Network-Based Naval Ship Distributed System Design using Architecture Flow Optimization

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ABSTRACT

This thesis describes the application of a distributed system architecture framework and Architecture Flow Optimization (AFO) to naval ship Concept & Requirements Exploration (C&RE). It describes refinements to both C&RE and AFO, and naval surface combatant concept design case studies. The architectural framework decomposes naval ship distributed systems into the physical, logical, and operational architectures representing the spatial, functional, and temporal relationships of distributed systems respectively. This decomposition greatly simplifies the Mission, Power, and Energy System (MPES) design process for use in C&RE. AFO is a network-based linear programming optimization method used to design and analyze MPES at a sufficient level of detail to understand system energy flow, define MPES architecture and sizing, reduce system vulnerability and improve system reliability. AFO incorporates system topologies, energy coefficient component models, preliminary arrangements, and (nominal and damaged) steady state scenarios to minimize the energy flow cost required to satisfy all operational scenario demands and constraints. This thesis provides an overview of design tools developed to implement this process and methods, including objective attribute metrics for cost, effectiveness and risk, ship synthesis model, hullform exploration and MPES explorations using design of experiments (DOEs) and response surface models.
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GENERAL AUDIENCE ABSTRACT

The design of modern warships presents many unique challenges not faced in the design of most commercial ships or past generations of warships. The objectives of warship design (e.g., effectiveness, design risk, and total lifecycle cost) cannot be summarized in a single quantitative metric as commonly done in commercial ship design (e.g., required freight rate: the minimum market price of a commodity to make a commercial ship design with a certain cargo capacity profitable). Furthermore, mission, power, and energy systems (MPES) of modern warships have become increasingly interdependent and complex, especially those of naval surface combatants (non-submarine warships designed to engage in direct combat with other ships). Determining quantitative metrics for these objectives is a difficult task to begin with. Determining accurate values for these metrics in early stage design (when designs have little detailed specifications and some technologies may even be still be in development) is another challenge altogether. This thesis describes simple and robust methods and processes to evaluate a warship’s arrangement and operational characteristics. Survivability characteristics, characteristics related to a warship’s ability to complete missions despite battle damage, are of particular interest in these methods. These methods incorporate physics and energy-based means of assessment rather than using historical parametric models that are insufficient in assessing new and revolutionary warship designs.
Dedication

For John Mueller: Fair Winds and Following Seas.
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Introduction

MANUSCRIPT THESIS

This thesis is presented in the Virginia Tech Graduate School’s manuscript format. In addition to the standard or traditional format for dissertations and theses, the Virginia Tech Graduate School accepts an alternative, manuscript, format. The manuscript thesis/dissertation format allows the incorporation of a student’s articles, book chapters, and the like to replace some of the standard chapters. Prior publication of the manuscript(s) is not a requirement for using this format. The following guidelines apply:

At least one manuscript (i.e., article, chapter) are required for the Master’s degree, or at least two manuscripts for the Doctoral degree. The manuscript(s) should be based on research done at Virginia Tech. The manuscript(s) can be previously published, to be published, or in preparation for submission.

The graduate student is the major contributor and writer of the manuscript(s), as usually represented by sole author. In the case of multiple authorship, the contribution of each author is detailed in the Introduction or separate Attribution section.

SUMMARY OF MANUSCRIPTS AND RESEARCH CONTRIBUTIONS


The first paper was published in the American Society of Naval Engineers’ (ASNE) Intelligent Ships Symposium 2019 proceedings. It was also resubmitted to ASNE’s Naval Engineers Journal and has been accepted with revisions (this revised draft is included in this thesis). This paper integrated the Architectural Framework for distributed naval ships systems with the Concept & Requirements Exploration (C&RE) and the Mission, Power, and Energy System (MPES) design processes. It also serves as the foundational paper for Virginia Tech’s network-based approach of naval ship distributed system design.

The second paper has been submitted to the Society of Naval Architects and Marine Engineers’ Journal of Ship Production and Design and has been accepted with minor revisions (this revised draft is included in this thesis). This paper defines the Architecture Flow Optimization (AFO) method mentioned in first paper and presents the AFO results or a notional Large Surface Combatant design. AFO is a simple but sufficient energy-based method to assess naval ship distributed system feasibility, sizing, survivability, and vulnerability in concept stage design.

The third paper’s has been accepted by ASNE’s Advanced Machinery Technology Symposium 2020. This paper refines the Architecture Flow Optimization (AFO) method defined in the second paper, updates the network-based MPES design process defined in the first paper, and presents the results of a notional surface ship case study.

COAUTHORS’ CONTRIBUTIONS

Several Colleagues aided in the writing and research behind the chapters presented as part of this thesis. A brief description of their contributions is included here:

Mark A. Parsons is currently a Ph.D. Candidate and Graduate Research Assistant at the Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech. Mark researches network-based methods to assess naval ship distributed system vulnerability, survivability, and battle damage recoverability in concept stage design (with Mustafa Kara, Kevin Robinson, and Dr. Alan Brown); naval ship distributed system design and total ship synthesis in concept stage ship design (with Nick Stinson and Dr. Alan Brown); and naval ship system deactivation analysis using network architecture framework (with Dan Snyder and Dr. Alan Brown). He is the lead author of the second and third papers and is the first author of all three papers.
Mustafa Y. Kara is currently a Ph.D. Candidate and Graduate Research Assistant at the Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech. He researches network-based methods to assess naval ship distributed system vulnerability, survivability, and battle damage recoverability in concept stage design with Mark Parsons and Dr. Alan Brown. He is a coauthor of all three papers.

LT Kevin M. Robinson, USCG, is currently a rotating instructor at the US Coast Guard Academy; Naval Architecture and Marine Engineering Section. He received his M.S. degree from the Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech in 2018. He researched network-based methods to assess naval ship distributed system vulnerability and survivability in concept stage design with Mark Parsons, Mustafa Kara, and Dr. Alan Brown. He is a coauthor of the first two papers.

Nicholas T. Stinson is currently a naval architect with the Brunswick Corporation. Nick received his M.S. degree from the Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech in 2019. He researched naval ship distributed system design and total ship synthesis in concept stage ship design with Mark Parsons, Mustafa Kara, Kevin Robinson, and Dr. Alan Brown. He is a coauthor of the first two papers.

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David C. Woodward is currently the Senior Naval Architect and Systems Engineer in the Advanced Machinery Systems Integration Branch at Naval Surface Warfare Center Philadelphia. Since 2001, he has worked numerous surface ship, submarine, submersible, and small craft concept designs and trade studies involving ship and machinery systems design synthesis, modeling and simulation, optimization, and systems analysis. He retired in 1999 with 21 years of U.S. Navy ship and submarine propulsion plant experience. He received a B.S. in Ocean Engineering from Virginia Tech (2001) and M.E. in Systems Engineering from the University of Virginia (2010). Dave Woodward served as the technical point of contact for the NEEC contract while working in the Advanced Machinery Systems Integration Branch, Code 326, Naval Surface Warfare Center, Philadelphia Division. Dave is a coauthor of the first paper.

Dr. Alan J. Brown, CAPT USN (ret), is currently NAVSEA Professor of Ship Design, Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech. He was Professor of Naval Architecture and directed the Naval Construction and Engineering Program at MIT from 1993 to 1997. Dr. Brown was the recipient of the 2015 SNAME William H. Webb Medal for outstanding contributions to education in naval architecture, marine or ocean engineering. He is also the recipient of the 2007 ASNE Solberg Award for significant contributions to naval engineering through personal research. As an Engineering Duty Officer from 1971 to 1998, he served in ships, fleet staffs, shipyards, NAVSEA, and OPNAV. He received his Ph.D. in Marine Engineering in 1986 from MIT. He is the principal investigator researching network-based methods to assess naval ship distributed system vulnerability, survivability, and battle damage recoverability in concept stage design; naval ship distributed system design and total ship synthesis in concept stage ship design; and naval ship system deactivation analysis using network architecture framework with Mustafa Kara, Kevin Robinson, Nick Stinson, and Dan Snyder. He also serves/served as their graduate advisor. He is the lead author of the first paper and a coauthor of the second and third papers.
Application of a Distributed System Architectural Framework to Naval Ship Concept and Requirements Exploration (C&RE)
Mark A. Parsons¹, Kevin M. Robinson², Mustafa Y. Kara¹, Nicholas T. Stinson¹, Daniel J. Snyder¹, David C. Woodward³, and Alan J. Brown¹

ABSTRACT
This paper describes an architectural framework, methods, and tools for designing and analyzing naval ship Mission, Power, and Energy Systems (MPES) 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 organize a mathematical analysis to efficiently consider an unrestricted 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 MPES 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.

ACRONYMS
AAW Anti-Air Warfare
AFO Architecture Flow Optimization
AIREX Air Explosion
ASUW Anti-Surface Warfare
ASW Anti-Submarine Warfare
CONOPS Concept of Operations
CTOC Total Ownership Cost
CW Chilled Water Cooling System
C&RE Concept & Requirements Exploration
DOE Design of Experiments
DP Design Parameter
DRM Design Reference Mission
DV Design Variable
EC Electronic Cooling System
E&SSM Exploration & Ship Synthesis Model
Glycol Glycol Cooling System
HVAC Heating, Ventilation, and Air conditioning System
ICD Initial Capabilities Document
MPES Mission Power and Energy Systems
LEAPS Leading Edge Architecture for Prototyping Systems

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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 & Thomas, 1998, Brown & Salcedo, 2003, Stepanchick & Brown, 2007, Strock & 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.

Mission, Power, and Energy Systems (MPES) are fundamental to the design and mission of naval surface combatant ships. MPES 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-based approach has proven to be exceptionally capable and flexible for this application. The entire C&RE process has been reworked to apply this architectural framework approach as described in this paper.

MPES 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. 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).

In naval ship concept exploration, ship designers often adapt distributed systems of parent designs or rely on parametric-based system sizing methods to obtain distributed system space, weight, and power characteristics. These two methods can be ineffective when new designs differ significantly in arrangement, system topology, mission, or system usage. It is time for to propose a more rigorous early-stage design approach and a framework for better understanding distributed systems. Particularly in early stage design, this architectural framework organizes a mathematical analysis to efficiently consider an unrestricted 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 paper describes an architectural framework approach, processes, 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 1. This representation describes the spatial and functional relationships of the system together with their temporal behavior characteristics. Much of this work and a partial implementation of the architectural framework is featured in Marine Engineering (2020). This paper describes a complete implementation of the architectural framework with the MPES Design Process (described later). 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 approach/framework, particularly for complex products. Recent tools or approaches that consider distributed systems and preliminary arrangements with the potential to work within the architectural 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, and van Oers et al., 2012), Architecture Flow Optimization (Trapp, 2015, and Robinson, 2018), and the Preliminary Arrangements and Architecture Model (Brown & Sajdak, 2015, Goodfriend & 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 architectural framework (Chalfant 2015, Chalfant et al., 2017a, and Chalfant et al., 2017b). There is ongoing research to interface with these tools,
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. The network representation is also being adapted in architecture flow optimizations (AFOs) (Robinson, 2018) to support MPES 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. 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: Naval Ship Concept & Requirements Exploration (C&RE) Process with Architectural Framework and Set-Based Domains](image)

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 (such as Model Center) 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.

MPES 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 MPES design process is illustrated in Figure 3 and will be a primary topic in this paper.

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.

![Figure 3: MPES Design Process approximately superimposed on the architectural framework](image)

Figure 3: MPES Design Process approximately superimposed onto the architectural framework
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 (see Figure 5 for overall effectiveness metric). 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, and Mierzwicki & Brown, 2004) and Overall Measure of Effectiveness (OMOE) metric (Demko 2005, Brown & 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 & 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.

![Figure 4: Ship Design Non-dominated Frontier (Brown and Sajdak 2015)](image)

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 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.

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 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.
This OMOE hierarchy is used to formulate an Overall Measure of Effectiveness (OMOE) function for use in optimization and trade-off studies (Demko, 2005, and Brown & 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).

\[
OMOE = \sum_i VOP_i(MOP_i)w_i
\]

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 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 6: VOP "S" Curve, VOP_i (Brown and Salcedo, 2003)](image-url)
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 6.

AHP pairwise comparison results are rolled up to a single set of weights for each MOP, illustrated in Figure 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 7: Notional Surface Combatant MOP Weights, w_i](image)

The MOP weights shown in Figure 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, and Mierzwicki & 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 (Pi) (Table 1) and the consequence of the event (Ci) (Table 2) as calculated in Equation (2):

\[ Risk = R_i = P_i \times C_i \] (2)
Table 1 and Table 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 (\( W_{\text{perf}} \), \( W_{\text{cost}} \), \( W_{\text{sched}} \)) 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 1: Event Probability Estimate (Mierzwicki and Brown, 2004)

<table>
<thead>
<tr>
<th>Probability</th>
<th>What is the Likelihood the Risk Event Will Occur?</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>Remote</td>
</tr>
<tr>
<td>0.3</td>
<td>Unlikely</td>
</tr>
<tr>
<td>0.5</td>
<td>Likely</td>
</tr>
<tr>
<td>0.7</td>
<td>Highly Likely</td>
</tr>
<tr>
<td>0.9</td>
<td>Near Certain</td>
</tr>
</tbody>
</table>

Table 2: Event Consequence Estimate (Mierzwicki and Brown, 2004)

<table>
<thead>
<tr>
<th>Consequence Level</th>
<th>Given the Risk is Realized, What is the Magnitude of the Impact?</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Performance</td>
<td>Schedule</td>
</tr>
<tr>
<td>0.1</td>
<td>Minimal or no impact</td>
<td>Minimal or no impact</td>
</tr>
<tr>
<td>0.3</td>
<td>Acceptable with some reduction in margin</td>
<td>Additional resources required; able to meet need dates &lt;5%</td>
</tr>
<tr>
<td>0.5</td>
<td>Acceptable with significant reduction in margin</td>
<td>Minor slip in key milestones; not able to meet need date 5.7%</td>
</tr>
<tr>
<td>0.7</td>
<td>Acceptable, no remaining margin</td>
<td>Major slip in key milestone or critical path impacted 7-10%</td>
</tr>
<tr>
<td>0.9</td>
<td>Unacceptable</td>
<td>Can’t achieve key team or major program milestone &gt;10%</td>
</tr>
</tbody>
</table>

\[
\text{OMOR} = W_{\text{perf}} \frac{\sum_i P_i C_i}{(P_i C_i)_{\text{max}}} + W_{\text{cost}} \frac{\sum_j P_j C_j}{(P_j C_j)_{\text{max}}} + W_{\text{sched}} \frac{\sum_k P_k C_k}{(P_k C_k)_{\text{max}}} \tag{3}
\]

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 & 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 8 shows the 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 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 8: Exploration and Ship Synthesis Model (E&SSM) in Model Center (MC) – tools used to implement the C&RE Process

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 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).
Table 3: Notional Surface Combatant Design Space for C&RE

<table>
<thead>
<tr>
<th>Input Value</th>
<th>DV</th>
<th>Design Variables</th>
<th>Values</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>100.00</td>
<td>1</td>
<td>Length on Deck (LOA)</td>
<td>510 to 750 m</td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>2</td>
<td>Lufft Ratio</td>
<td>7 to 7.05</td>
<td></td>
</tr>
<tr>
<td>3.5</td>
<td>3</td>
<td>Beam Ratio</td>
<td>3.25 to 3.6</td>
<td></td>
</tr>
<tr>
<td>0.400</td>
<td>4</td>
<td>Long Normal Tacking Control</td>
<td>0.1 to 0.4</td>
<td></td>
</tr>
<tr>
<td>0.000</td>
<td>5</td>
<td>Deadrise Mid</td>
<td>1 to 3</td>
<td></td>
</tr>
<tr>
<td>0.500</td>
<td>6</td>
<td>Fullness Fwd</td>
<td>3 to 8</td>
<td></td>
</tr>
<tr>
<td>35 to 40</td>
<td>7</td>
<td>Stern Tread</td>
<td>35 to 40</td>
<td></td>
</tr>
<tr>
<td>0.030</td>
<td>8</td>
<td>Section Fastness Mid</td>
<td>4 to 9</td>
<td></td>
</tr>
<tr>
<td>2400</td>
<td>9</td>
<td>Minimum Volume of Deckhouse (MVL)</td>
<td>2000 to 5000 m3</td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td>10</td>
<td>Planning and Automation Factor (CAFA)</td>
<td>0.5 to 1.0</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>11</td>
<td>Maintenance</td>
<td>1 to 3</td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>12</td>
<td>Degassing (DEGAUS)</td>
<td>0 to 0</td>
<td></td>
</tr>
<tr>
<td>0.12</td>
<td>13</td>
<td>CPS</td>
<td>0 to 0</td>
<td></td>
</tr>
<tr>
<td>30-60 days</td>
<td>14</td>
<td>Provision/Duration (TP)</td>
<td>30-60 days</td>
<td></td>
</tr>
</tbody>
</table>

2 Propulsion System (PSY3) - Architecture

1. IPS 2 pods, 2xGTRGM, 2xGFRGM, NVAC
2. IPS 2 TFFP 2 shafts, 2xPM, 2xGTRGM, 2xGTRGM, NVAC
3. CODOAG, DDG-51, LAVAC
4. HED, 2xCPP, 2 shafts, 2xGTRGM, 2xGTRGM, NVAC
5. CODOAG, 2 CPP, 2 shafts, 2xGTRGM, 2xGTRGM, NVAC
6. IPS 2 TFFP 2 shafts, 2xPM, 2xGTRGM, 2xGTRGM, NVAC
7. CODOAG, 2 CPP, 2 shafts, 2xGTRGM, 2xGTRGM, NVAC
8. HED, 2xCPP, 2 shafts, 2xGTRGM, 2xGTRGM, NVAC
9. |

16 MPE/PGM Main Propulsion Engine or PGF

1. MT30
2. LM2500+

17 SPE Secondary Engine or SPGM

1. MTU 26V1600 M63 (15 MW)
2. 2xK64E STC (6.1 MW)
3. 2xK64E STC (6.1 MW)
4. 2xK64E STC (6.1 MW)

18 Ship Service Generator

1. Allison 600/650 STG
2. CAT 3406E 550G
3. CAT 3406E 550G

19 AAV, SEW, CMS

1. AAV-SEW, CMS
2. AAV-SEW, CMS
3. AAV-SEW, CMS

20 ASW/WFS

1. ASW/WFS
2. ASW/WFS
3. ASW/WFS

21 ASW/CLM

1. ASW/CM
2. ASW/CM
3. ASW/CM

22 CAG

1. CAG
2. CAG
3. CAG

23 AIR

1. AIR
2. AIR
3. AIR
Figure 9: ORCA3D Hullform in Rhino

Figure 10: Initial DOE Result Histograms with GM/B>0.05 Constraint (in red)

Figure 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>0.05 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.

After a series of design space adjustments, Figure 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.

![Histograms](image)

Figure 11: Final DOE Result Histograms (feasible in red)

When hullform exploration is complete, RSMs are created from the final data and final design space. These RSMs are shown in the Figure 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 MPES Exploration runs down the right hand side of Figure 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 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 MPES 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 MPES 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, and Konak & 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.

Non-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 12.
Figure 12: AFO Execution Process

MPES EXPLORATION

Figure 3 and Figure 13 show process and notional views of how the MPES architectural framework, Figure 1, is implemented in the Figure 2 C&RE process. In Figure 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 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 14 and applied in the operational architecture as scenarios in the AFOs (Brown & Kerns, 2010, Kerns et al., 2011a, Kerns et al., 2011b, and Brown, 2013).

Figure 13: Notional Network Architecture Implementation in C&RE

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

In Figure 3 Step #3, MPES System options are defined using the selected technologies and organized using design variables (PSYS, AAW, ASW, ASUW, etc.) as listed in Table 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 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.

A simple logical system architecture for a mechanical subsystem in an integrated power system is shown in Figure 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 16.

Figure 15: Mechanical (Propulsion) Subsystem (MECH)

The mechanical subsystem logical architecture in Figure 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 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.

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, and Duchateau, 2016), Intelligent Ship Arrangements (Parsons et al., 2008), Subdivision Block (SDB) Compartment Allocation (Brown & Sajdak 2015, and Goodfriend & Brown, 2018) and nodal or network representations (Gillespie et al., 2012, Gillespie et al., 2013, and Gillespie & 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 17 and a nodal or network approach is illustrated in Figure 18.
Figure 17: Subdivision Block (SDB) Representation of Physical Architecture (Goodfriend and Brown, 2018)

Figure 18: Nodal or Network Representation of Physical Architecture

Figure 19: Vital Components (VCs) and Compartments Allocated to Subdivision Blocks (SDBs) (Brown, 2020)
The SDB approach begins with a preliminary hullform and deckhouse geometry generated with less than a dozen simple design variables (Figure 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 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 3, Step #8. From this point on, a network-approach may be used by representing SDBs using a nodal matrix consistent with Figure 18. 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 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 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.

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 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 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 23.

Figure 20: Routing of Distributed Systems (Red = electric, Blue = chilled water)
Figure 21: Weapon Hit Locations (Goodfriend and Brown, 2018)

Figure 22: Damage Ellipsoid Interactions with SDBs (Stark, 2016)

Figure 23: SDB Hit Probabilities (Goodfriend and Brown, 2018)
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 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 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 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 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 24: System Damage Response Intersection Process

Figure 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, Pk/h’s, for the various ship combat capabilities and system combinations (Goodfriend & 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 MPES Exploration AFO, Step #9, the resulting systems may then be applied in a second MPES 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 3, Step #12.

The MPES process, Figure 3 Steps #3 through #13, are completed for each combination of MPES 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. The SSM uses hullform-related RSMs from the Hullform Exploration, a Manning RSM from the Manning Exploration, and system combination MPES data including vulnerability, availability, recoverability and component sizing weight/space/power (including energy storage) from the MPES Explorations to assess design feasibility and calculate design objective attributes for cost, effectiveness and risk.

**CONCLUSIONS AND THE WAY AHEAD**

The network architectural 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 architectural 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 architectural 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 an architectural framework for use in vulnerability and reliability analyses.
• Extension of architectural framework applications in US Navy FOCUS-compliant ship design including the extraction of logical architecture from LEAPS data.
• Increase damage assessment fidelity by using an advanced system routing method and include distribution components (e.g. wires, pipes, shafts/mechanical linkages) as VCs to the plexes.
• Further refinement and implementation of architectural 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 architectural 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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Early-Stage Naval Ship Distributed System Design using Architecture flow Optimization

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ABSTRACT

This paper describes an Architecture Flow Optimization (AFO) method for naval ship system design. AFO is a network-based method. It is used to design and analyze naval ship Mission, Power, and Energy Systems (MPES) in a naval ship Concept and Requirements Exploration (C&RE) process at a sufficient level of detail to better understand system energy flow, define MPES architecture and sizing, reduce system vulnerability and improve system reliability. This method decomposes MPES into three architectures: logical, physical, and operational which describe the system’s spatial, functional, and temporal characteristics respectively. Using this framework, the AFO incorporates system topologies, input/output energy coefficient 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 scenario demands and constraints. AFO results are used to inform system topology design and assess the feasibility and survivability of representative designs in the C&RE process. AFO results may also be used in physics-based vital component sizing, calculation of vulnerability/effectiveness metrics in the C&RE process, and subsequent linear optimization formulations to assess recoverability and operational effectiveness in the time domain.

KEYWORDS

design (vessels), design (general), warships, systems engineering, machinery (general), electric propulsion

INTRODUCTION AND MOTIVATION

Mission, Power, and Energy Systems (MPES) are fundamental to the mission and design of modern naval surface combatant ships. MPES are distributed systems: mechanical, electrical, thermal, and electronic components distributed throughout a ship and connected to work together. Understanding MPES architecture and design is critical in determining a naval ship’s combat effectiveness and survivability (Brown, 2020).

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 MPES 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. MPES 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, 2020).

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

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interdependencies. Figure 26 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.

![Venn Diagram]

Figure 26: Architectural 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 & Thomas, 1998, Brown & 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 MPES Exploration process, illustrated in Figure 27. 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 MPES 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 MPES 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.

MPES 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 MPES 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 MPES 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.

An Architecture Flow Optimization (AFO) or energy flow assessment is performed in MPES Exploration #1 for each system option combination in the design space. Following the AFO, MPES components are sized based on their energy flow requirements. In previous versions of this MPES 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 MPES Exploration #2 where more complex operational scenarios and damage recoverability are assessed and in a MPES 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, 2020). 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 28 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)
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 29. 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.
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 30 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 30.

Figure 30: Excerpt from MEL Equipment Input and Output Energy Coefficient Matrix

Figure 31 and Figure 32 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.
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 33: energy enters the CW 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 (CW_Return3_VC), and exits the CW plex (to the HFC plex) at the chilled water coolers (CW_Cooler_3A_SYS and CW_Cooler_3B_SYS). A trace energy flow continues on the cold side of the CW plex from the coolers to the CW pumps and supply. Without a trace flow, there would be no flow through the chilled water pumps (CW_Pump3A_SYS and CW_Pump3B_SYS) or the chilled water supply (CW_Supply3_VC) and they would be removed by the AFO. 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 for component sizing. Trace Flows are implemented in the cooling fluid plexes (CW, HFC, EC, Glycol, LO, and SW).
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, average deck height and other “stylistic” design considerations (McDonald, 2009, and 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 (based on colocation requirements for operation) 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 34, which is sufficient to implement the damage algorithms used in early-stage design.

![Figure 34: AFO’s Nodal Description of SDBs (Physical Architecture)](image)

Figure 34: AFO’s Nodal Description of SDBs (Physical Architecture)

Figure 35 shows the same SDBs 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 26) and shows two plexes: the zonal electrical distribution (ELEC) plex in red and the chilled water (CW) plex in blue.

![Figure 35: ELEC and CW plexes (red and blue respectively) Physical Solution](image)

Figure 35: 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/afit, 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. 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 ARCHITECTURE CONSTRAINTS AND LINEAR OPTIMIZATION**

The operational architecture is applied to the AFO as linear nodal constraints that vary depending on the operational scenario. There are two primary types of scenarios in the MPES Exploration #1 (AFO): undamaged (sustained speed, endurance speed, and battle) and S-1 damaged. A damage scenario
in MPES 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 MPES 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 the same size. 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. There are three exceptions to the use of this equal-flow doctrinal constraint. It is not used in: (1) the ELEC plex in damage 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 cruise 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 SDB when their load is set to zero.

Theses operational and doctrinal constraints must be included in 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 remainder 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. \( A_p \)) 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.
- \( e_{n}^{s} \) is the quantity of energy demanded by node \( n \) in scenario \( s \).
- \( x_{i,j}^{s} \) is the aggregate energy flow through arc \((i, j)\).
- \( x_{i,j}^{p(s)} \) is the energy flow through arc \((i, j)\) in scenario \( s \).
- \( C_{p(i)}^{n} \) is the coefficient of arcs to node \( n \) from the nodes in the \( p \) plex.
- \( C_{p(j)}^{n} \) 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 installation 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):

\[
\sum_{(i,j)\in A} (\Pi_{i,j} B_{i,j} + \pi_{i,j} x_{i,j})
\]  \hspace{1cm} (4)

Subject to:

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

\[
x_{i,j}^s \geq 0
\]  \hspace{1cm} (5)

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

\[
e_n^s \geq \sum_{(n,j)\in A} x_{i,j}^s
\]  \hspace{1cm} (6)

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

\[
e_n^s \geq \sum_{(i,n)\in A} x_{i,j}^s
\]  \hspace{1cm} (7)

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:

\[
x_{i,n}^s = \begin{cases} 
0 & \text{if } b_{i,n}^s = 0 \\
x_{i,n}^s & \text{if } b_{i,n}^s = 1
\end{cases}
\quad \text{and} \quad
x_{n,j}^s = \begin{cases} 
0 & \text{if } b_{n,j}^s = 0 \\
x_{n,j}^s & \text{if } b_{n,j}^s = 1
\end{cases}
\]  \hspace{1cm} (8)

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:

\[
b_{i,j}^s = \begin{cases} 
0, & \text{if the edge is deactivated} \\
1, & \text{if the edge available}
\end{cases}
\]  \hspace{1cm} (9)
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:

\[ x_{m,n}^s = e_n^s \]  
\[ x_{n,o}^s = e_n^s \]  

(10)  

(11)

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:

\[ x_{i,n}^s = C_n^p(i) \left( x_{m,n}^s \right) \]  

(12)

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

\[ x_{n,j}^s = C_n^p(j) \sum_{(l,n) \in A} x_{l,j}^s \]  

(13)

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

\[ \sum_{(i,n) \in A} x_{i,j}^s = \sum_{(n,j) \in A} x_{i,j}^s - e_n^s = 0 \]  

(14)

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:

\[ x_{i,j} = \max_{s \in S} x_{i,j}^s \]  

(15)

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:

\[ B_{i,j} = \begin{cases} 
0, & \text{if } x_{i,j} = 0 \\
1, & \text{if } x_{i,j} > 0 
\end{cases} \]  

(16)

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 36. 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 4. Each arc has a direction, flow cost per unit flow, and an upper capacity limit.
Figure 37 and Table 5 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 4: Example Network Flow Optimization Parameters (Trapp, 2015)

<table>
<thead>
<tr>
<th>Edge</th>
<th>Cost</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1,2)</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>(1,3)</td>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td>(3,4)</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>(4,2)</td>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td>(4,6)</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>(5,3)</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>(5,6)</td>
<td>10</td>
<td>15</td>
</tr>
</tbody>
</table>
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 26. 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 damage 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).

Figure 38 through Figure 40 show the MECH plex’s system responses. Figure 13 shows how the mechanical power for propulsion is split evenly between the port and starboard shafts in the endurance scenario. Figure 39 shows how the starboard shaft is deactivated when the starboard propulsion motor module (located in MMR 2 Lower) is deactivated. Figure 40 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). All of these results are generated automatically by the AFO without direct user intervention once setup. This is important for the C&RE application.

![Diagram](image)

Figure 38: MECH Plex Endurance System Response
Figure 39: MECH Plex Damaged MMR2 Lower System Response

Figure 40: MECH Plex Aggregate System Response
Figure 41 through Figure 44 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 ultimately distributed to the power conversion modules (PCMs) and load centers (LCs). Figure 41 shows that both PGMs are turned off (secured) in the endurance scenario. In this scenario, the ship is required to achieve endurance speed using only the secondary power generation modules SPGMs. Figure 41 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 MPES components in battle and damaged scenarios. The energy magazines are modeled as fully charged at the start of a battle scenario and will only provide power for a limited duration of time. This is the most that can be modeled in a static analysis. The future DAFO will be able to more correctly model energy storage and pulse power applications. Figure 42 shows the battle system response. PGMs, SPGMs, and stored energy magazines are all active. Nearly all arcs are used in this system response. Figure 43 shows the Damaged MMR 2 Lower system response. PGM 2 is in the MMR 2 Lower SDB and is deactivated in this figure. Figure 44 shows the aggregate ELEC plex system response, which is primarily governed by the battle scenario. This system response will satisfy the demands shown in Figure 41 through Figure 43.
Figure 43: ELEC Plex Damaged MMR2 Lower System Response

Figure 44: ELEC Plex Aggregate System Response

Figure 45 through Figure 48 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 45 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 46 shows the battle system response. Required cooling in Zone 2 exceeds the 3000 tons 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 47 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 Figure 46 and Figure 47). Figure 48 shows the aggregate system response. This system response is heavily influenced by the cooler 1500 ton limit and the damage scenarios.
Figure 49 through Figure 52 show the FO plex system responses. Figure 49 shows the endurance system response. As noted in the ELEC system responses, the PGMs are deactivated and only the SPGMs are active. Figure 50 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 50. 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 51 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. Figure 52 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 48: CW Plex Aggregate System Response

Figure 49: FO Plex Endurance System Response
Figure 50: FO Plex Battle System Response

Figure 51: FO Plex Damaged MMR2 Lower System Response

Figure 52: FO Plex Aggregate System Response

Figure 53 through Figure 55 show the LO plex system responses. The LO plex provides cooling to PGMs, SPGMs, and PMMs. Figure 53 shows the endurance system response. Unlike the FO endurance system response, Figure 49, Zone 3 is still active due the presence of the PMM in Zone
3/MMR 2. Figure 54 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 trend is also seen in the MECH and ELEC Damaged MMR 2 Lower system response (Figure 39 and Figure 43). Figure 55 shows the aggregate system response, which is primarily governed by a combination of the sustained speed and battle system responses.

Figure 53: LO Plex Endurance System Response

Figure 54: LO Plex Damaged MMR 2 Lower System Response

Figure 55: LO Plex Aggregate System Response
Figure 56 through Figure 58 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 56 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 57 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 58 shows the aggregate system response, which is governed by the battle scenario.
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. The AFO method may be integrated with any early-stage ship design software that includes:

- A list of VCs
- A list of directed connections between VCs
- An arrangement of VCs at a SDB level of detail
- A list of relative operating point energy inputs and outputs per VC type
- A list of active mission VCs per operational scenario
- Linearized arc cost or penalty factors based on length, commodity type (e.g. electricity, water, etc.), energy capacity, and operational scenario usage. Examples are provided in this paper.
- Linearized operational constraints enforced at the discretion of the designer (e.g. power loads are split evenly between redundant VCs, certain VCs are deactivated in certain operational scenarios, etc.). Examples are provided in this paper.

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

- Adding distribution components (e.g. wires, pipes, shafts, etc.) and implementing a system routing algorithm.
- 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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REFERENCES
Refinement of a Mission, Power, and Energy System Architecture Flow Optimization Method and Tool for Surface Ship Concept Design
Mark A. Parsons¹, Mustafa Y. Kara¹, and Alan J. Brown¹

ABSTRACT
This paper describes a Mission, Power, and Energy System (MPES) Architecture Flow Optimization (AFO) method and tool refinement applied in the Concept and Requirements Exploration (C&RE) of a notional surface ship. AFO is a system energy flow optimization that uses a network-based definition of MPES architecture to reduce system vulnerability, improve reliability, and aid in vital component sizing in early stage ship design. The AFO uses linearized energy vital component models, a preliminary ship arrangement model and a linear programming formulation to minimize required energy flow costs and satisfy nominal operating and deactivation quasi-static constraints. AFO results are used to inform system logical architecture design, develop preliminary (physical) arrangements and assess the feasibly and survivability of representative designs in the C&RE process. AFO results may also be used in subsequent physics-based vital component sizing, calculation of vulnerability/effectiveness metrics, and additional linear optimization formulations to assess recoverability and operational effectiveness in the time domain.

INTRODUCTION
Power and Energy Systems (MPES) are fundamental to the design, mission, and operation of surface ships. MPES design and architecture are critical to determining all aspects of a surface ship’s effectiveness, survivability, and cost. MPES 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 “equipment lists”. Over time, distributed systems have become increasingly interconnected and interdependent, particularly in modern surface 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 (Brown, 2020).

Parsons et al. (2019) presented an update describing a surface ship Concept & Requirements Exploration (C&RE) process developed over two decades at Virginia Tech and MIT (Brown & Thomas, 1998, Brown & Salcedo, 2003, Stepanchick & Brown, 2007, Strock & Brown, 2008, and Brown & Sajdak, 2015). Goodfriend & Brown (2018) described the application of this process to early concept exploration considering vulnerability. Typically, survivability analysis for surface 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.

Goodfriend & Brown (2018); Snyder (2019); Snyder, Parsons, Brown, & Chalfant (2019); and Habben Jansen, Kana, & Hopman (2019) use a traditional system vital-component deactivation diagram approach (or a Markov chain variation) to assess system vulnerability. In these methods, deactivation
Diagrams are used both to define the system architecture and assess its vulnerability to vital component loss. However, these methods only consider system connectivity; they do not consider power, or commodity flow capacity.

Working in a Naval International Cooperative Opportunities in Science and Technology Program (NICOP), the authors began exploring the use of networks and a simple network architecture framework to provide an alternative approach to system architecture and different paradigms for preliminary arrangements, system topology, and for considering survivability in early design decisions. Figure 59 shows how this Architecture Framework decomposes the total system into three primary views: physical, logical, and operational, representing the spatial, connectivity/functional and temporal relationships of a distributed system respectively (Brefort et al., 2018).

![Figure 59: Architectural Framework for Distributed Naval Ship Systems (Brefort et al., 2018)](image)

Distributed systems are interdependent with each other and with the ship’s general arrangement, which itself may be considered a distributed system. The physical locations, connectivity, and operation of ship distributed systems 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, surface ship survivability and affordability (Brown, 2020).

Distributed energy systems and their components may be characterized by their logical architecture, commodity flow (mechanical or electric power, chilled water, lube oil, seawater, glycol coolant, data, etc.) and their ability to transport, store, or convert energy. Our simple energy flow models do not use “through” variables (i.e. current, flow rate, speed) or “cross” variables (i.e. voltage, pressure, torque). Initially they assume a steady or quasi-steady state and model 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 initially 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 and is computationally very efficient.

A system 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 resultplexes are similar to traditional marine engineering distributed systems (i.e. fuel oil service system, electrical distribution system, chilled water system, MS1 system) (Brown, 2020).

In this logical architecture, a node represents single or multiple flow operations (e.g. source, sink, distribution, or conversion). Most nodes model the behavior performed by a 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.

Figure 60 shows a Power Generation Module (PGM) gas turbine generator set as an example nodal vital 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 an energy coefficient of 1, 100% of this energy enters the node. A small trace flow energy input comes (is pulled) from the LO plex (.01*FO Energy) cold side. 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 (coefficient = .438). 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.

Energy coefficients are assigned to the input and output arcs of vital components based on these simple component models. Figure 61 shows the coefficient matrix 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 for this is 1. The other input coefficients are assigned values based on the percentage of energy (relative to the primary input) pulled from other input arcs. Output coefficients are assigned values based on the percentage of total input energy that the nodes send to their respective plex and other plexes through output arcs. 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 61. Note the PGM coefficients are consistent with Figure 60.
Directed edges connecting nodes in a single plex are called explicit arcs and arcs connecting nodes in different plexes are called implicit arcs. Figure 62 shows a notional multiplex network for a surface ship 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. Mission System 1 (MS1)
14. Mission System 2 (MS2)
15. Mission System 3 (MS3)
This network approach has proven to be exceptionally capable and flexible for the C&RE application. As a result, our entire C&RE process was reworked to apply this approach and its associated framework as described in Parsons et al. (2019) and Chapter 1 of Marine Engineering (Brown, 2020). Robinson (2018) and Parsons et al. (2020) describe the incorporation of this Architecture Framework into an energy-based variation of Trapp’s (2015) non-simultaneous multi-commodity which we now call Architecture Flow Optimization (AFO). AFO has become the primary method used in our C&RE to explore the MPES design, preliminary arrangements, and survivability (Parsons et al., 2019). The AFO determines the aggregate power and energy flows of the total ship system topology subject to nominal operating and deactivation scenario constraints. A commodity flow-based vital component (VC) sizing algorithm (Stinson, 2019 and Stinson & Brown, 2019) uses the AFO results to determine VC space, weight, and required power in total ship synthesis (in place of older parametric-based VC sizing algorithms).

This paper describes refinements to this AFO method subsequent to Robinson (2018), and compares the impact of VC sizing methods (parametric vs. energy-based) in the context of a surface ship C&RE case study. AFO refinements include modeling trace flows (liquid cold-side flows in thermal cooling systems) within and across system zones, mission system VC model refinement, and additional design/operational constraints. This paper also presents a notional surface ship C&RE case study. Three representative surface ship concept designs are evaluated using three similar MPES design processes resulting in nine MPES designs. Characteristics of these nine designs are compared to show the capability of the AFO method in the MPES design process and in the context of a surface ship C&RE. Conclusions and possible future work are described in the last section.

CONCEPT & REQUIREMENTS EXPLORATION (C&RE)

Our C&RE process, illustrated in Figure 63, 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 mission, 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 63: Surface ship Concept & Requirements Exploration (C&RE) process with set-based domains and Architectural Framework (Parsons et al., 2019).

Next comes domain-specific concept explorations in at least six important domains: hullform and deckhouse geometry; MPES (e.g propulsion, other distributed systems, and mission systems); preliminary arrangements; manning and automation; survivability (for surface 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.
Four of these domains: MPES design, preliminary arrangements, survivability and RM&A, are closely coupled and computationally extensive so they are explored simultaneously using representative designs. Representative designs including hull, deckhouse, subdivision and preliminary arrangements are synthesized for each combination of MPES system options. A single set of midrange hullform design variable (DV) values except LOA are used for all representative designs. LOA values for each representative design are calculated (not optimized) as required to support system option weight, space and electric power requirements using a less definitive parametric synthesis approach, but providing feasible designs. Vital Component (VC) sizing data, vulnerability probabilities, measures of effectiveness (MOEs), reliability and architecture data are saved for each system option combination in their respective representative designs for recall in the final ship synthesis whenever a particular set of system options is selected. This approach uncouples the MPES process from the other explorations and avoids having to include it explicitly in the final synthesis, greatly reducing computational effort.

Figure 64: Mission, Power, and Energy System (MPES) design process approximately superimposed on the Architectural Framework (Parsons et al., 2020).

Figure 64 illustrates the MPES design process. This process integrates a representative hullform and deckhouse with various MPES system options into a representative design in the context of a larger design space exploration. The system options are defined using the architecture framework described in the previous section and the Architecture Flow Optimization (AFO), shown as Exploration #1 in Figure 64, is the primary means of integrating and sizing these systems. The Exploration #1 AFO and its solution also provide the framework and many of the constraints for subsequent Vulnerability AFO (VAFO) and Dynamic AFO (DAFO), the focus of our ongoing research and future papers which connect more directly to the Operational Architecture.

Table 6 shows the design space of MPES design variables considered in our notional surface ship C&RE case study. These include power and propulsion system options: an integrated power system (IPS), hybrid electric drive system (HED), and combined diesel and gas turbine propulsion system (CODAG) with various engines and power generation modules; and mission system options for each
mission area: threshold, moderate, and goal systems, options 4, 5, and 6 respectively for each warfighting area. Each of these MPES options has a corresponding system logical and physical architecture.

Table 6: Notional surface ship C&RE MPES design variable options. Options numbers not used are omitted.

<table>
<thead>
<tr>
<th>Design Variables</th>
<th>Values</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>Propulsion System (PSYS) - Architecture</td>
<td>Option 6</td>
<td>IPS, 2 FPP, 2 Shafts, 2 x PMM, 1 x GTPGM, 2 x DSPGM, MVDC</td>
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<tr>
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<td>Option 7</td>
<td>HED, 2 CRP, 2 Shafts, 1 x GTMPE, 2 x DSPGM, 2 x SPMM, 2 x SSG, MVAC</td>
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<td>Option 8</td>
<td>CODAG, 2 CRP, 2 Shafts, 1 x GTMPE, 2 DSPE, 4 x SSG, CODAG</td>
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<tr>
<td>MPE/PGM Main Propulsion Engine or PGM</td>
<td>Option 1 MT30</td>
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<tr>
<td></td>
<td>Option 2 LM2500</td>
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<tr>
<td>SPE Secondary Engine or SPGM</td>
<td>Option 1 MTU 20V 8000 M91L (10 MW)</td>
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<td>Option 2 20PA6B STC (8.1 MW)</td>
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<td>Option 3 16PA6B STC (6.48 MW)</td>
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<td>Option 4 CAT 280V16 (5.06 MW)</td>
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<td>Ship Service Generator</td>
<td>Option 1 Allison 501K34 SSGTG</td>
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<tr>
<td></td>
<td>Option 2 CAT 280V12 SSDG</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Option 3 CAT 280V8 SSDG</td>
<td></td>
</tr>
<tr>
<td>MS1</td>
<td>Option 4 Goal Effectiveness VCs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Option 5 Intermediate Effectiveness VCs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Option 6 Threshold Effectiveness VCs</td>
<td></td>
</tr>
<tr>
<td>MS2</td>
<td>Option 4 Goal Effectiveness VCs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Option 5 Intermediate Effectiveness VCs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Option 6 Threshold Effectiveness VCs</td>
<td></td>
</tr>
<tr>
<td>MS3</td>
<td>Option 4 Goal Effectiveness VCs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Option 5 Intermediate Effectiveness VCs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Option 6 Threshold Effectiveness VCs</td>
<td></td>
</tr>
<tr>
<td>Energy Storage</td>
<td>Option 1 2 MWhr</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Option 2 1 MWhr</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Option 0 none</td>
<td></td>
</tr>
</tbody>
</table>

As a preliminary to applying our new MPES process and AFO, a multi-objective genetic optimization (MOGO) was run for the full surface ship design space including the DV ranges in Table 6, but using our parametric synthesis model. The MOGO’s three objectives were cost (Cfola), effectiveness (OMOE), and risk (OMOR). The MOGO non-dominated frontier results are shown in Figure 65 through Figure 67. Figure 65 shows cost, effectiveness and risk in one plot with risk indicated by colors blue to red (low to high). Figure 66 shows cost and effectiveness but with PSYS in color, PSYS=8 (CODAG) at the low end, PSYS=6 (IPS) at the high end and PSYS=7 (HED) underlying both. Figure 66 shows cost and effectiveness but with MS1 in color, MS1=6 at the low end and MS1=4 at the high end. Figure 65 shows the expected increase in non-dominated effectiveness with increased cost and risk. Higher risk in the surface ship designs comes primarily from increased automation, integrated power system (IPS)
technologies, laser and anti-denial system technologies, and new radar technologies.

Three designs are labeled in the NDF plots. PSYS8-1 uses CODAG mechanical propulsion (PSYS=8) which is relatively low risk, but unable to support the higher (pulse) power demands of the high-end MS1 systems as efficiently as the IPS and HED systems. This is a low-risk, low-cost, low-effectiveness design, but still feasible and non-dominated for its cost and risk. PSYS7-1 uses hybrid electric drive (HED, PSYS=7) which is medium risk, but still not quite able to support the high-end MS1 systems. PSYS6-1 uses IPS power and propulsion which enables the high-end MS1 Option 4. Representative designs based on the same system options as in PSYS6-1, PSYS7-1 and PSYS8-1 are used.
in the surface ship case study presented later to demonstrate the impact of applying our new MPES Exploration process and AFO. These system options are listed in Table 7.

![Figure 67: Surface ship MS1 Option Non-Dominated Frontier](image)

**Figure 67**: Surface ship MS1 Option Non-Dominated Frontier

**Table 7**: Notional surface ship representative designs with propulsion and combat system design variable options.

<table>
<thead>
<tr>
<th>Design Variable</th>
<th>DV</th>
<th>PSYS6</th>
<th>PSYS7</th>
<th>PSYS8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propulsion System Architecture</td>
<td>PSYS</td>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Mission System 1</td>
<td>MS1</td>
<td>4</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Mission System 2</td>
<td>MS2</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Mission System 3</td>
<td>MS3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Main Propulsion Engine / Power Generation Module</td>
<td>MPE / PGM</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Secondary Propulsion Engine / Secondary Power Generation Module</td>
<td>SPE / SPGM</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Ship Service Generator</td>
<td>SSG</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Energy Storage</td>
<td>ENER</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

**ARCHITECTURE FLOW OPTIMIZATION REFINEMENT**

The AFO method described by Robinson (2018) minimizes the aggregate energy flow cost of a total ship system across multiple nominal and deactivation operational scenarios. This section describes recent changes to this AFO formulation and incorporates refinements into the mathematical formulation described by Robinson (2018) and Parsons et al. (2020). Refinements were required in:

- trace energy flows
- system cross-zonal continuity
- zonally redundant vital component operational use
- optimization slack variables
- chilled water plant size limit
- combat system vital component heat dissipation
Figure 68: CW plex for sustained-speed-scenario flow in a previous surface ship application using original AFO formulation. Zones 1-4 are numbered from right to left. Cross-connecting arcs link each zone’s supply and return respectively (Robinson, 2018).

Figure 68 shows a four-zone CW plex sustained-speed-scenario flow in a surface ship application generated using our original AFO method (Robinson 2018). It illustrates problems that need AFO refinement. Similar problems were found in other plexes and in the original surface ship application. Trace energy flows, the cold-side commodity flows in liquid cooling systems, are not present for all active cold-side VCs as they should be (compare Glycol_HeatExch2_CW_SYS with Glycol_HeatExch3_CW_SYS in Figure 68). System cross-zonal continuity is closely related to these trace energy flows and is also incorrect in this example. In a closed system, if a commodity leaves a zone it must return to the same zone. In Figure 68, system cross-zonal continuity is not present between all zones (compare the cross-connecting arcs between zones 1 and 2 with those between zones 2 and 3 in Figure 68). Similarly, the CWplex system flows generated using the original AFO formulation routed all heat in the CWplex through one or two massively large CW coolers and pumps. There was no upper limit to the size of these components. A design with one or two large CW plants is undesirable from both vulnerability and maintenance perspectives, but in the original formulation two plants side by side in the same compartment was considered unnecessary with no advantage. Refinement was needed.

All AFO refinements are ultimately implemented in the objective function and constraints of the AFO mathematical formulation:

Objective Function

\[
\min \left( \sum_{(i,j) \in A} \left( I_{i,j} B_{i,j} + \pi_{i,j} x_{i,j} \right) + \sum_{(n) \in N} \left( 1 \times 10^{12} \times d_n \right) \right)
\]

Directed Arc Constraint

\[
x_{i,j}^s \geq 0
\]

Sink Node Constraint

\[
e_n^s \geq \sum_{(ln) \in A} x_{ln}^s \quad \text{ (ex: Propulsion_SYS)}
\]

Scenario Arc Deactivation Flow Constraint

\[
x_{i,n}^s = \begin{cases} 0, & \text{if } b_{ln}^s = 0 \\ x_{i,n}^s, & \text{if } b_{ln}^s = 1 \end{cases}
\]

Scenario Arc Deactivation Binary Constraint

\[
b_{l,j}^s = \begin{cases} 0, & \text{if the edge is deactivated} \\ 1, & \text{if the edge available} \end{cases}
\]
Known Scenario Load Arc Flow Constraint  
\[ x_{m,n}^s = e_n^s \]  
(ex: AAW VC electric load)  
(22)

Known Scenario Heat Arc Flow Constraint  
\[ x_{m,0}^s = e_n^s \]  
(ex: AAW VC heat load)  
(23)

Scenario Arc In-Flow Capacity Constraint  
\[ x_{m,n}^s \leq e_n^s \]  
(ex: CW Cooler capacity)  
(24)

Scenario Arc Out-Flow Capacity Constraint  
\[ x_{n,0}^s \leq e_n^s \]  
(ex: PGM power capacity)  
(25)

Scenario Incoming Arc Flow Constraint  
\[ x_{i,n}^s = c_p^{(j)}(x_{n,m}^s) \]  
(appplies VC In-flow coefficients)  
(26)

Scenario Outgoing Arc Flow Constraint  
\[ x_{n,j}^s = c_p^{(j)}(\sum_{(i,j)\in A} x_{i,j}^s) \]  
(appplies VC Out-flow coefficients)  
(27)

Scenario Redundant VC Arc Flow Constraint  
\[ x_{m,a}^s = x_{m,b}^s \]  
(28)

Scenario Continuity Constraint  
\[ \sum_{(i,j)\in A} x_{i,j}^s - \sum_{(n,j)\in A} x_{n,j}^s - d_n^s = 0 \]  
(29)

Aggregate Arc Flow Constraint  
\[ x_{i,j} = \max_{s\in S} x_{i,j}^s \]  
(30)

Aggregate Slack Variable Constraint  
\[ d_n = \max_{s\in S} d_n^s \]  
(31)

Binary Arc Constraint  
\[ B_{i,j} = \begin{cases} 0, & \text{if } x_{i,j} = 0 \\ 1, & \text{if } x_{i,j} > 0 \end{cases} \]  
(fixed-cost binary)  
(32)

- \( N \) 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 supplied or 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 \( s \).
- \( d_n^s \) is the aggregate energy flow slack variable for node \( n \).
- \( d_n \) is the energy flow slack variable for node \( n \) in scenario \( s \).
- \( c_p^{(j)}(n) \) is the coefficient of arcs to node \( n \) from the nodes in the \( p \) plex.
- \( c_p^{(j)}(n) \) is the coefficient of arcs from node \( n \) to the nodes in the \( p \) plex.
- \( b_{i,j} \) 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 fixed cost 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.

Earlier refinements to the original AFO (Robinson’s 2018) added scenario incoming arc flow constraints, Equation 8, to limit component capacities like in CW coolers avoiding single very large components. The trace energy flow and system cross-zonal continuity issues were more difficult, and complicated by the need to allow and account for small numerical errors. Adjustments were made to the VC coefficients in the coefficient matrix, Figure 61, to insure continuity (the sum of output coefficients for each VC must equal one), the input coefficient for the primary plex input must equal one, and in and out (pull and push) trace flow coefficients were required to properly manage cold-side flow. Small adjustments were made to the output coefficients to keep everything balanced, but still insuring that their...
sum was equal to one for continuity. With all of this, there were still some small numerical errors resulting from some of the coefficients having to be irrational numbers. Since irrational numbers cannot be used in Cplex, the linear optimization program used by the AFO, a small round-off error was introduced. This required using slack flow variables in Equations 13 and 15 to fully enforce continuity. The slack variable flow is minimized by adding their sum multiplied by a penalty factor to the objective function in Equation 1. This penalty factor was set to one trillion (five orders of magnitude larger than the final objective value), ensuring the optimization favored solutions where slack flow was minimized and energy conserved. This worked well except for the CW plex where the error was the same order of magnitude as the trace flows in other plexes. It was found that this problem could be fixed by not including the CW slack flow at the CW Supply nodes, where the flow was being over-constrained, in the objective function. With all of these changes, everything balanced and the problems with the original formulation were solved.

For the operational use of zonally redundant VCs, the input arcs of redundant components were set equal to each other using the scenario redundant VC arc flow constraint, Equation 12. This ensured redundant components would be sized the same.

Figure 69 shows an example of a refinement to mission system vital component heat dissipation. This was a minor refinement to the AFO method, but greatly reduced the cooling demands of designs. Energy enters the VC from the ELEC plex and is transformed into heat. In the original AFO formulation, all of this heat was removed by the VC’s cooling system. The refined method models heat dissipated directly to the environment for certain mission system VCs. An arc connecting the mission system VC to the External Air Sink or Salt Water Sink represents its heat transfer to the environment. This improvement resulted in a smaller and more realistic total ship system cooling loads.

Figure 69: MS1 Vital Component (VC) Energy Model.

FRIGATE CASE STUDY RESULTS

This section presents the representative designs described in the Concept & Requirements Exploration section (PSYS6-1, PSYS7-1, and PSYS8-1) obtained using sizing parametrics without performing additional optimization and compares these designs with two variants per representative design. The first variant is an optimized version of the representative design also obtained using the parametric sizing approach (PSYS6-2, PSYS7-2, and PSYS8-2). The second variant is an optimized design using power and energy components sized with the refined-AFO results (PSYS6-3, PSYS7-3, and PSYS8-3). A single objective hullform optimization (SOO) was used for the 2nd and 3rd variants to minimize the cost of follow-ship acquisition cost (Cfola) while constraining effectiveness and risk to be at least as good as in the original variant. This process resulted in nine designs for comparison. Table 8 presents the results of these nine designs.
A number of observations can be made about these results:

- The PSY6, 7 and 8 baseline designs are substantially larger than their optimized variants, particularly in terms of length and displacement, although they have the same system options. They are all feasible. This is to be expected because they are sized large to insure feasibility without manual intervention or iteration. Effectiveness and risk are at least as good in the variants. Follow-ship cost improves in the first variant, but then increases a bit in the refined AFO for the hybrid and IPS designs as SWBS 200, 300 and 500 weights increase.

- Effectiveness ranking between PSY6, 7 and 8 designs does not change with the variants, particularly for non-endurance related performance. This is an important underlying assumption for using representative designs to estimate performance and effectiveness in designs with the same system options.

- Power and energy SWBS groups 200, 300 and 500 are generally heavier in the refined-AFO variants particularly when compared to the non-AFO optimized variants. Cost is higher in PSYS7-3 and PSYS 8-3 compared to their non-AFO optimized variants. These are non-conservative results that could
impact feasibility at later design stages. Without even considering vulnerability directly, these results demonstrate the value of the refined-AFO C&RE.

Finally, the surface ship refined-AFO flow results show that deficiencies in the previous surface ship flow results have been corrected. Figure 70 shows the flow for the surface ship CW plex sustained speed scenario and illustrates the impact of the AFO refinements. All active heat sources (e.g. zonal HVAC, EC, and Glycol nodes) have trace flows. System cross-zonal continuity is maintained. In Figure 70, energy leaves Zone 3 at CW_Return3_VC and a corresponding trace energy flow returns at CW_Supply3_VC. Components of the same type in the same zone have equal flow ensuring equal sizing (e.g. energy is evenly split between the pumps of each zone). In this scenario, Zones 2 and 3 are cross-connected and Zones 1 and 4 are split. The AFO refinements show excellent improvement compared to the original AFO results (Robinson 2018).

Figure 70: PSYS8-3 sustained speed scenario CW system response. Energy flows are plotted using a logarithmic scale.

The remaining system response figures in this section compare the MECH and ELEC plex Main Machinery Room 2 (MMR2) Lower deactivation system response for each refined-AFO representative design. In the deactivation scenarios, the designs are only required to deliver half of the propulsion power required for endurance speed (20 kts). Figure 71 and Figure 72 show the MECH and ELEC system responses for PSYS6-3. PSYS6 has an IPS. This is indicated by the propulsion motor modules (PMMs) in the MECH and ELEC plexes and the lack of mechanically-connected engines to the shafts. All three representative designs achieve the propulsion requirement with a single shaft. MMR 2 is in Zone 3 of all three representative designs and as a result, power is not generated in Zone 3 in any of the system responses. In PSYS6-3 power reaches Zone 3 and Zone 4 loads only through the port bus.
Figure 71: PSYS6-3 MECH plex deactivated MMR2 Lower system response.

Figure 72: PSYS6-3 ELEC plex deactivated MMR2 Lower system response.

Figure 73 and Figure 74 show the MECH and ELEC system responses for PSYS7-3. PSYS7 has a HED propulsion system. This is indicated by the propulsion motor modules (PMMs) in the MECH and ELEC plexes and a main propulsion engine (MPE) mechanically connected to both shafts via a cross reduction gear in the MECH plex.
Figure 73: PSYS7-3 MECH plex deactivated MMR2 Lower system response

Figure 74: PSYS7-3 ELEC plex deactivated MMR2 Lower system response.

Figure 75 and Figure 76 show the MECH and ELE system responses of PSYS8-3. PSYS8 is has a CODAG propulsion system. This is indicated by the lack of propulsion motor modules (PMMs) in the MECH and ELEC plexes and presence of secondary propulsion engines (SPEs) a main propulsion engine (MPE) mechanically connected to both shaft via a cross reduction gear in the MECH plex.
CONCLUSIONS AND FUTURE WORK

In summary, propulsion and distributed system design are an integral part of the overall ship design and must be considered even in early ship design stages like concept exploration at a sufficient level of detail for making early design decisions and moving on to later design stages without costly backtracking. Early stage ship design decisions based on total ship cost, effectiveness, risk, balance and feasibility are impacted greatly by propulsion and distributed system design decisions.

AFO is an energy-based linear optimization of a surface ship total system considering nominal operating and deactivation conditions. AFO incorporates the architectural framework for distributed surface ship systems (Brefort et al., 2018) and has applications in early-stage ship design, the C&RE
process, the MPES design process, system validation, commodity-based VC sizing, and vulnerability/survivability analysis.

This paper presents refinements to the AFO methodology and an AFO surface ship case study. However, after multiple case studies (Robinson, 2018, Parsons et al., 2020, and this case study) and method refinement, the underlying simplifying approaches based on the Architecture Framework remain intact:

1. Use of subdivision blocks (SDBs) vice curvilinear geometry to define the physical architecture
2. Assignment of vital components (VCs) to compartments and compartments to SDBs rather than using x, y, z coordinates for VCs
3. Use of simplified energy flow component models
4. Use of simplified steady or quasi-steady state operational scenarios.

As a result of this work, the authors conclude these simplifications provide sufficient information in surface ship C&RE. Furthermore, the AFO provides a useful tool to help surface ship designers understand the energy flow, size components, and assess feasibility & survivability in early-stage surface ship design.

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

- Decreasing computation time with parallel processing of different designs in a single generation of a multi-objective genetic optimization.
- Improvement of tools for preliminary surface ship arrangements with UNDEX and UNDEX Shock Vulnerability Assessment criteria in addition to AIREX.
- Development of time-based operational architecture methods and tools in the network architecture framework for surface 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.
- Vulnerability metric refinement using thermal signatures from AFO energy flow results
- Overall design vulnerability assessment using a Vulnerability Architecture Flow Optimization (VAFO)
- Cascading and secondary deactivation analysis using a DAFO
- Deactivation 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. Recent work in this field includes Sinsely, Opila, & Steven, 2019.

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REFERENCES

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Conclusions and Future Work

CONCLUSIONS

This thesis describes the application of a distributed system architecture framework to naval ship Concept & Requirements Exploration (C&RE), the Architecture Flow Optimization (AFO) method, refinements to both C&RE and AFO, and concept design case studies of surface ships. Applying the decomposition of the architectural framework for naval ship distributed systems greatly simplified the Mission, Power, and Energy System (MPES) design process to a suitable degree for use in C&RE. AFO incorporated system topologies, energy component models, preliminary arrangements, and (nominal and damaged) steady state operational scenarios into a linear optimization method minimizing the energy flow cost to satisfy all operational scenario demands and constraints. AFO results were used to inform system topology design, size component, and assess the feasibly/survivability of representative designs in the C&RE process.

PROPOSED FUTURE WORK

The next steps will focus on mission system capability modeling and developing design reference missions of the operational architecture. Incorporating these areas of research with the energy based demonstrated in this thesis in an expanded but similar linear optimization formulations would provide a means to assess battle damaged recovery, pulsed power loading, and operational effectiveness against a common set of measurable requirements in the time domain during concept stage ship design.