shown in Table 4-6. The Macro calculates weights and CG locations based on SWBS groups from the AFO commodity flow data on the PSYS worksheet. The results also include space and volume requirements for specific main compartments and electric power usage in battle, sustained, and endurance conditions. These results are output on the Machinery worksheet and used in the Weight worksheet to compare results from the AFO to values calculated using empirical equations at the single digit SWBS level.

Table 4-6: Post-AFO SWBS Weights and LCGS for PSYS 2

After AFO Sizing:									
	Weight (MT	SWBS			LCG (m)		TCG (m)		VCG (m)
WW_233	0.00	233	DIESEL ENGINES	LCG_233	0.00	TCG_233	0.00	VCG_233	0.00
WW_234	0.00	234	GAS TURBINES	LCG_234	0.00	TCG_234	0.00	VCG_234	0.00
WW_235	605.92	235	ELECTRIC PROPULSION & SERVICE	LCG_235	99.93	TCG_235	-1.30	VCG_235	3.67
WW_241	0.00	241	REDUCTION GEARS	LCG_241	0.00	TCG_241	0.00	VCG_241	0.00
WW_242	11.01	242	CLUTCHES + COUPLINGS	LCG_242	110.50	TCG_242	-2.16	VCG_242	3.67
WW_243	0.00	243	SHAFTING	LCG_243	0.00	TCG_243	0.00	VCG_243	0.00
WW_244	48.55	244	SHAFT BEARINGS	LCG_244	113.87	TCG_244	-1.19	VCG_244	3.67
WW_245	89.91	245	PROPULSORS	LCG_245	118.00	TCG_245	0.00	VCG_245	3.67
WW_251	121.18	251	COMBUSTION AIR SYSTEM	LCG_251		TCG_251		VCG_251	
WW_252	12.91	252	PROPULSION CONTROL SYSTEMS	LCG_252	73.21	TCG_252	0.31	VCG_252	12.91
WW_256	48.34	256	SW COOLING SYSTEMS	LCG_256	100.84	TCG_256	0.00	VCG_256	3.67
WW_259	100.83	259	UPTAKES (INNER CASING)	LCG_259		TCG_259		VCG_259	
WW_261	9.88	261	FUEL SERVICE SYSTEM	LCG_261	85.99	TCG_261	0.00	VCG_261	3.67
WW_262	34.73	262	LUBE OIL SERVICE SYSTEM	LCG_262	85.40	TCG_262	0.00	VCG_262	3.67
WW_311	0.00	311	SHIP SERVICE POWER GENERATION	LCG_311	0.00	TCG_311	0.00	VCG_311	0.00
WW_312	0.00	312	EMERGENCY GENERATORS	LCG_312	0.00	TCG_312	0.00	VCG_312	0.00
WW_313	214.66	313	ENERGY STORAGE	LCG_313	31.50	TCG_313	0.00	VCG_313	7.00
WW_314	194.87	314	POWER CONVERSION EQUIPMENT	LCG_314	97.93	TCG_314	0.00	VCG_314	6.97
WW_324	89.22	324	SWITCHGEAR & PANELS	LCG_324	83.14	TCG_324	0.16	VCG_324	8.70
WW_512	0.00	512	VENTILATION SYSTEM	LCG_512	0.00	TCG_512	0.00	VCG_512	0.00
WW_513	0.00	513	CPS	LCG_513	0.00	TCG_513	0.00	VCG_513	0.00
WW_514	76.16	514	AIR CONDITIONING SYSTEM	LCG_514	85.30	TCG_514	0.00	VCG_514	9.50
WW_521	0.00	521	FIREMAIN & FLUSHING SYSTEM	LCG_521	0.00	TCG_521	0.00	VCG_521	0.00
WW_531	0.00	531	DISTILLERS	LCG_531	0.00	TCG_531	0.00	VCG_531	0.00
WW_532	148.01	532	COOLING WATER	LCG_532	79.62	TCG_532	0.00	VCG_532	18.96
WW_533	0.00	533	POTABLE WATER SYSTEMS	LCG_533	0.00	TCG_533	0.00	VCG_533	0.00
WW_541	0.00	541	SHIP FUEL+COMPENSATING	LCG_541	0.00	TCG_541	0.00	VCG_541	0.00
WW_542	0.00	542	AVIATION+GENERAL PURPOS	LCG_542	0.00	TCG_542	0.00	VCG_542	0.00
WW_551	0.00	551	COMPRESSED AIR SYSTEMS	LCG_551	0.00	TCG_551	0.00	VCG_551	0.00
WW_555	0.00	555	FIRE EXTINGUISHING SYSTEMS	LCG_555	0.00	TCG_555	0.00	VCG_555	0.00
WW_561	0.00	561	STEERING CONTROL SYSTEM	LCG_561	0.00	TCG_561	0.00	VCG_561	0.00

Result Comparison

Table 4-7 shows a comparison of weights estimated using the parametric method (in the third column) and the AFO method (in the far right column) for a future surface combatant ship. Numbers highlighted in yellow are being sized by the AFO. SWBS groups 200, 300, and 500 are the main focus of the AFO and VC sizing analyzed here.

SWBS group 200 shows a 7% increase in weight estimated with the AFO sizing. The largest contributor to the weight is the electric propulsion motors and PGMs. Characteristics for these components are very sensitive to technology improvement and the use of an integrated power system is poorly represented by the parametrics for past ships which did not use IPS. This has a significant effect on both SWBS 200 and 300 weights. The PMM weight and the eight other AFO-estimated weights are also used to parametrically estimate weights for other related three digit SWBS groups such as uptakes, lube oil handling and support systems. These higher fidelity relationships produce a more accurate, detailed result that was not possible with the previous overall parametric calculations for single and double digit SWBS groups. Users can now understand where the majority of weight for a system comes from and focus research on developing new components with less weight where it counts. Additionally, the three digit SWBS breakdown and the center of gravity calculations provides a better estimate of the ship's center of gravity for use in stability applications and analysis compared to the parametrics.

The 300 SWBS group shows a similar 9% increase with AFO estimates. The single digit weight is similar but the distribution of this weight within the double digit groups varies. The electric power generation AFO estimate is 30% lower compared to the original parametrics while the power distribution system is significantly heavier with the new estimation method. This is largely due to the fact that all power generation is included in SWBS 235 for IPS vice SWBS 311 and the FSC uses significant energy storage, a new technology, to support its high power combat systems like rail gun. The new IPS power distribution logical architecture is also very different from past ships. As before, triple digit groups can now be more accurately estimated based on the AFO scaled components.

Auxiliary systems in SWBS group 500 show a slight 3% decrease in total weight. The previous parametric estimate includes a payload, CPS, and auxiliary weight estimate. The new AFO estimate provides weights for the HFC, CW, fresh water cooling, glycol cooling, and control systems which can then be used to define other key related weights. Since the original parametrics were so inclusive, individual comparisons are not possible lower than the single 500 SWBS group. Data from a real in-service ship is essential for this group to determine if the estimates are truly reasonable and if the associated new parametric relationships are accurate enough for preliminary design.

Holistically the results support the entire AFO-supported process implemented up to this point. Similarities indicate that the scaling method introduced is sufficient for early stage design and greatly improves the understanding of where the components are in the ship and the amount of space they require. This also implies that the initial machinery equipment list and power/weight densities chosen are applicable for this design. The results show that the macro developed works as expected. Moving a step further back, the scaling work implemented here would not function without an accurate AFO process and correct architecture setup. The weights calculated provide a checkpoint to determine if the AFO is running correctly and note any system irregularities that were not caught by interpreting the system diagrams.

Table 4-7: Weight Results for AFO vs Parametrics

SWBS	COMPONENT	WT-MT	WAFO(MT)
	FULL LOAD WEIGHT + MARGIN	13232.89	13232.90
	MINOP WEIGHT AND MARGIN	11717.73	11856.08
	LIGHTSHIP WEIGHT + MARGIN	10869.22	11007.56
	LIGHTSHIP WEIGHT	9881.11	10006.88
	MARGIN	988.11	1000.69
100	HULL STRUCTURES	4471.12	4471.12
200	PROPULSION PLANT	1529.43	1629.82
230	PROPULSION UNITS / BASIC MACHINERY	1373.98	969.48
233	DIESEL ENGINES		0.00
234	GAS TURBINES		0.00
235	ELECTRIC PROPULSION (PGMs + PMMs +)		969.48
240	TRANSMISSION+PROPULSOR SYSTEMS	155.44	183.34
241	REDUCTION GEARS		0.00
242	CLUTCHES + COUPLINGS		11.01
243	SHAFTING	33.87	33.87
244	SHAFT BEARINGS	29.58	48.55
245	PROPULSORS	92.00	89.91
250	SUPPORT SYSTEMS		314.84
251	COMBUSTION AIR SYSTEM		129.26
252	PROPULSION CONTROL SYSTEMS		29.69
256	SW COOLING SYSTEMS		48.34
259	UPTAKES (INNER CASING)		107.55
260	PROPUL SUP SYS- FUEL, LUBE OIL		76.05
261	FUEL SERVICE SYSTEM		12.85
262	MAIN PROPULSION LUBE OIL SYSTEM		45.14
264	LUBE OIL HANDLING		18.06
290	SPECIAL PURPOSE SYSTEMS		86.12
298	OPERATING FLUIDS		57.04
299	REPAIR PARTS AND TOOLS		29.08
300	ELECTRIC PLANT, GENERAL	731.05	796.61
310	ELECTRIC POWER GENERATION	635.20	448.50
	BASIC MACHINERY	420.54	0.00
311	SHIP SERVICE POWER GENERATION		0.00
312	EMERGENCY GENERATORS		0.00
313	BATTERIES+SERVICE+ENERGY STORAGE	214.66	214.66
314	POWER CONVERSION + PMM DRIVES		233.85
320	POWER DISTRIBUTION SYS	65.51	272.92
321	SHIP SERVICE POWER CABLE		134.55
323	CASUALTY POWER CABLE		4.54
324	SWITCHGEAR & PANELS		133.83
330	LIGHTING SYSTEM	30.33	30.33
331	LIGHTING DISTRIBUTION		
332	LIGHTING FIXTURES		
340	POWER GENERATION SUPPORT SYS		35.88
341	SSTG LUBE OIL		
342	DIESEL SUPPORT SYS		13.46
343	TURBINE SUPPORT SYS		22.43
390	SPECIAL PURPOSE SYS		8.97
398	ELECTRIC PLANT OP FLUIDS		2.24
399	REPAIR PARTS AND TOOLS		6.73
400	COMMAND+SURVEILLANCE	609.10	609.10
500	AUXILIARY SYSTEMS, GENERAL	1223.28	1183.10
	WAUX	1068.47	
	PAYLOAD	43.57	43.57
510	CLIMATE CONTROL		352.70
	CPS	66.58	66.58
511	COMPARTMENT HEATING SYSTEM		11.31
512	VENTILATION SYSTEM		113.12
513	MACHINERY SPACE VENT SYSTEM		36.37
514	AIR CONDITIONING SYSTEM (HFC+CW)		121.86
516	REFRIGERATION SYSTEM		3.47
517	AUX BOILERS		0
520	SEA WATER SYSTEMS		144.44
521	FIREMAIN & FLUSHING SYSTEM		75.41
522	SPRINKLING SYSTEM		0.38
523	WASHDOWN SYSTEM		5.66
526	SCUPPERS+DECK DRAINS		1.89
528	PLUMBING DRAINAGE		34.65
529	DRAINAGE+BALLASTING		26.47
530	FRESH WATER SYSTEMS		204.63
531	DISTILLING PLANT		14.41
532	COOLING WATER (FRESH & GLYCOL)		177.62
533	POTABLE WATER SYSTEMS		12.61
534	AUX STEAM DRAINS		0
540	FUELS/LUBRICANTS,HANDLING+STORAGE		108.00
541	SHIP FUEL STOR AND COMPENSATING SYS		92.63
542	AVIATION+GENERAL PUPOSE FUEL SYS		5.02
543	SHIP LO STOR, PURIFY AND TRANSFER SYS		9.03
545	TANK HEATING		1.32
550	AIR,GAS+MISC FLUID SYSTEM		113.12
551	COMPRESSED AIR SYSTEMS		56.56
555	FIRE EXTINGUISHING SYSTEMS		56.56
560	SHIP CNTL SYS		72.28
561	STEERING CONTROL SYSTEM		23.00
562	RUDDER		55.20
570	UNDERWAY REPLENISHMENT SYSTEMS		45.58
580	MECHANICAL HANDLING SYSTEMS		97.68
581	ANCHOR HANDLING+STOWAGE SYSTEMS		65.12
582	MOORING+TOWING SYSTEMS		19.54
583	BOATS,HANDLING+STOWAGE SYSTEMS		13.02
585	AIRCRAFT WEAPONS ELEVATORS		
586	AIRCRAFT RECOVERY SUPPORT SYS		
587	AIRCRAFT LAUNCH SUPPORT SYSTEM		
588	AIRCRAFT ELEVATORS		
589	AIRCRAFT HANDLING, SUPPORT		
590	SPECIAL PURPOSE SYSTEMS		44.66
593	ENVIRONMENTAL POLLUTION CNTL SYS	10.16	10.16
598	AUX SYSTEMS OPERATING FLUIDS	34.50	34.50
599	AUX SYSTEMS REPAIR PARTS & TOOLS		
600	OUTFIT+FURNISHING,GENERAL	761.63	761.63
700	ARMAMENT	555.50	555.50

CONCLUSIONS AND FUTURE WORK

Architecture Flow Optimization allows preliminary system design to be performed in the C&RE stage of ship design. Energy flow results can be transformed into commodity flows which subsequently allows for component sizing to yield a higher fidelity weight, space and power estimates for the analyzed ship systems.

The results of this paper show that this method of energy analysis and component sizing is both feasible and applicable during early ship design.

More important than the specific tools described here is their application in the overall C&RE process, tool methodologies, and necessary design elements and consideration. Independent of tools, the elements and considerations described in this paper are necessary for any early-stage surface combatant design. Cost, effectiveness and risk, system architecture, basic 3D preliminary arrangements, survivability, operability, system reliability, and energy demands are all crucial variables that must be fully understood and accounted for during all stages of ship design. The AFO and sizing methodology developed here not only shows that early stage estimation is possible, but that there can be immense payoffs in optimized systems and sensitivity studies to show where component research should focus in order to make the biggest impact on a ship's capabilities. These tools allow for a more focused research and development roadmap to be developed.

One key component to the function of this method is baseline machinery data maintenance. Continually improving and updating this information will lead to more accurate estimations moving forward and will also aid in the development and verification of the network architectures.

Using a known data set from a constructed ship would also provide a more accurate validation of the accuracy of the AFO and VC sizing methods described in this paper.

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5. CONCLUSIONS AND FUTURE WORK

The tools developed through this series of research efforts and network architecture framework can fundamentally change how we approach early stage ship design. The architecture flow optimization (AFO) allows for designers create a system architecture that can be optimized for a ship based on the initial capabilities and installed systems. Not only does this create a better ship model, but it also allows for deeper analysis and sensitivity studies for future research and development needs.

Converting from energy to commodity flows also marks a step forward in early stage design. Being able to relate conservation of energy back to simple fluid flows for an entire ship allows the possibility of component sizing for weight and space optimization along with the energy optimization. Both the AFO and machinery sizing tools are leaps forward in our ability to quantify a ship design early on at a higher fidelity than previously possible with the added benefit of future technology integration through a machinery equipment list change. The results of this thesis show that the AFO and machinery sizing tools are functioning and accurate for further implementation and refinement.

The next steps focus around verification of the results provided by the two systems and expansion to be more robust by including different power systems and automating the creation of the architectures. Comparing calculated data to actual ship data is essential to confirming the work completed is accurate and a viable method moving forward for early stage ship design. Once verified, work can move towards analyzing the results in terms of sensitivities of certain components to the overall ship performance and system design to mitigate risk and increase effectiveness.