

Network-Based Naval Ship Distributed System Design and Mission Effectiveness using Dynamic Architecture Flow Optimization

Mark Allen Parsons

Dissertation submitted to the faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

**Doctor of Philosophy
In
Aerospace Engineering**

Alan J. Brown, Chair
Stefano Brizzolara
Julie S. Chalfant
Pradeep Raj

25 June 2021
Blacksburg, Virginia

Keywords: Naval Ship Design, Distributed System, Operational Modeling, Mission Effectiveness, and Survivability

© 2021 by Mark Allen Parsons

Network-Based Naval Ship Distributed System Design and Mission Effectiveness using Dynamic Architecture Flow Optimization

Mark Allen Parsons

ABSTRACT

This dissertation describes the development and application of a naval ship distributed system architectural framework, Architecture Flow Optimization (AFO), and Dynamic Architecture Flow Optimization (DAFO) to naval ship Concept & Requirements Exploration (C&RE). The architectural framework decomposes naval ship distributed systems into 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 and DAFO are a network-based linear programming optimization methods used to design and analyze MPES at a sufficient level of detail to understand system energy flow, define MPES architecture and sizing, model operations, 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. DAFO applies the same principles as AFO and adds a second commodity, data flow. DAFO also integrates with a warfighting model, operational model, and capabilities model that quantify tasks and capabilities through system measures of performance at specific capability nodes. This enables the simulation of operational situations including MPES configuration and operation during C&RE. This dissertation 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.

Network-Based Naval Ship Distributed System Design and Mission Effectiveness using Dynamic Architecture Flow Optimization

Mark Allen Parsons

GENERAL AUDIENCE ABSTRACT

This dissertation describes the development and application of a warship system architectural framework, Architecture Flow Optimization (AFO), and Dynamic Architecture Flow Optimization (DAFO) to warship Concept & Requirements Exploration (C&RE). The architectural framework decomposes warship systems into physical, logical, and operational architectures representing the spatial, functional, and time-based relationships of systems respectively. This decomposition greatly simplifies the Mission, Power, and Energy System (MPES) design process for use in C&RE. AFO and DAFO are a network-based linear programming optimization methods used to design and analyze MPES at a sufficient level of detail to understand system energy usage, define MPES connections and sizing, model operations, reduce system vulnerability and improve system reliability. AFO incorporates system templates, simple physics and energy-based component models, preliminary arrangements, and simple undamaged/damaged scenarios to minimize the energy flow usage required to satisfy all operational scenario demands and constraints. DAFO applies the same principles and adds a second commodity, data flow representing system operation. DAFO also integrates with a warfighting model, operational model, and capabilities model that quantify tasks and capabilities through system measures of performance. This enables the simulation of operational situations including MPES configuration and operation during C&RE. This dissertation provides an overview of design tools developed to implement this process and methods, including optimization objective attribute metrics for cost, effectiveness and risk.

Ut Prosim
(That I May Serve)
—Virginia Tech

Dedication

For Jim, Ann, and Sarah Parsons. During the course of my studies, through personal sacrifice, selflessness, and without material reward, you bestowed the support and understanding without which my graduation would not have been possible. You freely gave the confidence, guidance, wisdom, and assistance to help me attain this important milestone in my life.

The Lord is my light and my salvation; whom shall I fear?

—Psalm 27

Artes, Scientia, Veritas
(Arts, Knowledge, Truth)
–University of Michigan

Challenge the Future
–Technische Universiteit Delft
(Delft University of Technology)

Cuncti adsint meritaque expectent praemia palmae
(Let all come who by merit deserve the most reward)
–University College London

Ut Prosim
(That I May Serve)
–Virginia Tech

Science & Technology
–Office of Naval Research

Acknowledgements

Funding

Major funding for this research was provided by:

- The Office of Naval Research (ONR) through grant N00014-15-1-24-76 Naval International Cooperative Opportunities in Science and Technology Program (NICOP): Naval Ship Distributed System Vulnerability and Battle Damage Recovery in Early-Stage Ship Design
- The Naval Surface Warfare Center, Philadelphia Division (NSWCPD) through Naval Engineering Education Consortium (NEEC) grant N00174-16-C-0048 Network-Based System Architecture Assessment and Improvement in Support of S3D/LEAPS Ship System Design.

Additional funding was provided by:

- The Society of Naval Architects and Marine Engineers (SNAME) through the 2016 Wilbur N. Landers Scholarship and the 2019 Bruce and Dorothy Rylander Johnson Scholarship
- The American Society of Naval Engineers (ASNE) through the 2016 ASNE Graduate Scholarship
- The Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech (VT AOE) through the 2019 Walts Fellowship and 2019-2020 Brian Nerney Graduate Research Fellowship

Any opinions, findings, and conclusions or recommendations expressed in this dissertation are those of the author and do not necessarily reflect the views of the sponsors.

Academic

Dr. Al Brown, CAPT USN (ret), served as Ph.D. Advisory Committee Chair and Principal Investigator providing a wealth of knowledge, research guidance, mentoring, funding, and an occasional sea story that was always related to the topic at hand. Dr. Stefano Brizzolara, Dr. Julie Chalfant, and Dr. Pradeep Raj served as Ph.D. Advisory Committee Members providing regular research guidance, mentoring, and both a deep and broad research perspective.

Co-researchers Mustafa Kara, Kevin Robinson, Alan Shane, Dave Berrow, Nick Stinson, and Dan Snyder became friends and sacrificed many late nights making this research possible. I wish you the best of luck in your future endeavors.

Collaborating NICOP researchers at ONR, the Defensie Materieel Organisatie (Defense Materiel Organization), the University of Michigan, the Technische Universiteit Delft (Delft University of Technology), and the University College London served as a regularly meeting peer review board sharpening this research and this researcher.

The S3D/LEAPS Integration Team included professionals from ONR; the Naval Surface Warfare Center, Carderock Division (NSWCCD); NSWCPD; the University of South Carolina; and the Massachusetts Institute of Technology.

Dr. Lothar Birk, Dr. Brandon Taravella, and Dr. Chris McKesson provided the foundation for and encouraged me to pursue graduate school.

Professional

Kelly Cooper, Bob Ames, Dave Woodward, Jeff Hough, Kris Rutkowski, and Bob Keane, provided mentoring and guided me through the public release process for these manuscripts. The Navy needs more outstanding leaders like you.

The Science, Mathematics, and Research for Transformation (SMART) Scholarship-for-Service Program; NSWCCD; VT AOE; SNAME; and ASNE worked together to ensure I began graduate school immediately after completing my undergraduate degree. A special thanks to Dr. Jim Sheehy and Alexis Schade.

Personal

Carlos Michelen, Oliver Raj, R.J. Bay, Matthew Roberts, Jonathan Eastridge, Jackie Caporella, Nicolas Rivero, Kyle Marlantes, Shawn Waltz, and Melody Waltz provided encouragement and friendship.

Finally, my family provided unending support and encouragement. I could not have done this without your help every step along the way. You make everything worthwhile.

*Very Respectfully
Mark A. Parsons*

American's Fleet Starts Here

–Naval Surface Warfare Center, Carderock Division

Powering Today's Fleet. Innovating Tomorrow's

–Naval Surface Warfare Center, Philadelphia Division

Emollit Mores Nec Sinit Esse Feros

(Learning humanizes character and does not permit it to be cruel)

–University of South Carolina

Mens et Manus

(Mind and Hand)

–Massachusetts Institute of Technology

Ut Prosim

(That I May Serve)

–Virginia Tech

Science & Technology

–Office of Naval Research

Table of Contents

Abstract	ii
General Audience Abstract	iii
Dedication	v
Acknowledgements	vii
Table of Contents	ix
List of Figures	xiii
List of Tables	xvii
Dissertation Introduction	1
Introduction	1
Gaps in Concept Design MPES Literature	1
Proposed Objectives	1
Manuscript Format Dissertation	2
Summary of Manuscripts and Research Contributions	2
Coauthors' Contributions	3
Dissertation Manuscripts	7
Paper #1 – Application of a Distributed System Architectural Framework to Naval Ship Concept and Requirements Exploration (C&RE)	9
Abstract	9
Acronyms	9
Introduction and Motivation	10
Concept & Requirements Exploration (C&RE)	11
Architecture Flow Optimization (AFO)	20
MPES Exploration	21
Conclusions and the Way Ahead	27
Acknowledgements	27
Author Biographies	27
References	28
Paper #2 – Early-Stage Naval Ship Distributed System Design using Architecture Flow Optimization ...	33
Abstract	33
Keywords	33
Introduction and Motivation	33
Logical Architecture	36
Physical Architecture and Physical Solution	39
Operational Architecture Constraints and Linear Optimization	40
Example Network Flow Optimization	42
AFO System Response	43
Conclusions and Future work	53
Acknowledgements	53
References	53
Paper #3 – Refinement of a Mission, Power, and Energy System Architecture Flow Optimization Method and Tool for Surface Ship Concept Design	55
Abstract	55
Introduction	55
Concept & Requirements Exploration (C&RE)	56
Architecture Flow Optimization (AFO)	58
AFO Refinement	62
Surface Ship Case Study C&RE	65
Surface Ship Case Study with Refined AFO Results	69
Conclusions and Future Work	73

Acknowledgements	74
Author Biographies	74
References	75
Paper #4 – Operational Architecture and Framework for Assessing Mission Effectiveness in Surface Ship Concept and Requirements Exploration	79
Abstract	79
Introduction	79
Ship System Behavior Models and Architecture for Missions.....	81
Lexicon and Identification	81
Mission Means Framework (MMF).....	82
Ship Behavior and Interaction Models.....	82
SBIM Application.....	85
Warfighting Model (WM)	86
Agent Movement	87
Kill/Impact Resolution and Damage.....	87
Limitations and Assumptions	87
Operational Architecture (OA) and the Operational Model (OM).....	88
Scenarios Modeled and Results.....	91
OPSIT 1: Enemy Aircraft, Allied Ship, & Neutral Ship.....	91
OPSIT 2: Enemy Ship & Enemy Aircraft.....	92
OPSIT 3: Enemy Ship with Special Anti-Ship Missiles (ASMs)	92
Additional Test Cases During Development	95
Conclusion.....	95
Acknowledgments	96
Author Biographies	96
References	96
Paper #5 - Capability Modeling for Assessing Mission Effectiveness in Surface Ship Concept and Requirements Exploration	99
Abstract	99
Introduction	99
Ship Operational Architecture, Behavior and Interaction Models	101
Lexicon and Identification	101
Mission Means Framework (MMF).....	102
Ship Behavior and Interaction Models.....	102
Capability Modelling.....	105
SBIM Execution Example	106
Warfighting Areas.....	107
Detect Capability	109
Detect Capability – Active Radar	110
Detect Capability – ESM	111
Detect Capability – Infrared.....	111
Detect Capability – Visual.....	112
Detect Capability – Prioritization	112
Track Capability	113
Track Capability – Prioritization	113
Identify Capability	113
Identify Capability – Prioritization	113
Decision Capability.....	114
Decide Capability – Prioritization	114
Engage Capability.....	115
Single Object Vital Components (SOVCs).....	116

Capability Model Demonstration	117
Conclusions and Future Work	118
Acknowledgments	119
Author Biographies	119
References	119
Paper #6 – System Dynamic Architecture Flow Optimization to Assess Mission Effectiveness in Surface Ship Concept and Requirements Exploration	123
Abstract	123
Introduction	123
Mission-Means Framework and Ship System Behavior Models	124
Dynamic Architecture Flow Optimization (DAFO).....	127
DAFO Examples and Results.....	132
SBIM Execution Process at t = 3 seconds	132
DAFO Result Comparison to System with Power Generation Offline.....	134
Condition A at t = 3 Seconds	134
Condition A at t = 4 Seconds	138
Condition B at t = 3 Seconds	140
Condition B at t = 4 Seconds	140
Conclusions and Future Work	142
Acknowledgments	142
Author Biographies	142
References	143
Dissertation Conclusions and Future Work	147
Conclusions	147
Achieved Objectives.....	147
Future Work	148

*It follows then as certain as that night succeeds the day,
that without a decisive naval force we can do nothing definitive,
and with it,
everything honorable and glorious.*
—George Washington

*A good navy is not a provocation to war.
It is the surest guaranty of peace.*
—Theodore Roosevelt

List of Figures

Figure 1. Representation of Architectural Framework for Ship Distributed Systems (Brefort, et al., 2018).....	11
Figure 2. Naval Ship Concept and Requirements Exploration (C&RE) Process with Architectural Framework and Set-Based Domains.....	13
Figure 3. MPES Design Process approximately superimposed onto the architectural framework.....	13
Figure 4. Ship Design Non-dominated Frontier (Brown and Sajdak 2015).....	14
Figure 5. OMOE Hierarchy (Brown and Salcedo, 2003).....	14
Figure 6. VOP "S" Curve, VOPi (Brown and Salcedo, 2003).....	16
Figure 7. Notional Surface Combatant MOP Weights, w_i	16
Figure 8. Exploration and Ship Synthesis Model (E&SSM) in Model Center (MC) – tools used to implement the C&RE Process.....	17
Figure 9. ORCA3D Hullform in Rhino	19
Figure 10. Initial DOE Result Histograms with GM/B > 0.05 Constraint (in red).....	19
Figure 11. Final DOE Result Histograms (feasible in red).....	19
Figure 12. AFO Execution Process.....	21
Figure 13. Notional (Network-Based) Architectural Framework Implementation in C&RE.....	22
Figure 14. Drug Interdiction Event Tree (Kerns et al. 2011b).....	22
Figure 15. Mechanical (Propulsion) Subsystem (MECH)	23
Figure 16. Notional Total-Ship System Architecture	23
Figure 17. Subdivision Block (SDB) Representation of Physical Architecture (Goodfriend and Brown, 2018).....	24
Figure 18. Nodal or Network Representation of Physical Architecture	24
Figure 19. Vital Components (VCs) and Compartments Allocated to Subdivision Blocks (SDBs) (Brown, 2020).....	24
Figure 20. Routing of Distributed Systems (Red = electric, Blue = chilled water)	25
Figure 21. Weapon Hit Locations (Goodfriend and Brown, 2018)	25
Figure 22. Damage Ellipsoid Interactions with SDBs (Stark, 2016)	25
Figure 23. SDB Hit Probabilities (Goodfriend and Brown, 2018).....	25
Figure 24. System Damage Response Intersection Process.....	26
Figure 25. Gun System DBD (Goodfriend and Brown, 2018)	26
Figure 26. Architectural Framework for Ship Distributed Systems (Brefort et al. 2018).....	34
Figure 27. Mission, Power, & Energy Systems (MPES) Design Process approximately superimposed with the Architectural Framework (Parsons et. al 2019)	35
Figure 28. Notional Future Surface Combatant Total-Ship Multiplex Logical Architecture	36
Figure 29. Excerpt of Vital Components, Their Compartment Assignments, and Their Implicit Arcs.....	37
Figure 30. Excerpt from MEL Equipment Input and Output Energy Coefficient Matrix.....	38
Figure 31. Nominal Power Generation Module (Gas Turbine and Generator Set Combination) Nodal Input and Output Coefficients.....	38
Figure 32. PGM - Gas Turbine Generator Set (Doerry & Amy 2016)	38
Figure 33. Zone 3 CW Loop	39
Figure 34. AFO's Nodal Description of SDBs (Physical Architecture)	40
Figure 35. ELEC and CW plexes (red and blue respectively) Physical Solution	40
Figure 36. Example Network Flow Optimization Network (Trapp 2015).....	42
Figure 37. Example Network Flow Optimization Solution (Trapp 2015)	43
Figure 38. MECH Plex Endurance System Response	44
Figure 39. MECH Plex Damaged MMR2 Lower System Response	44
Figure 40. MECH Plex Aggregate System Response	44
Figure 41. ELEC Plex Endurance System Response.....	45

Figure 42. ELEC Plex Battle System Response.....	45
Figure 43. ELEC Plex Damaged MMR2 Lower System Response.....	46
Figure 44. ELEC Plex Aggregate System Response	46
Figure 45. CW Plex Endurance System Response	47
Figure 46. CW Plex Battle System Response	47
Figure 47. CW Plex Damaged MMR2 Lower System Response	48
Figure 48. CW Plex Aggregate System Response	48
Figure 49. FO Plex Endurance System Response	49
Figure 50. FO Plex Battle System Response	49
Figure 51. FO Plex Damaged MMR2 Lower System Response	49
Figure 52. FO Plex Aggregate System Response	50
Figure 53. LO Plex Endurance System Response.....	50
Figure 54. LO Plex Damaged MMR2 Lower System Response	51
Figure 55. LO Plex Aggregate System Response	51
Figure 56. SW Plex Endurance System Response	52
Figure 57. SW Plex Damaged MMR2 Lower System Response.....	52
Figure 58. SW Plex Aggregate System Response	52
Figure 59. Architectural Framework for Distributed Ship Systems (Brefort et al., 2018).....	56
Figure 60. Surface Ship C&RE Process with Set-Based Domains and Architectural Framework (Parsons, et al., 2019)	57
Figure 61. MPES Design Process Approximately Superimposed on the Architectural Framework (Parsons et al., 2021).....	57
Figure 62. Notional Surface Ship Total-Ship Multiplex Logical Architecture.....	60
Figure 63. Nominal PGM (Gas Turbine and Generator Set Combination) Nodal Input and Output Coefficients	60
Figure 64. Excerpt from MEL Equipment Input and Output Energy Coefficient Matrix.....	61
Figure 65. 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).	62
Figure 66. MS1 VC Energy Model.....	65
Figure 67. Surface Ship Non-Dominated Frontier.....	67
Figure 68. Surface Ship PSYS Option Non-Dominated Frontier.	67
Figure 69. Surface Ship MS1 Option Non-Dominated Frontier.	68
Figure 70. PSYS 8-3 Sustained Speed Scenario Chilled Water (CW) System Response. Energy flows are plotted using a logarithmic scale.....	70
Figure 71. PSYS 6-3 MECH Plex Deactivated MMR2 Lower System Response	71
Figure 72. PSYS 6-3 ELEC Plex Deactivated MMR2 Lower System Response	71
Figure 73. PSYS 7-3 MECH Plex Deactivated MMR2 Lower System Response.	72
Figure 74. PSYS 7-3 ELEC Plex Deactivated MMR2 Lower System Response	72
Figure 75. PSYS 8-3 MECH Plex Deactivated MMR2 Lower System Response.	73
Figure 76. PSYS 8-3 ELEC Plex Deactivated MMR2 Lower System Response	73
Figure 77. Architectural Framework for Distributed Ship Systems (Brefort et al., 2018).....	80
Figure 78. Virginia Tech Ship Architectural Framework	81
Figure 79. Modified Mission-Means Framework (Purdy, 2004).....	82
Figure 80. Ship Behavior and Interaction Models (SBIMs)	83
Figure 81. Notional Mission System Vital Components and Capability Nodes with Data Commodity Flows (adapted from Friedman, 2006, p 105 and Chalfant et. al, 2017).....	83
Figure 82. Effectiveness Hierarchy.....	84
Figure 83. Ship Design Development Methodology & Force/Fleet Interfaces.....	86
Figure 84. Warfighting Model and System Interface.....	88
Figure 85. Kill Chain Operational Architecture.....	89

Figure 86. Ship Operational Architecture	89
Figure 87. OPSIT 1 – Tactical Picture and Kill Chain Progression.....	90
Figure 88. SBIM Execution Process	91
Figure 89. OPSIT 2 3D View at Time=10.5 seconds	92
Figure 90. OPSIT 3 Aerial View at Time=0.....	93
Figure 91. OPSIT 3 Aerial View Time=38 seconds	93
Figure 92. OPSIT 3 Aerial View Time=38.5 seconds	94
Figure 93. OPSIT 3 Aerial View Time = 100 seconds (end of scenario)	94
Figure 94. Architectural Framework for Distributed Ship Systems (Brefort et al., 2018).....	100
Figure 95. Ship System Architectural Framework (Shane et al., 2021).....	100
Figure 96. Modified Mission-Means Framework (Purdy, 2004)	102
Figure 97. Ship Behavior and Interaction Models (SBIMs)	103
Figure 98. AAW Mission Plex Vital Components and Circled Capability Nodes with Data Commodity Flows (adapted from Friedman, 2006, p 105 and Chalfant et. al, 2017).....	103
Figure 99. Effectiveness Hierarchy.....	104
Figure 100. Kill Chain Operational Architecture.....	105
Figure 101. SBIM Execution Process	106
Figure 102. ASUW Plex (adapted from Friedman, 2006, p 105 and Chalfant et. al, 2017).....	108
Figure 103. ASW Plex (adapted from Friedman, 2006, p 105 and Chalfant et. al, 2017)	108
Figure 104. Mechanical System Plex Logical Architecture (Parsons, et al., 2020a).....	109
Figure 105. Ship System Architectural Framework (Shane et al., 2021).....	124
Figure 106. Modified Mission-Means Framework (Purdy, 2004)	124
Figure 107. Ship Behavior and Interaction Models (SBIMs)	125
Figure 108. AAW Mission Plex Vital Components and Circled Capability Nodes with Data Commodity Flows (adapted from Friedman, 2006, p 105 and Chalfant et. al, 2017).....	126
Figure 109. Effectiveness Hierarchy.....	126
Figure 110. Notional Surface Ship Total-Ship Multiplex Logical Architecture.....	128
Figure 111. Nominal PGM (Gas Turbine and Generator Set Combination) Nodal Input and Output Coefficients	129
Figure 112. Excerpt from MEL Equipment Input and Output Energy Coefficient Matrix.....	130
Figure 113. MS1 VC Energy Model.....	131
Figure 114. Condition A, AAW Plex, t = 3 seconds – ASM1 and 2 Track-Capability Response (adapted from Friedman, 2006, p 105 and Chalfant et. al, 2017)	135
Figure 115. Condition A, AAW Plex, t = 3 seconds – ASM 1 and 2 Identify-Capability Response (adapted from Friedman, 2006, p 105 and Chalfant et. al, 2017.....	135
Figure 116. Condition A, AAW Plex, t = 3 seconds, Aggregate System Response (adapted from Friedman, 2006, p 105 and Chalfant et. al, 2017).....	135
Figure 117. Condition A, ELEC Plex, t = 3 seconds, System Response	136
Figure 118. Condition A, MECH, t = 3 seconds, System Response	137
Figure 119. Condition A, CW Plex, t = 3 seconds, System Response	137
Figure 120. Condition A, AAW Plex, t = 4 seconds, Aggregate System Response (adapted from Friedman, 2006, p 105 and Chalfant et. al, 2017	138
Figure 121. Condition A, ELEC Plex, t = 4 seconds, System Response	139
Figure 122. Condition A, CW Plex, t = 4 seconds, System Response	140
Figure 123. Condition B, ELEC Plex, t = 3 seconds, System Response	141
Figure 124. Condition B, ELEC Plex, t = 4 seconds, System Response	141

Semper Fidelis
(Always Faithful)
–United States Marine Corps

Semper Fortis
(Always Courageous)
–United States Navy

Semper Paratus
(Always Ready)
–United States Coast Guard

List of Tables

Table 1: Co-authors' Contributions and Tasks (Papers 1 – 3)	4
Table 2: Co-authors' Contributions and Tasks (Papers 4 – 6)	5
Table 3. Event Probability Estimate (Mierzwicki and Brown, 2004)	16
Table 4. Event Consequence Estimate (Mierzwicki and Brown, 2004)	16
Table 5. Notional Surface Combatant Design Space for C&RE	18
Table 6. Example Network Flow Optimization Parameters (Trapp 2015)	42
Table 7. Example Network Flow Optimization Solution Parameters (Trapp 2015)	43
Table 8. Notional Surface Ship C&RE MPES Design Variable Options (Options not used are Omitted)	65
Table 9. Notional Surface Ship Representative Designs with Propulsion and Mission System Design Variable Options	66
Table 10. Notional Surface Ship Case Study Results.	69
Table 11. Capability Request Prioritization	89
Table 12. OPSIT 3 Hit table for Blue Ship	94
Table 13. Ship CM Decide Rules of Engagement	114
Table 14. OPSIT Event Log	118
Table 15. OPSIT SBIM Request and Response at $t = 3$ seconds	134

Ex Scientia Tridens
(From Knowledge, Seapower)
–United States Naval Academy

Scientiæ Cedit Mare
(The Sea Yields To Knowledge)
–United States Coast Guard Academy

Acta Non Verba
(Deeds Not Words)
–United States Merchant Marine Academy

Dissertation Introduction

Introduction

Survivability is a critical naval ship design capability. Because of its complexity and perceived requirement for detail, survivability, particularly distributed system survivability, is rarely considered until preliminary design or later except indirectly in design standards and parametric equations for weight and space. Survivability is an important factor in assessing mission effectiveness, which is an important objective attribute in concept exploration and must be considered in early ship design decisions. Once related design decisions are made, they are often very difficult to change which may be costly or limit the survivability of the as-built design. This is particularly true for distributed systems and distributed system architectures including Mission, Power, and Energy Systems (MPES).

Gaps in Concept Design MPES Literature

Survivability considers three major components: susceptibility, vulnerability and recoverability. Susceptibility considers the time before being hit and the probability of hit. Recoverability considers the time after being hit and initial damage. By its definition, vulnerability is assessed at a single point in time, $t = 0^+$, immediately following a weapon hit. Recoverability and fight-through are more difficult characteristics to assess because they consider a period of time following a weapon hit to predict the ship's ability to recover capability, to continue to fight and to achieve a stable condition. This is particularly true for distributed systems and distributed system architectures including MPES. Prior concept stage naval ship survivability research typically does not include:

- Design, analysis tools and methods that encompass the entire Architectural Framework (physical architecture, logical architecture, and operational architecture)
- Total distributed naval ship system (multisystem) modeling
- Component sizing (particularly to support new technology) methods/tools

- Scalable energy-based capability models (necessary and sufficient for concept stage-design)
- Capacity/energy/commodity-based vulnerability analysis methods/tools
- Design Reference Mission (DRM) models
- Combat system information/data flow validation
- Capability-based vulnerability analysis methods/tools
- Cascading and secondary damage analysis methods/tools
- Capability-based and time-based operational models (for total ship system)
- Capability-based and time-based operational effectiveness models
- Capability-based and time-based recoverability methods/tools
- Energy state transition analysis methods/tools
- Vulnerability in concept stage design tools

Proposed Objectives

1. Develop a simplified approach to consider survivability in concept exploration using a system network architectural framework to design MPES systems for effective function, operability, vulnerability and recoverability.
2. Work from a ship synthesis model with hullform and deckhouse definition, add primary subdivision, primary structure, locate mission-critical components, and model ship damage scenarios to assess system vulnerability.

This initial work will use a quasi-steady state AFO that determines optimum energy flows for a range of operational and damage scenarios. This will enable component sizing and $t = 0$ vulnerability analysis sufficient to make early design decisions considering air explosion (AIREX) vulnerability. The application of a network architectural framework with an AFO as a preliminary exploration to ship synthesis will have a number of significant advantages:

- Explicit sizing of all major distributed system power and energy components including piping and cable early in the design process allows a much broader range of system options and architectures to be considered that might otherwise be outside of the range of historical data-based parametrics.
- Enable early preliminary general arrangements as a “physical architecture”.
- Enable a more specific consideration and application of an “operational architecture” including operability and warfighting weapons effects.
- Enable early flow-based maintenance, reliability and availability analyses.
- Enable early vulnerability analyses.
- Enable early recoverability analyses in a Dynamic AFO.
- Enable the application of multiple constraint sets in an automated manner insuring that all results are feasible.
- Multiple combinations of design variable options will be considered and applied to better understand their total ship impact on operability and survivability.

Products of the quasi-static AFO will include a linear programming formulation of the ship MPES, an optimum system architecture and optimum sizing solution based on $t = 0+$ scenarios.

3. Continue the same AFO formulation and $t = 0+$ solution to perform a time-based recoverability analyses in an operational scenario, performing an expanded AFO after each time step to apply specified battle doctrine and load priority and to simulate a controlled system recovery potentially including the sizing and definition of required energy storage. This will be called a Dynamic AFO (DAFO). The logical architecture will be expanded to include capability, task, and mission operational sink nodes to support a discrete event design reference mission and/or a multi-time step optimization.

Manuscript Format Dissertation

This dissertation 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 this 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 six manuscripts included in this dissertation are: Paper #1: “Application of a Distributed System Architectural Framework to Naval Ship Concept and Requirements Exploration (C&RE)”, Paper #2: “Early-Stage Naval Ship Distributed System Design using Architecture Flow Optimization”, Paper #3: “Refinement of a Mission, Power, and Energy System Architecture Flow Optimization Method and Tool for Surface Ship Concept Design”, Paper #4: “Operational Architecture and Framework for Assessing Mission Effectiveness in Surface Ship Concept and Requirements Exploration”, Paper #5: “Capability Modeling for Assessing Mission Effectiveness in Surface Ship Concept and Requirements Exploration”, and Paper #6: “System Dynamic Architecture Flow Optimization to Assess Mission Effectiveness in Surface Ship Concept and Requirements Exploration.”

The first paper, “Application of a Distributed System Architectural Framework to Naval Ship Concept and Requirements Exploration (C&RE),” was published in the American Society of Naval Engineers’ (ASNE) Intelligent Ships Symposium 2019 proceedings. A revised version of this paper

was also published in ASNE's Naval Engineers Journal. The revised journal version is included in this dissertation). This paper integrates 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, "Early-Stage Naval Ship Distributed System Design using Architecture Flow Optimization," was published in the Society of Naval Architects and Marine Engineers' Journal of Ship Production and Design. This paper defines the Architecture Flow Optimization (AFO) method mentioned in first paper and presents the AFO results for a notional Large Surface Combatant (LSC) 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, "Refinement of a Mission, Power, and Energy System Architecture Flow Optimization Method and Tool for Surface Ship Concept Design," was published in ASNE's Advanced Machinery Technology Symposium 2020 proceedings. It was also resubmitted to ASNE's Naval Engineers Journal and is currently in review with revisions (the revised draft is included in this dissertation). 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.

The fourth paper, "Operational Architecture and Framework for Assessing Mission Effectiveness in Surface Ship Concept and Requirements Exploration," was published in ASNE's Virtual Intelligent Ships Symposium 2021 proceedings. This paper proposes and demonstrates a framework and surface ship Operational Architecture (OA) for assessing ship system designs using a Design Reference Mission (DRM) in naval ship C&RE. It applies a Mission

Means Framework (MMF) approach to decompose missions, tasks, and capabilities in a MPES Dynamic Architecture Flow Optimization (DAFO). Interaction with other agents in the warfighting environment is modeled as a discrete event operational simulation based on the DRM.

The fifth paper, "Capability Modeling for Assessing Mission Effectiveness in Surface Ship Concept and Requirements Exploration," will be submitted to ASNE's Combat Systems 2021. This paper describes the development and implementation of mission capability models necessary in the development of a system design framework for MPES in naval ship C&RE. The mission capability models provide a critical interface between logical and operational architectures, quantifying warfighting capabilities through system measures of performance at specific capability nodes.

The sixth paper, "System Dynamic Architecture Flow Optimization to Assess Mission Effectiveness in Surface Ship Concept and Requirements Exploration," will be submitted to ASNE's Combat Systems Symposium. This paper describes the development and implementation of a DAFO for MPES design in naval ship C&RE. The DAFO interfaces with a warfighting model, ship operational model, and mission capability models to determine optimum MPES alignment and provide capabilities over multiple time steps as required for operational effectiveness in ship operational situations (OPSITs). These Ship Behavior and Interaction Models (SBIMs) are part of a system design framework that includes architectures for ship operations, physical arrangements and the logical relationship of MPES vital energy and data components (VCs).

Coauthors' Contributions

Table 1 and Table 2 show a summary of contributions made by colleagues to these papers. Significant conceptual contributions are highlighted. Military ranks and job titles are representative of the date when an author made his final contribution to these chapters.

Co-Authors' Contributions	Mark A. Parsons	Mustafa Y. Kara	LT Kevin M. Robinson	Alan Shane	David J. Berrow	Nicholas T. Stinson	Daniel J. Snyder	David C. Woodward	Dr. Alan J. Brown
Implementing the architectural framework for distributed naval ship systems in the C&RE process and MPES design process	✓	✓	✓	✓	✓	✓	✓	✓	✓
Implementing the VT preliminary arrangements model (VTPAM) as a physical architecture	✓	✓	✓						✓
Developing the logical architectures of subsystems/plexes	✓	✓	✓				✓		✓
Energy-based power and propulsion systems	✓	✓	✓			✓			✓
Data-based combat/mission systems	✓								✓
Developing the operational architecture	✓	✓		✓					✓
Developing the AFO	✓	✓	✓			✓			✓
Modeling power and propulsion systems with an energy commodity vs. individual flow commodities	✓	✓	✓						✓
Modeling VC energy consumption and distribution with energy coefficients	✓	✓	✓						✓
Developing M-1 Subdivision Block (SDB) deactivation operating conditions		✓	✓						✓
Aggregating energy flow across operating conditions	✓	✓	✓						✓
Sizing individual VCs based on their energy flows	✓	✓	✓	✓					✓
Developing the objective function to minimize energy flow cost			✓						✓
Developing the AFO mathematical formulation	✓		✓						✓
Plotting the physical solution	✓								✓
Plotting the system response	✓								✓
Conducting the LSC AFO case study	✓	✓	✓						✓
Refining the logical architecture	✓	✓	✓						✓
Refining the physical solution	✓	✓							✓
Refining the AFO	✓	✓							✓
Developing push/pull energy flow constraints		✓							✓
Developing trace energy flows modeling cold side energy flows in fluid	✓	✓							✓
Implementing split plant power doctrine	✓								✓
Implementing slimming limits for selected VCs	✓								✓
Implementing equal flow constraints for redundant VCs	✓								✓
Refining the AFO mathematical formulation	✓	✓							✓
Conducting the surface ship C&RE and AFO case study	✓	✓							✓
Developing power and propulsion system architecture options	✓	✓							✓
Integrated power system (IPS)	✓	✓							✓
Hybrid electric drive (HED)	✓	✓							✓
Combined diesel and gas turbine (CODAG)	✓	✓							✓
Writing and Editing	✓	✓	✓						✓
Writing paper 1	✓	✓	✓						✓
Editing paper 1	✓	✓	✓			✓	✓	✓	✓
Writing paper 2	✓	✓	✓						✓
Editing paper 2	✓	✓	✓						✓
Writing paper 3	✓	✓							✓
Editing paper 3	✓	✓							✓

Table 1: Co-authors' Contributions and Tasks (Papers 1 – 3)

Co-Authors' Contributions	Mark A. Parsons	Mustafa Y. Kara	LT Kevin M. Robinson	Alan Shane	David J. Berrow	Nicholas T. Stinson	Daniel J. Snyder	David C. Woodward	Dr. Alan J. Brown
Developing the Ship Behavior and Interactions Models (SBIMs) interface	✓			✓	✓				✓
Implementing the Mission-Means Framework	✓	✓							✓
Developing the warfighting effectiveness hierarchy	✓			✓	✓				✓
Developing the discrete-event, agent-based Warfighting Model	✓			✓	✓				✓
Developing a threat class and threat library	✓			✓	✓				✓
Plotting the warfighting model				✓					✓
Developing the Ship Agent Operational Architecture	✓			✓	✓				✓
Implementing a kill chain of tasks as an operational architecture	✓			✓					✓
Prioritizing threats	✓			✓					✓
Prioritizing Capabilities	✓			✓					✓
Modeling hard kill and soft kill engagement	✓			✓	✓				✓
Modeling engagements requiring tracking/illumination	✓			✓	✓				✓
Developing the Ship Capabilities Model	✓			✓	✓				✓
Developing capability nodes to model operation sinks in the logical	✓				✓				✓
Prioritizing VCs that could respond to capability request	✓				✓				✓
Modeling measures of performance (MOPs)	✓				✓				✓
Developing a detection prioritization method	✓				✓				✓
Modeling engagement phit and pkill					✓				✓
Modeling an OPSIT event log					✓				✓
Developing the DAFO	✓	✓							✓
Modeling combat/mission systems with a data commodity	✓								✓
Modeling combat/mission system VC electric and thermal loads based on data commodity usage	✓	✓							✓
Integrating the AFO energy-based constraints	✓	✓							✓
Developing the warfighting effectiveness objective function	✓								✓
Developing the DAFO mathematical formulation	✓								✓
Writing and Editing	✓	✓		✓	✓				✓
Writing paper 4	✓			✓	✓				✓
Editing paper 4	✓	✓		✓	✓				✓
Writing paper 5	✓			✓	✓				✓
Editing paper 5	✓	✓		✓	✓				✓
Writing paper 6	✓	✓							✓
Editing paper 6	✓	✓		✓	✓				✓

Table 2: Co-authors' Contributions and Tasks (Papers 4 – 6)

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; naval ship distributed system design and total ship synthesis in concept stage ship design; operational modeling of naval ships and their

distributed systems; and naval ship system deactivation analysis using network architecture framework. The key contributions of Mark's research illuminated in this dissertation are modeling naval power and propulsion systems with an energy commodity instead of individual flow commodities, modeling naval combat and mission systems with a data commodity, modeling combat and mission system electric and thermal loads based on the data commodity usage,

developing the Ship Behavior and Interaction Models, and developing a warfighting effectiveness-based objective function to determine the energy and data commodity usage. This research was accomplished in the overall architectural framework-based Concept & Requirements Exploration and depended on the contributions from fellow researchers. He is the first author of the first, second, third, and sixth papers. He is the coordinating author of all six 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. He is a coauthor of all six papers.

LT Kevin M. Robinson, USCG, was 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. He is a coauthor of the first two papers.

Alan Shane was an Ocean Engineering Master's Degree Candidate at the Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech. He is interested in developing ship concept development and assessment tools that supports a path towards MBSE and DE in those processes. He received his M.S. and B.S. in Ocean Engineering from Virginia Tech in 2020 and 2010 respectively. He is a student member of ASNE and SNAME. He is the first author of paper four and a coauthor of papers five and six.

David J. Berrow is currently a M.S. Ocean Engineering Student of the Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech. He is employed with the Department of National Defence (Canada). He received his B.S. in Ocean Engineering and Naval Architecture from Memorial University of Newfoundland in 2011. He is the first author of paper five and a coauthor of papers four and six.

Nicholas T. Stinson was 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.

Daniel J. Snyder was a Senior Naval Architect at Fincantieri Marinette Marine. Dan received his M.S. degree from the Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech in 2019. He researched naval ship system deactivation analysis using network architecture framework with Mark Parsons and Dr. Alan Brown. He is a coauthor of the first paper.

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; naval ship system deactivation analysis using network architecture framework; and with Mustafa Kara, Kevin Robinson, Nick Stinson, Dan Snyder, Alan Shane, and David Berrow. He also serves/served as their graduate advisor. He is a coauthor of all six papers.

Dissertation Manuscripts

Parsons, M. A., Robinson, K. M., Kara, M. Y., Stinson, N. T., Snyder, D., Woodward, D., & Brown, A. J. (2020b). Application of a Distributed System Architectural Framework to Naval Ship Concept and Requirements Exploration (C&RE). *Naval Engineers Journal*, 132(4), 105–124.

<https://www.ingentaconnect.com/contentone/asn/nej/2020/00000132/00000004/art00031%0A>

Parsons, M. A., Kara, M. Y., Robinson, K. M., Stinson, N. T., & Brown, A. J. (2021). Early-Stage Naval Ship Distributed System Design Using Architecture Flow Optimization. *Journal of Ship Production and Design*, 37(02), 78–96.

<https://doi.org/10.5957/JSPD.10190058>

Parsons, M. A., Kara, M. Y., & Brown, A. J. (2020a). Refinement of a Mission, Power, and Energy System Architecture Flow Optimization Method and Tool for Surface

Ship Concept Design. ASNE Advance Machinery Technology Symposium 2020.

Shane, A., Parsons, M. A., Berrow, D. J., Kara, M. Y., & Brown, A. J. (2021). Operational Architecture and Framework for Ship Concept and Requirements Exploration. For publication: ASNE Intelligent Ships Symposium 2021.

Berrow, D. J., Parsons, M. A., Shane, A., Kara, M. Y., & Brown, A. J. (2021). Capability Modeling for Assessing Mission Effectiveness in Surface Ship Concept and Requirements Exploration. For publication: ASNE Combat Systems Symposium 2021.

Parsons, M. A., Kara, M. Y., Shane, A., Berrow, D. J., & Brown, A. J. (2021). System Dynamic Architecture Flow Optimization to Assess Mission Effectiveness in Surface Ship Concept and Requirements Exploration. For publication: ASNE Combat Systems Symposium 2021.

Viribus Mari Victoria
(Victory By Seapower)
–United States Naval War College

Praestantia Per Scientiam
(Excellence Through Knowledge)
–Naval Post Graduate School

Paper #1 – 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 architectural framework organizes a mathematical analysis to efficiently consider an unrestricted design space, to create knowledge, to encourage innovation, and support the synthesis of effective and affordable ship designs. This architectural 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
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
LO	Lube Oil Cooling System
MOGO	Multi Objective Genetic Optimization
MOP	Measure of Performance
NMETL	Navy Mission Essential Task List
OMOE	Overall Measure of Effectiveness
OMOR	Overall Measure of Risk
OpSits	Operational Situations
PSYS	Propulsion System
RM&A	Reliability/Maintainability and Availability
ROC	Required Operational Capability
RSM	Response Surface Model
S3D	Smart Ship System Design
SDB	Subdivision Block
SSM	Ship Synthesis Model
SW	Saltwater Cooling System
UNDEX	Underwater Explosion
VC	Vital Component
VOP	Value of Performance

¹ Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech

² Naval Architecture and Marine Engineering Section, US Coast Guard Academy

³ Naval Surface Warfare Center, Philadelphia Division

Introduction and Motivation

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

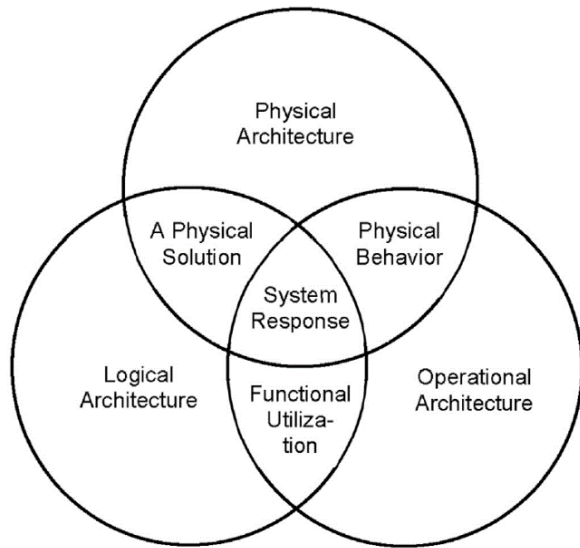


Figure 1. Representation of Architectural Framework for Ship Distributed Systems (Brefort, et al., 2018)

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 architectural 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, van Oers et al. 2012), Architecture Flow Optimization (Trapp

2015 and Robinson 2018), and the Preliminary Arrangements and Architecture Model (Brown and Sajdak 2015, Goodfriend and Brown 2018). A growing number of semi-automated design and analysis tools that specifically address ship distributed-systems are also being developed. These include the Smart Ship Systems Design (S3D/LEAPS) tool which is intended to perform high fidelity design and analysis of distributed naval systems and is being adapted for the proposed architectural framework (Chalfant 2015, Chalfant et al. 2017a, 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.

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.

Domain DOEs, RSMs and MOGOs initially use domain-specific objectives and constraints, but ultimately these are refined and expanded to overall design objectives (see Figure 5 for overall effectiveness metric) and constraints. Typically, these would include life-cycle or total ownership cost, technology risk and operational effectiveness. Indices may be used for risk and effectiveness as in an Overall Measure of Risk (OMOR) metric (Mierzwicki 2003, Mierzwicki and Brown 2004) and Overall Measure of Effectiveness (OMOE) metric (Demko 2005, Brown and Demko 2006). The OMOE may be calculated using the analytical hierarchy process, pairwise comparison and expert opinion or by war-gaming analyses in the case of a naval ship. Maintenance and logistics policy for a ship design should be considered in a RM&A (Reliability, Maintainability and Availability) analysis which is greatly facilitated by having a logical system-architecture early in the design process. A basic manning analysis should also be performed as early as possible (Scofield and Brown 2007). It is essential that maintenance and manning policy decisions are explicit in early stage design because they have a major impact on the design, particularly on space, cost and risk.

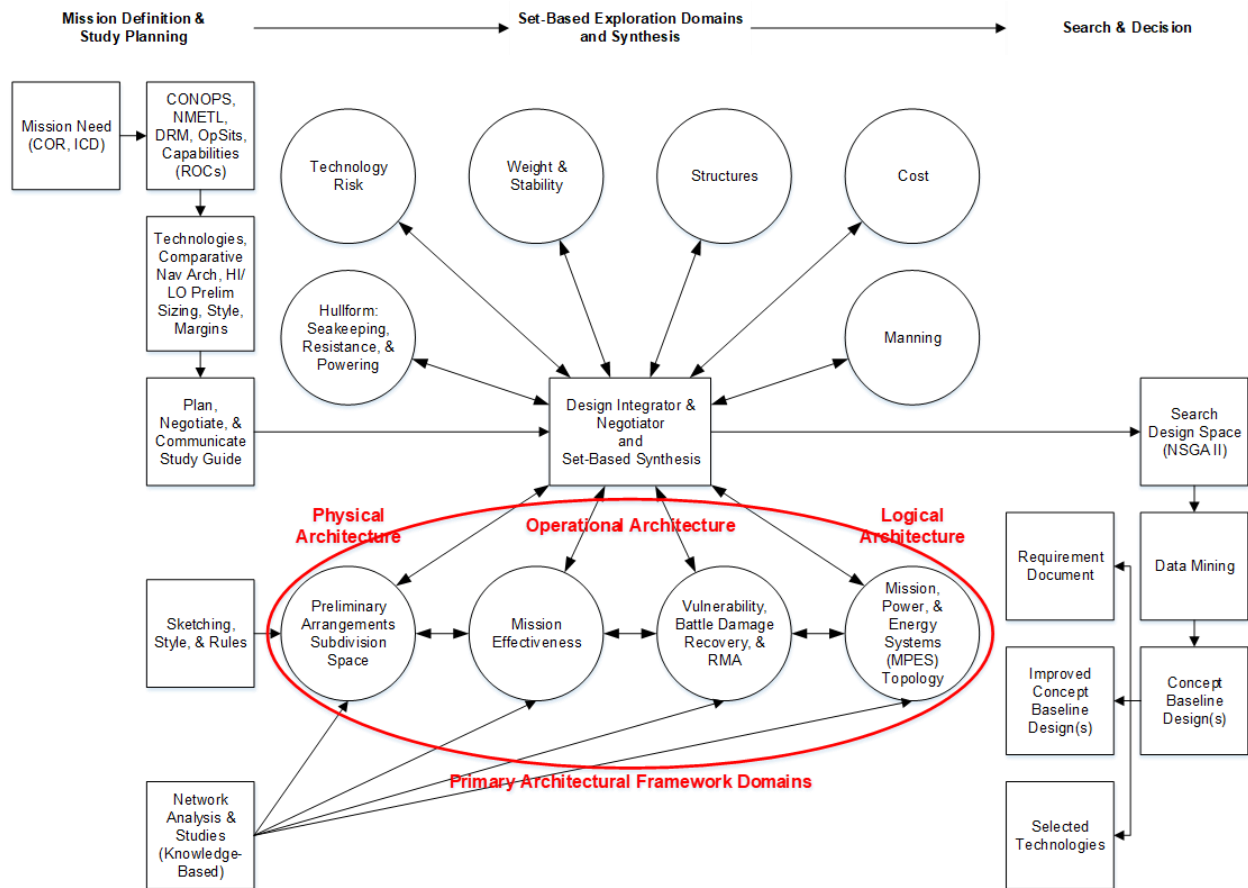


Figure 2. Naval Ship Concept and Requirements Exploration (C&RE) Process with Architectural Framework and Set-Based Domains

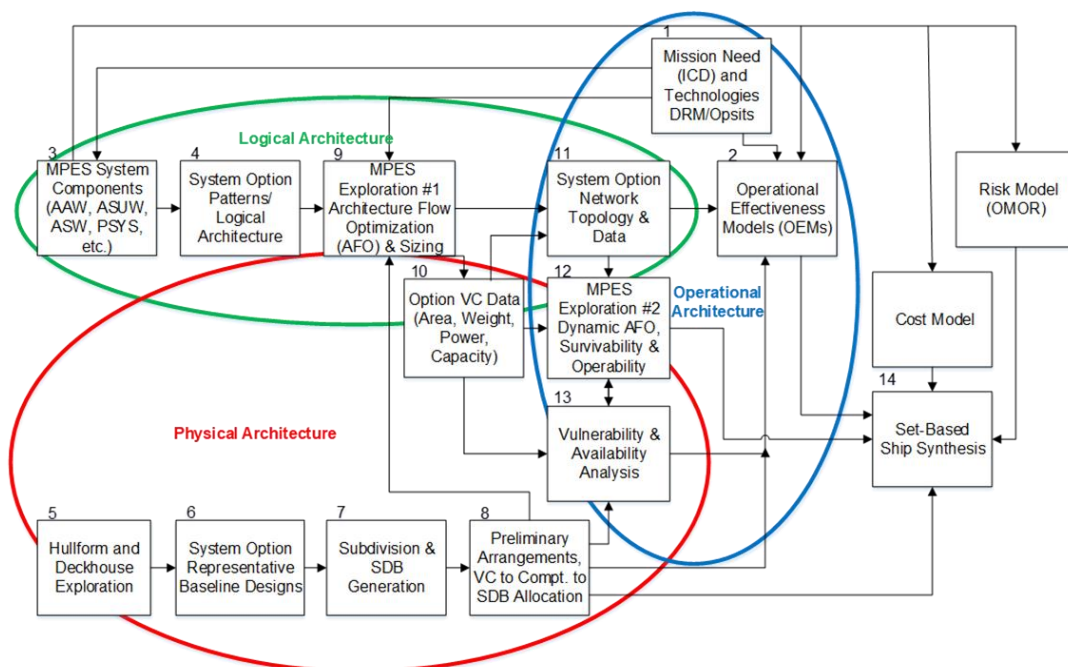


Figure 3. MPES Design Process approximately superimposed onto the architectural framework

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-axis, 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.

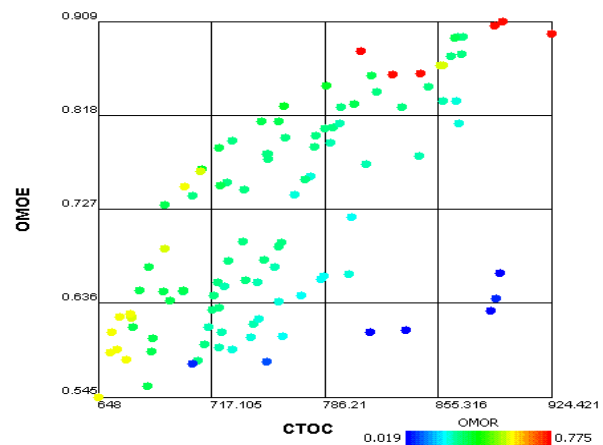


Figure 4. Ship Design Non-dominated Frontier (Brown and Sajdak 2015)

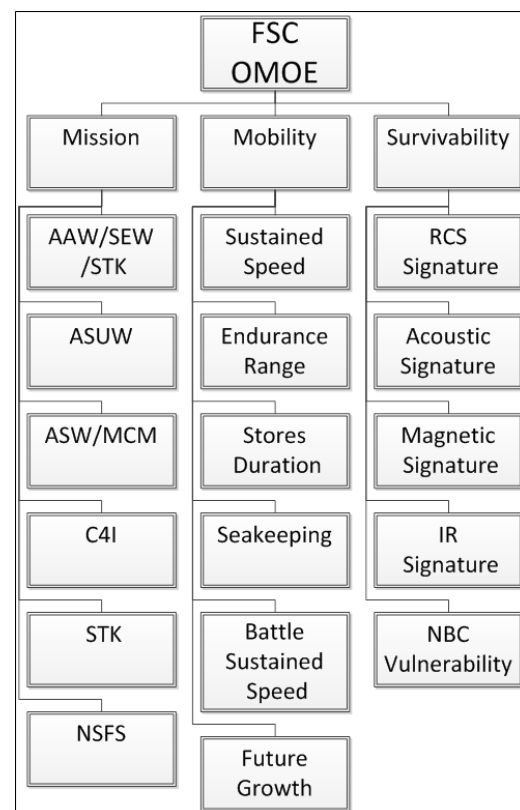


Figure 5. OMOE Hierarchy (Brown and Salcedo, 2003)

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

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

$$OMOE = \sum_i VOP_i(MOP_i)w_i \quad (1)$$

The Analytical Hierarchy Process (AHP) (Saaty 1996) and Multi-Attribute Utility Theory (Belton 1986) are two well-accepted methods for structuring these problems. These two methods may be combined to define Multi-Attribute Value Functions (VOPi), and calculate MOPi weights (wi). 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 (VOPi) 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.

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.

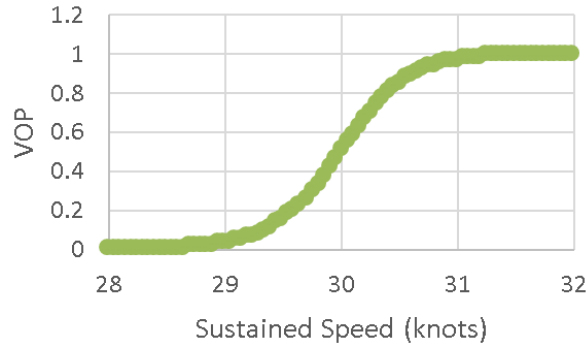


Figure 6. VOP "S" Curve, VOPi (Brown and Salcedo, 2003)

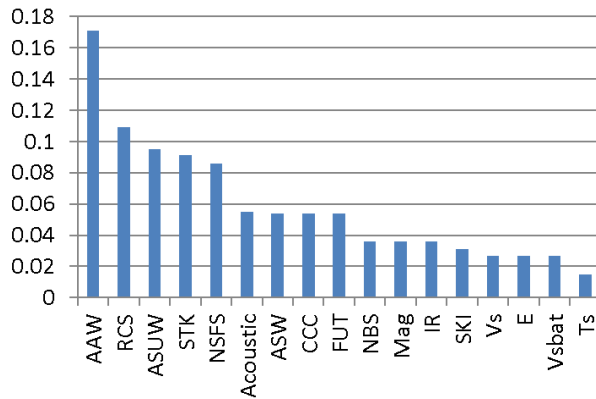


Figure 7. Notional Surface Combatant MOP Weights, w_i

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.

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, Mierzwicki and Brown 2004). Performance, cost and schedule risk must be

considered for developing technologies. An Overall Measure of Risk (OMOR) is a quantitative measure of the total risk for a specific design based on selected technologies. As with the OMOE, OMOR is a merit index with a value of 0 to 1. The risk for each technology is the product of the probability of risk event occurrence (P_i) (Table 1) and the consequence of the event (C_i) (Table 2) as calculated in Equation (2):

$$Risk = R_i = P_i * C_i \quad (2)$$

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_{perf} , W_{cost} , W_{sched}) for each risk event. Technology Readiness Levels (TRLs) may also be used to quantify OMOR. The OMOR function is assembled as shown in Equation (3).

Probability	What is the likelihood the risk even will occur?
0.1	Remote
0.3	Unlikely
0.5	Likely
0.7	Highly Likely
0.9	Near Certain

Table 3. Event Probability Estimate (Mierzwicki and Brown, 2004)

Consequence Level	Given the risk is realized, what is the magnitude of the impact?		Cost
	Performance	Schedule	
0.1	Minimal or no impact	Minimal or no impact	Minimal or no impact
0.3	Acceptable with some reduction in margin	Additional resources required; able to meet need date	< 5%
0.5	Acceptable with significant reduction in margin	Minor slip in key milestones; not able to meet need date	5-7%
0.7	Acceptable; no remaining margin	Major slip in key milestone or critical path impacted	7_10%
0.9	Unacceptable	Can't achieve key team or major program milestone	> 10%

Table 4. Event Consequence Estimate (Mierzwicki and Brown, 2004)

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

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

The third critical metric is cost. In early stage design, acquisition cost is typically estimated using weight-based or modified weight-based methods. Complexity and producibility factors consider the technology selection for a particular design, including hull, machinery and combat

system technologies and various producibility metrics such as deck height, outfit density and maintenance clearances (Brown and Barentine 1996).

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

Figure 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.

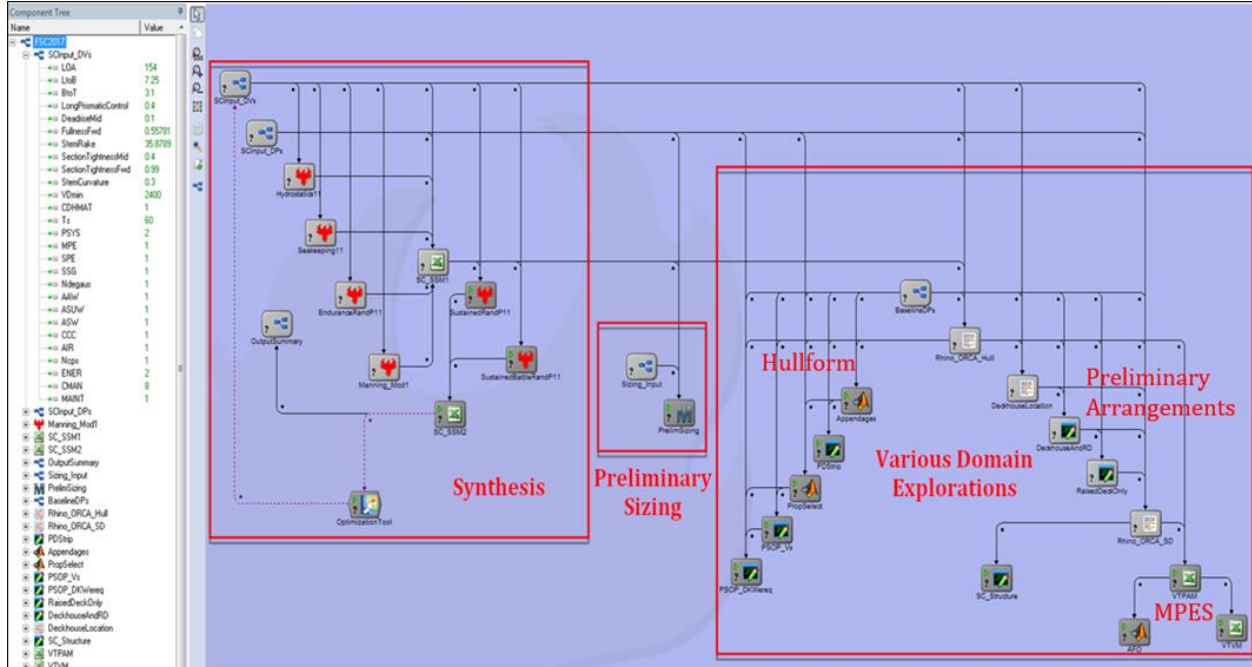


Figure 8. Exploration and Ship Synthesis Model (E&SSM) in Model Center (MC) – tools used to implement the C&RE Process

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

Table 5. Notional Surface Combatant Design Space for C&RE

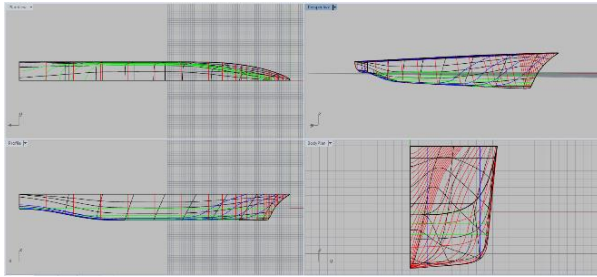


Figure 9. ORCA3D Hullform in Rhino

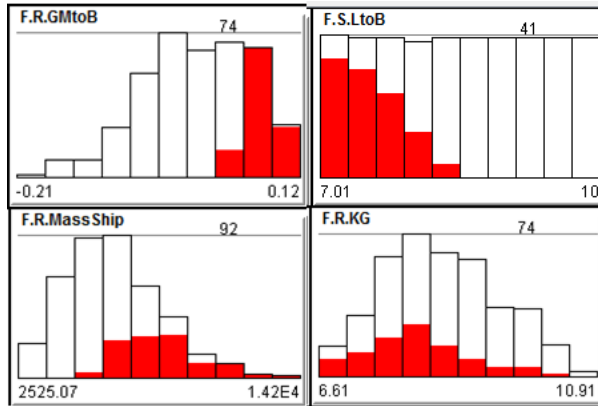


Figure 10. Initial DOE Result Histograms with GM/B > 0.05 Constraint (in red)

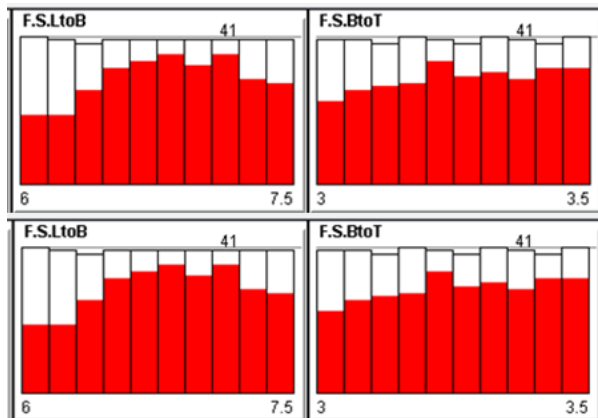


Figure 11. Final DOE Result Histograms (feasible in red)

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).

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 $GM/B > .05$ 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.

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

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:

- 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.
- 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.
- The number of plexus included in the multiplex model is much larger and essentially unlimited.
- 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.

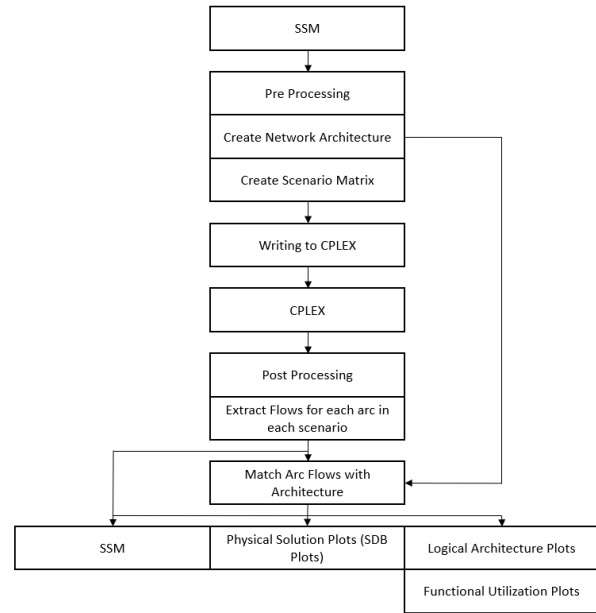


Figure 12. AFO Execution Process

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.

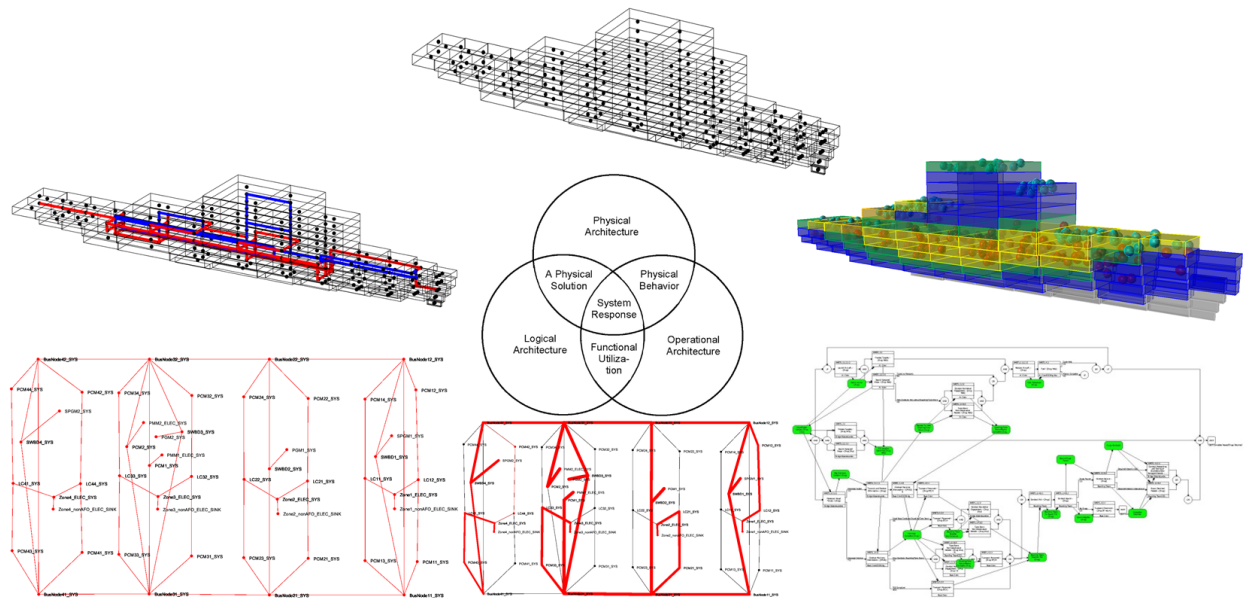


Figure 13. Notional (Network-Based) Architectural Framework Implementation in C&RE

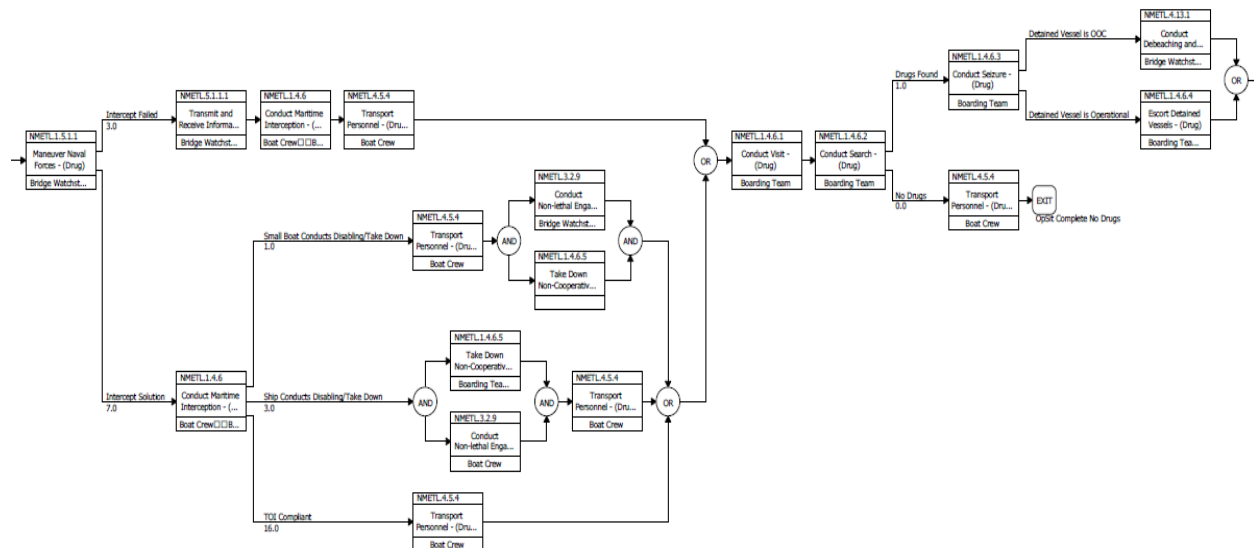


Figure 14. Drug Interdiction Event Tree (Kerns et al. 2011b)

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 and Kerns 2010, Kerns et al. 2011a, Kerns et al. 2011b, Brown 2013).

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 5. 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.

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 15. Mechanical (Propulsion) Subsystem (MECH)

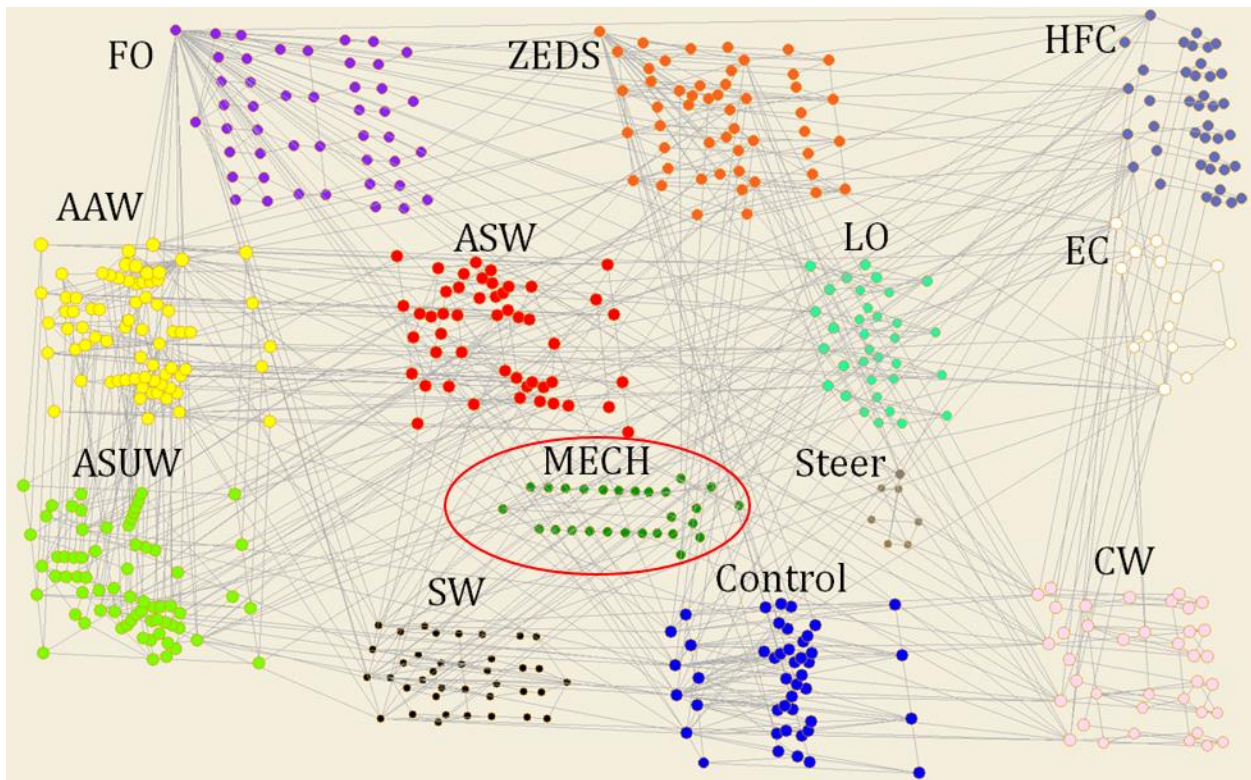


Figure 16. Notional Total-Ship System Architecture

A number of different ship design approaches exist for developing the constraining ship physical architecture: Design Building Blocks (Pawling 2007, Andrews et al. 2012), Bin-Packing (van Oers et al. 2010, van Oers 2011, Duchateau 2016), Intelligent Ship Arrangements (Parsons et al. 2008), Subdivision Block (SDB) Compartment Allocation (Brown and Sajdak 2015, Goodfriend and Brown 2018) and nodal or network representations (Gillespie et al. 2012, Gillespie et al. 2013, Gillespie and Singer 2013). Some of these approaches work from the inside-out (blocks

The top diagram, labeled "Isometric View", shows a 3D perspective of a hull structure. It consists of a series of rectangular blocks arranged in a stepped fashion, representing the hull's profile. Arrows point to the "Hull Extent" at various points along the structure. A small coordinate system with x and y axes is shown in the bottom left corner.

The bottom diagram, labeled "Profile View", shows a 2D side view of the same hull structure. It is a stepped profile of rectangular blocks. Arrows point to the "Deck" at the top edges and the "Watertight Bulkhead" at the vertical interfaces between sections. A small coordinate system with x and y axes is shown in the bottom left corner.

Figure 1 is a dot plot showing the number of cases by age group and sex. The x-axis represents age groups from 0 to 90, and the y-axis represents the number of cases from 0 to 35. The plot shows a distribution of cases across age groups, with a peak in the 40-49 age group.

[illegible]

24

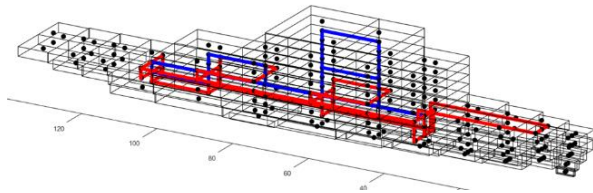


Figure 20. Routing of Distributed Systems (Red = electric, Blue = chilled water)

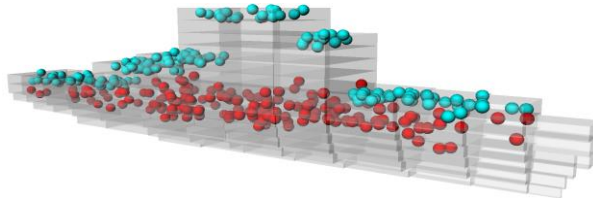


Figure 21. Weapon Hit Locations (Goodfriend and Brown, 2018)

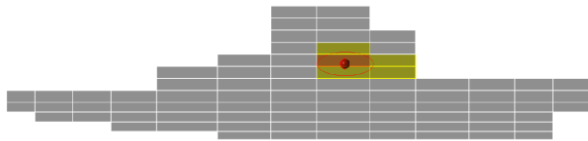


Figure 22. Damage Ellipsoid Interactions with SDBs (Stark, 2016)

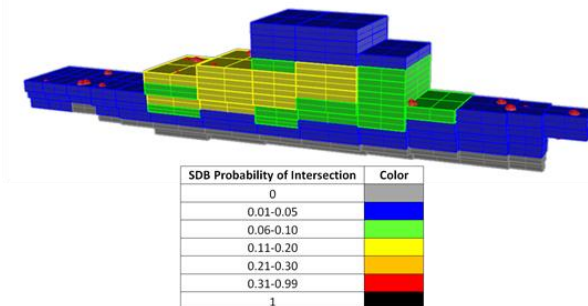


Figure 23. SDB Hit Probabilities (Goodfriend and Brown, 2018)

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.

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). Both methods are used in the 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 10, 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.

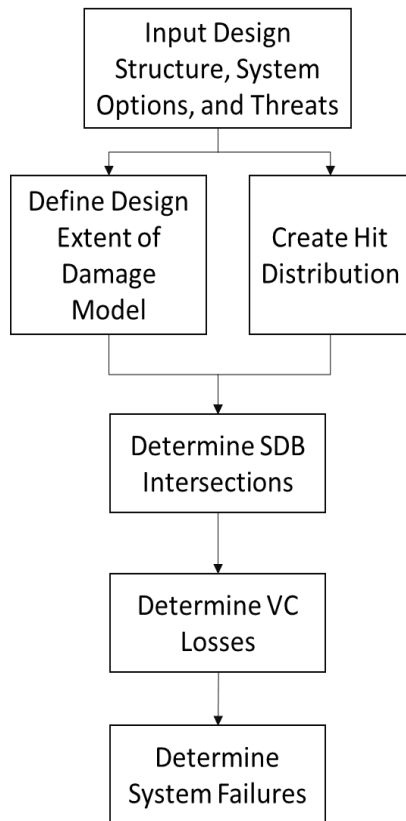


Figure 24. System Damage Response Intersection Process

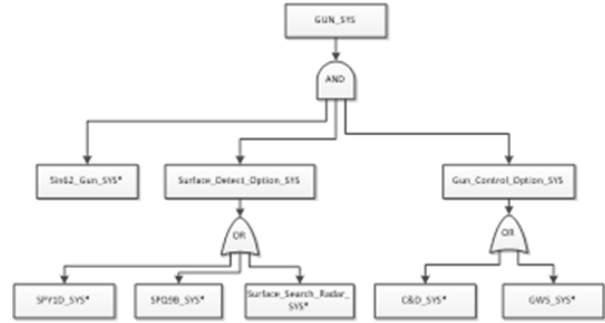


Figure 25. Gun System DBD (Goodfriend and Brown, 2018)

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 and Brown 2018). This data is stored and can be recalled for use in OEMs and to calculate the OMOE during ship synthesis. The reliability analysis calculates system availability and is also used in OEMs and to calculate the OMOE.

Once system components are sized and the architecture optimized in the first 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.

Acknowledgements

The authors would like to thank Ms. Kelly Cooper, ONR Code 331; Mr. David Woodward, NSWCPD; and the US Navy Naval Engineering Educational Consortium (NEEC) for supporting this effort. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the sponsors.

Author Biographies

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. He researches networked-based methods to assess naval ship distributed system vulnerability, survivability, and battle damage recovery in concept stage ship

design. He received a B.S. in Naval Architecture and Marine Engineering from the University of New Orleans in 2016. He is a Student Member of ASNE and SNAME.

Kevin M. Robinson, LT USCG, is currently a rotating instructor at the US Coast Guard Academy; Naval Architecture and Marine

Engineering section. As a Naval Engineer in the US Coast Guard, he has supported the patrol boat fleet as a depot level project manager and served over four years onboard cutters performing counter drug, living marine resource protection and humanitarian operations. He received his B.S. in Naval Architecture and Marine Engineering from the US Coast Guard Academy in 2009 and his M.S. in Ocean Engineering from Virginia Tech in 2018.

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. He received his B.S. in Naval Architecture and Marine Engineering from the Turkish Naval Academy in 2006. He received his S.M. in Naval Architecture and Marine Engineering from MIT in 2010. He is a student member of ASME and SNAME and alumni of MIT (Educational Counselor)

Nicholas T. Stinson, is currently a naval architect with the Brunswick Corporation. His work focuses on designing, testing, and certifying all new products for the Bayliner, Heyday, Quicksilver, and Uttern boat brands. He received his B.S. and M.S. degrees from Virginia Tech in Ocean Engineering where his research focused on naval ship synthesis.

Daniel J. Snyder, Is currently a Senior Naval Architect at Fincantieri Marinette Marine. He

currently performs hydrodynamic analysis for naval combatant concept design and has contributed to the development of ship design and analysis software tools for the marine industry. He received his M.S. in Ocean Engineering in 2019 from Virginia Tech.

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).

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 Webb Medal for Outstanding Contributions to NA&ME Education. 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.

References

- Andrews, D., "Choosing the Style of a New Design – The Key Ship Design Decision," *Transactions RINA, International J. Maritime Eng.*, 160 - Part A1, DOI No: 10.3940/rina.ijme.2018.a1.457, 2018.
- Andrews, D., Pawling, R., Gillespie, J. W., Singer, D. J., Duchateau, E. and Hopman, H., "State of the Art Report: Design for Layout," *Proceedings of the 11th International Marine Design Conference*, Glasgow, Scotland, June 2012.
- Ashish, G., "Chapter 5 Network Flows," http://web.stanford.edu/~ashishg/msandde111/notes/chapter_5, 2008a.
- Ashish, G. "Chapter 3 Linear Programs," http://web.stanford.edu/~ashishg/msandde111/notes/chapter_3, 2008b.
- Belton, V., "A comparison of the analytic hierarchy process and a simple multi-attribute value function", *European Journal of Operational Research*, 1986.
- Brefort, D., C. Shields, A. Habben, E. Duchateau, R. Pawling, K. Droste, T. Jasper, M. Synniewski, C. Goodrum, M. A. Parsons, M. Kara, M. Roth, D. J. Singer, D. Andrews, H. Hopman, A. J. Brown and A. Kana, "An architectural framework for distributed naval ship systems," *Ocean Engineering*, 147: 375–385, 2018.

- Brown, A.J., "Ship and Marine Engineering System Concept Design", Chapter 1, *Marine Engineering*, 4th ed., M. G. Parsons (ed.), Alexandria VA, Society of Naval Architects and Marine Engineers (SNAME), expected publication 2020.
- Brown, A.J., S. Brizzolara and S. Choi, "Set-Based Design Framework for Naval Ship Concept Exploration with Tight Integration of High-Fidelity Physics-Based Simulations," ASNE Set-Based Design Symposia, Washington DC, Sept., 2017.
- Brown, A.J., Sajdak, J., "Still Re-Engineering the Naval Ship Concept Design Process", *Naval Engineers Journal*, Vol 127, No 1, March 2015.
- Brown, A.J., "Application of Operational Effectiveness Models in Naval Ship Concept Exploration and Design," *Ship Science and Technology*, Vol. 7, No. 13, pgs. 9-21, July 2013.
- Brown, A.J. and C. Kerns, "Multi-Objective Optimization in Naval Ship Concept Design," *Marine Systems and Technology (MAST)* 2010 Conference, Rome, Italy, 9-11 November, 2010.
- Brown, A.J. and Demko, D., "Application and Validation of an Overall Measure of Effectiveness for Multi-Objective Optimization in Naval Ship Design", paper to be presented at Ships and Ship Systems (S3) Technology Symposium, NSWC Carderock, September, 2006.
- Brown, A.J., Salcedo, J., "Multiple Objective Genetic Optimization In Naval Ship Design", *Naval Engineers Journal*, Vol. 115, No. 4, pp. 49-61, 2003.
- Brown, A.J., Thomas, M., "Reengineering the Naval Ship Concept Design Process", From Research to Reality in Ship Systems Engineering Symposium, ASNE, 1998.
- Brown, A.J., Barentine, J., "The Impact of Producibility on Cost and Performance in Naval Combatant Design", paper presented to NE Section of SNAME, November, 1996.
- Chalfant, J., C. Chrysosostomidis, D. Snyder, M. A. Parsons and A. J. Brown, "Graph Theory Applications in FOCUS-compliant Ship Designs," IEEE Electric Ship Technologies Symposium, IEEE ESTS 2017, Arlington, VA, August, 2017a.
- Chalfant, J., B. Langland, D. Rigterink, C. Sarles, P. McCauley, D. Woodward, A. J. Brown and R. Ames, "Smart Ship System Design (S3D) Integration with the Leading Edge Architecture for Prototyping Systems (LEAPS)," IEEE Electric Ship Technologies Symposium, IEEE ESTS 2017, Arlington, VA, August, 2017b.
- Chalfant, J., "Early-Stage Design for Electric Ship," *Proceedings of the IEEE*, 103-12: 2252–2266, 2015.
- Cramer, A.M., Chen, H. and Zivi, E.L., "Shipboard electrical system modeling for early-stage design space exploration," in IEEE Electric Ship Technologies Symp., Arlington, VA 2013.
- Chinneck, J. W., "Practical Optimization: A Gentle Introduction", 2017.
- Demko, D., "Tools for Multi-Objective and Multi-Disciplinary Optimization in Naval Ship Design", MS Thesis, Virginia Tech, May 2005.
- de Vos, P., Stapersma, D., Duchateau, E.A.E., van Oers, B.J., *Design Space Exploration for on-board Energy Distribution Systems - A New Case Study*, Proc. of 17th Conference on Computer and IT Applications in the Maritime Industries (COMPIT), TUHH, Pavone, Italy, ISBN 978-3-89220-707-8, 2018.
- Duchateau, E., "Interactive Evolutionary Concept Exploration in Preliminary Ship Design," PhD Dissertation, Delft University of Technology, The Netherlands, 2016.
- Gillespie, J. and D. J. Singer, "Identifying drivers of general arrangements through the use of network measures of centrality and hierarchy," *Ocean Engineering*, 57: 230–239, 2013.
- Gillespie, J. W., A. S. Daniels and D. J. Singer, "Generating functional complex-based ship arrangements using network partitioning and community preferences," *Ocean Engineering*, 72: 107–115, 2013.
- Gillespie, J.W., A. S. Daniels and D. J. Singer, "Approaching Ship Arrangements from a Non-spatial Point of View using Network Theory," *Proceedings of the 11th International Marine Design Conference*. Glasgow, Scotland, 2012.
- Goodfriend, D. and A. J. Brown, "Exploration of System Vulnerability in Naval Ship Concept Design," *Journal of Ship Production and*

- Design*, 34-1: 42-58.
<http://dx.doi.org/10.5957/JSPD.33.3.160006>, 2018.
- IBM, *IBM ILOG CPLEX Optimization Studio CPLEX User's Manual Version 12 Release 6*. USA: International Business machines Corp, 2014.
- Kerns, C., A. J. Brown and D. Woodward, "Application of a DoDAF Total-Ship System Architecture in Building Naval Ship Operational Effectiveness Models," MAST Americas 2011, Washington DC, November 2011a.
- Kerns, C., A. J. Brown and D. Woodward, "Application of a DoDAF Total-Ship System Architecture in Building a Design Reference Mission for Assessing Naval Ship Operational Effectiveness," ASNE Global Deterrence and Defense Symposium 2011, Bloomington, IN, Sept. 2011b.
- Konak, A. and A. E. Smith, "Network Reliability Optimization," In *Handbook of Optimization in Telecommunications*, by M. G. C. Pardalos and P. Resende, 735-760. Springer Verlag, USA. Accessed 04 15, 2018.
- McDonald, T., "A Library Based Approach for Exploring Style in Preliminary Ship Design," University College London, 2009.
- Mierzwicki, T., Brown, A.J., "Risk Metric for Multi-Objective Design of Naval Ships", *Naval Engineers Journal*, Vol. 116, No. 2, pp. 55-71, 2004.
- Mierzwicki, T., "Risk Index for Multi-objective Design Optimization of Naval Ships", MS Thesis, Department of Aerospace and Ocean Engineering, Virginia Tech, 2003.
- Parsons, M. G., H. Chung, E. Nick, A. S. Daniels, S. Liu and J. Patel, "Intelligent Ship Arrangements (ISA): a New Approach to General Arrangement," *Naval Engineers Journal*, 120-3: 51-65, 2008.
- Pawling, R., Piperakis, A., Andrews, D., "Developing Architecturally Oriented Concept Ship Design Tools for Research and Education," *Proceedings of the 12th International Marine Design Conference*, Vol. 2, 2015.
- Pawling, R., "The Application of the Design Building Block Approach to Innovative Ship Design," University College London, 2007.
- Phoenix Integration, Model Center, Version 12.0, 2017.
- Robinson, K., "Modeling Distributed Naval Ship Systems using Architecture Flow Optimization," MS Thesis, Ocean Engineering, Virginia Tech, 2018.
- Saaty, T.L., *The Analytic Hierarchy Process*, RWS Publications, Pittsburgh, 1996.
- Scofield, T., Brown, A.J., "Manning and Automation Model for Naval Ship Analysis and Optimization", ASNE Human Systems Integration Symposium, Philadelphia, PA, March 2007.
- Singer, D. J., N. Doerry and M. E. Buckley, "What is Set-Based Design?" *Naval Engineers Journal*, 121-4: 31-43, 2009.
- Singer, D. J., "A Hybrid Agent Approach for Set-Based Conceptual Ship Design through the use of a Fuzzy Logic Agent to Facilitate Communications and Negotiation," PhD Dissertation, University of Michigan, 2003.
- Stark, Sean A., "Definition of Damage Volumes for the Rapid Prediction of Ship Vulnerability to AIREX Weapon Effects," M.S. Thesis, Virginia Polytechnic Institute and State University, 2016.
- Stepanchick, J., Brown, A.J., "Revisiting DDGX/DDG-51 Concept Exploration", *Naval Engineers Journal*, Vol. 119, No. 3, 67-88, 2007.
- Strock, J., Brown, A.J., "Methods for Naval Ship Concept and Propulsion System Technology Exploration in a CGX Case Study", *Naval Engineers Journal*, Vol. 120, No. 4, pp. 95-122, 2008.
- Trapp, T., "Shipboard Integrated Engineering Plant Survivable Network Optimization," Ph.D. Disseratation, Massachusetts Institute of Technology, 2015.
- van Oers, B., G. van Ingen and D. Stapersma, "An integrated approach to design, route and evaluation of resilient ship service systems," in *International Naval Engineering Conference and Exhibition (INEC)*. Edinburgh, Scotland, 2012.
- van Oers, B., "A Packing Approach for the Early Stage Design of Service Vessels," PhD Dissertation, Delft University of Technology, The Netherlands, 2011.
- van Oers, B. J., D. Stapersma and J. J. Hopman, "A 3D Packing Approach for the Early Stage

Configuration Design of Ships," *Proceedings* of the 10th International Naval Engineering Conference. Portsmouth, United Kingdom, 2010.

Winyall, D., Edwards, J., Brown, A.J., "3D Hullform Modeling to Support Naval Ship Design Synthesis and Multi-Objective Optimization," International Ship Design Conference (ISDC), Glasgow, Scotland, 2012.

Seapower Through Engineering
–U.S. Navy Engineering Duty Officers

Paper #2 – Early-Stage Naval Ship Distributed System Design using Architecture Flow Optimization

Mark A. Parsons (SM)¹, Mustafa Y. Kara (SM)¹, Kevin M. Robinson (AM)², Nicholas T. Stinson (AM)¹, and Alan J. Brown (FL)¹

Abstract

This article 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 interdependencies. Figure 26

¹ Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech

² Naval Architecture and Marine Engineering Section, US Coast Guard Academy

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.

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

An important element of the C&RE Process is the 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.

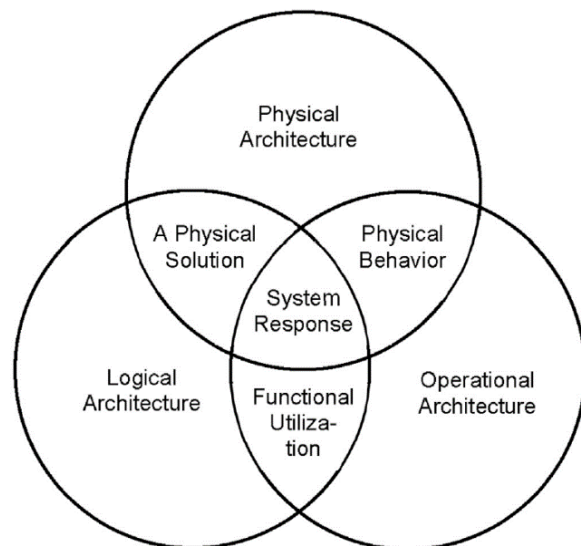


Figure 26. Architectural Framework for Ship Distributed Systems (Brefort et al. 2018)

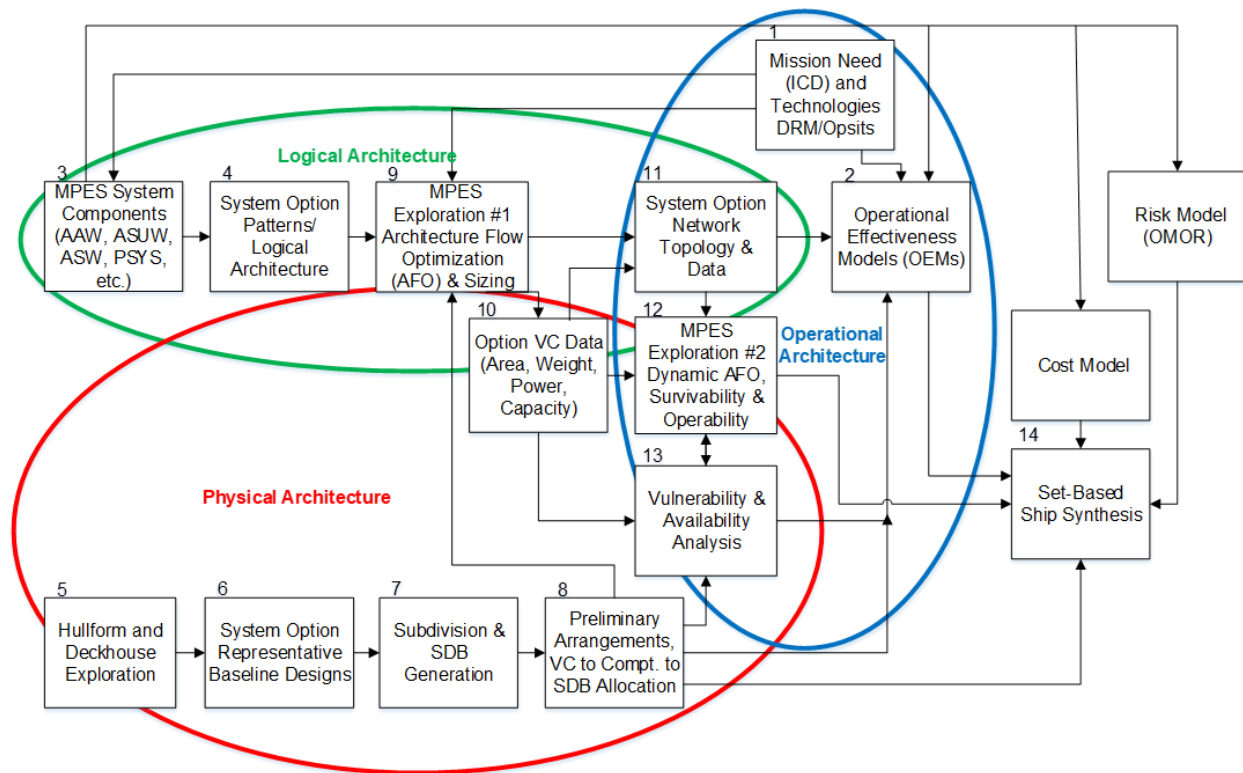


Figure 27. Mission, Power, & Energy Systems (MPES) Design Process approximately superimposed with the Architectural Framework (Parsons et. al 2019)

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 plexes (or subsystems) 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)

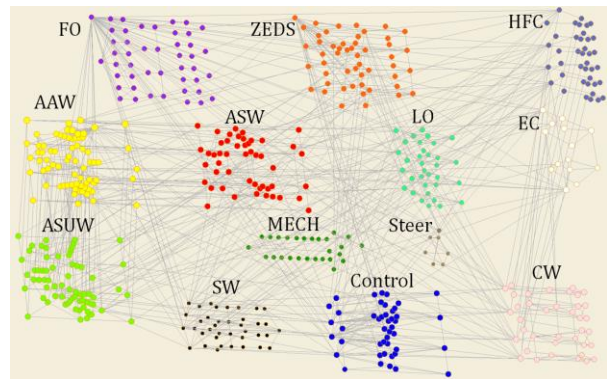


Figure 28. Notional Future Surface Combatant Total-Ship Multiplex Logical Architecture

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

Figure 29. Excerpt of Vital Components, Their Compartment Assignments, and Their Implicit Arcs

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.

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

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

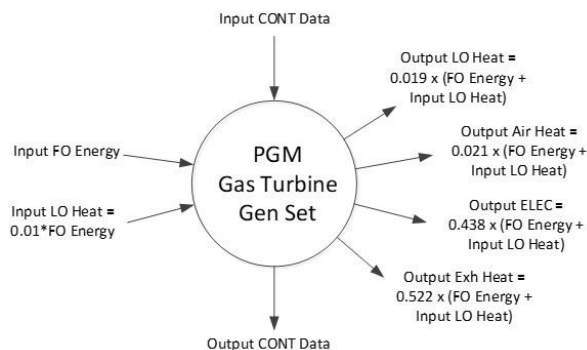


Figure 31. Nominal Power Generation Module (Gas Turbine and Generator Set Combination) Nodal Input and Output Coefficients

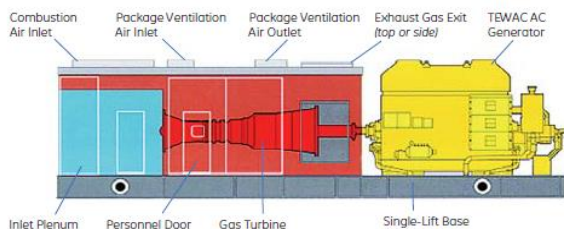


Figure 32. PGM - Gas Turbine Generator Set (Doerry & Amy 2016)

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).

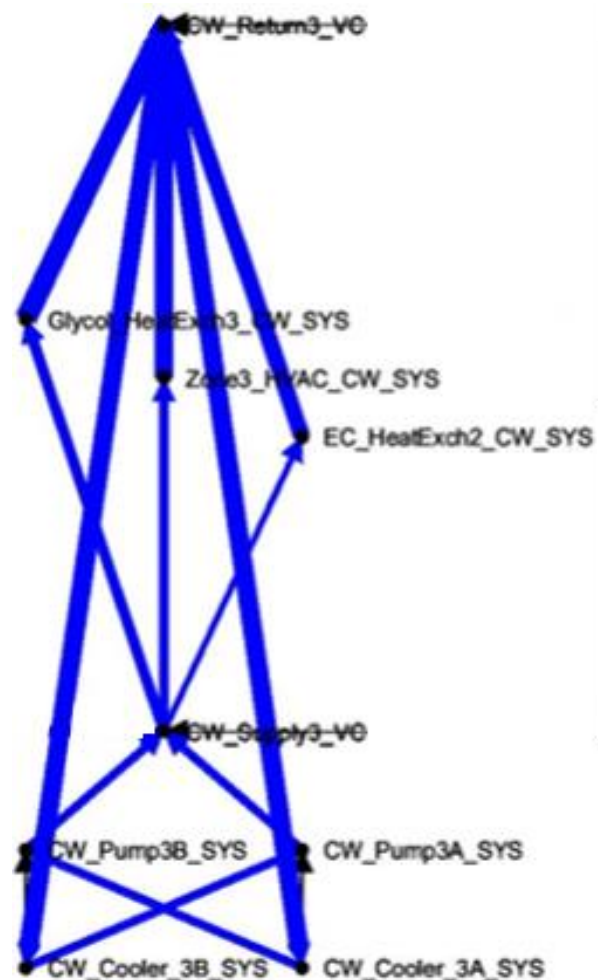


Figure 33. Zone 3 CW Loop

Conservation of energy is enforced at all nodes in the multiplex except nodes identified as sources or sinks. The source nodes are: FO_SOURCE (FO plex), ExtAir_SOURCE

(HVAC plex), and SW_SOURCE (SW plex). The sink nodes are Propulsion_SYS (MECH plex), ExtAir_SINK (HVAC plex), and SW_SINK (SW plex). These nodes act as interfaces to the environment, providing commodities (air and saltwater) and accepting waste heat carried by commodities (exhaust and warm saltwater). The FO_SOURCE node receives fuel from the ship's fuel oil storage tanks and the Propulsion_SYS node transfers energy to the ocean through the propellers as the ship moves through the water.

Physical Architecture and Physical Solution

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

The VCs of logical architecture plexes are assigned to compartments (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.

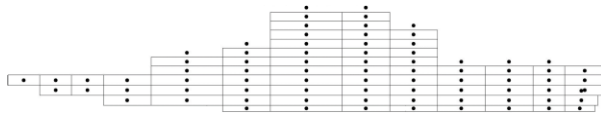


Figure 34. AFO's Nodal Description of SDBs (Physical Architecture)

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.

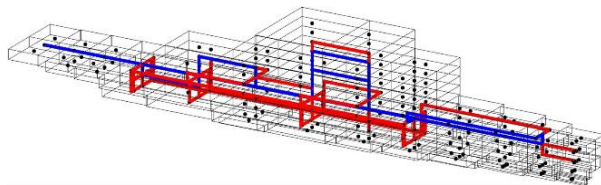


Figure 35. ELEC and CW plexes (red and blue respectively) Physical Solution

If two VCs connected by an arc are located in different SDBs, then the arcs are visible in the physical solution. The current routing of these arcs is accomplished by a simple algorithm modeling the forward/aft, transverse, and vertical distances between VCs as straight paths while remaining within the hullform and deckhouse. These straight path distances serve as the arc length used in the next section. Arcs that start and end in same SDB use a standard minimum arc length dependent on the plex. 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.

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.

These 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_b) is a nodal parameter and a parameter with two subscripts (e.g., $A_{b,c}$) is an arc parameter. The following parameters are used in the formulation:

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

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

$$(i, n) \in A = (i, j) \in A \quad \forall j = n \quad (4)$$

$$(n, j) \in A = (i, j) \in A \quad \forall i = n \quad (5)$$

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

$$\sum_{(i,j) \in A} (\Pi_{i,j} B_{i,j} + \pi_{i,j} x_{i,j}) \quad (6)$$

Subject to:

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

$$x_{i,j}^s \geq 0 \quad (7)$$

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

$$e_n^s \geq \sum_{(n,j) \in A} x_{n,j}^s \quad (8)$$

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

$$e_n^s \geq \sum_{(i,n) \in A} x_{i,n}^s \quad (9)$$

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:

$$x_{i,n}^s = \begin{cases} 0 & \text{if } b_{i,n}^s = 0 \\ x_{i,n}^s & \text{if } b_{i,n}^s = 1 \end{cases} \quad (10)$$

$$x_{n,j}^s = \begin{cases} 0 & \text{if } b_{n,j}^s = 0 \\ x_{n,j}^s & \text{if } b_{n,j}^s = 1 \end{cases} \quad (11)$$

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:

$$b_{i,j}^s = \begin{cases} 0, & \text{if the edge is deactivated} \\ 1, & \text{if the edge available} \end{cases} \quad (12)$$

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:

$$x_{m,n}^s = e_n^s \quad (13)$$

$$x_{n,o}^s = e_n^s \quad (14)$$

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:

$$x_{i,n}^s = C_n^{p(i)}(x_{m,n}^s) \quad (15)$$

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

$$x_{n,j}^s = C_n^{p(j)} \sum_{(i,n) \in A} x_{i,j}^s \quad (16)$$

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

$$\sum_{(i,n) \in A} x_{i,j}^s - \sum_{(n,j) \in A} x_{i,j}^s - e_n^s = 0 \quad (17)$$

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:

$$x_{i,j} = \max_{s \in S} (x_{i,j}^s) \quad (18)$$

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:

$$B_{i,j} = \begin{cases} 0, & \text{if } x_{i,j} = 0 \\ 1, & \text{if } x_{i,j} > 0 \end{cases} \quad (19)$$

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.

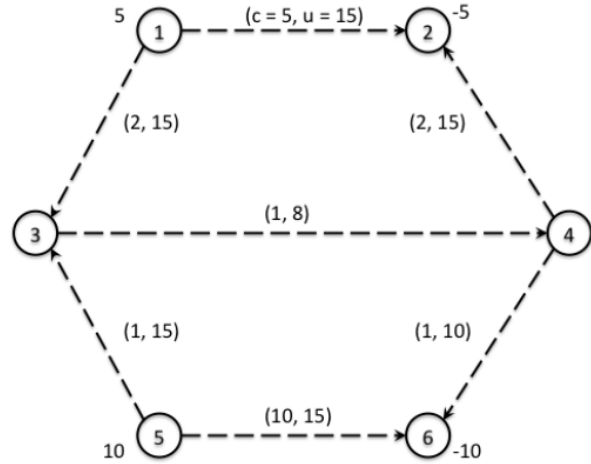


Figure 36. Example Network Flow Optimization Network (Trapp 2015)

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

Table 6. Example Network Flow Optimization Parameters (Trapp 2015)

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 6. Each arc

has a direction, flow cost per unit flow, and an upper capacity limit.

Figure 37 and Table 7 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.

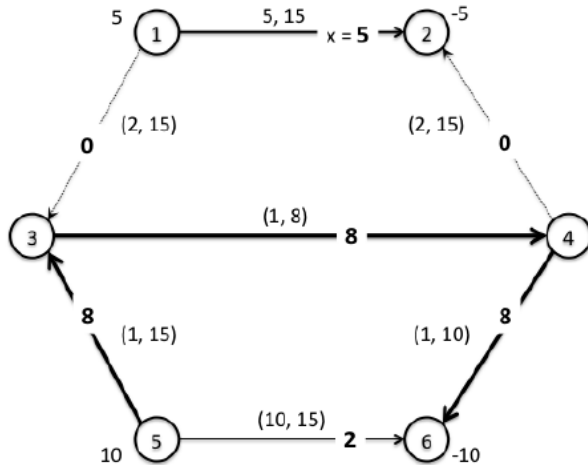


Figure 37. Example Network Flow Optimization Solution (Trapp 2015)

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

Table 7. Example Network Flow Optimization Solution Parameters (Trapp 2015)

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 38 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.

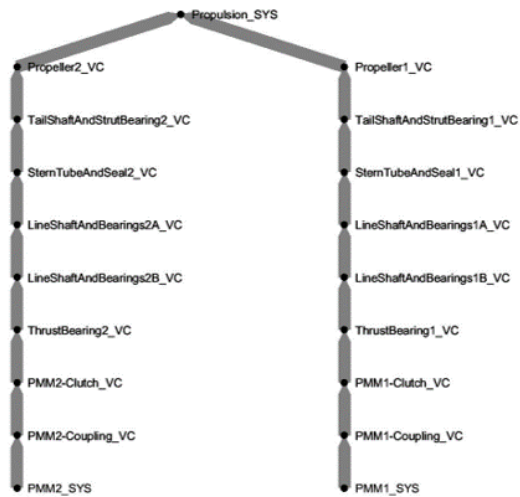


Figure 38. MECH Plex Endurance System Response

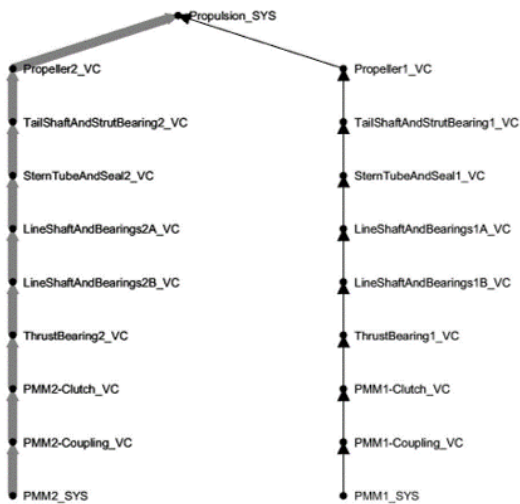


Figure 39. MECH Plex Damaged MMR2 Lower System Response

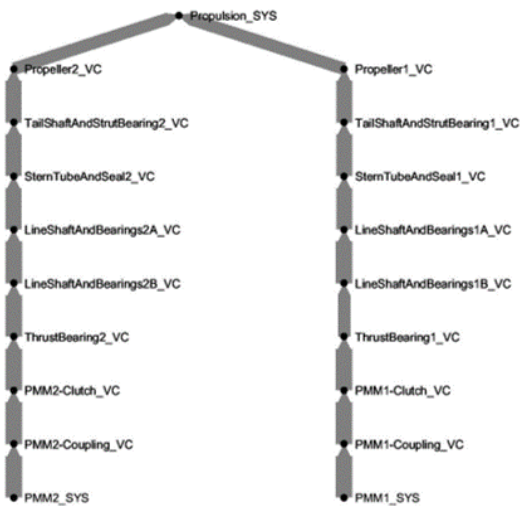


Figure 40. MECH Plex Aggregate System Response

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.

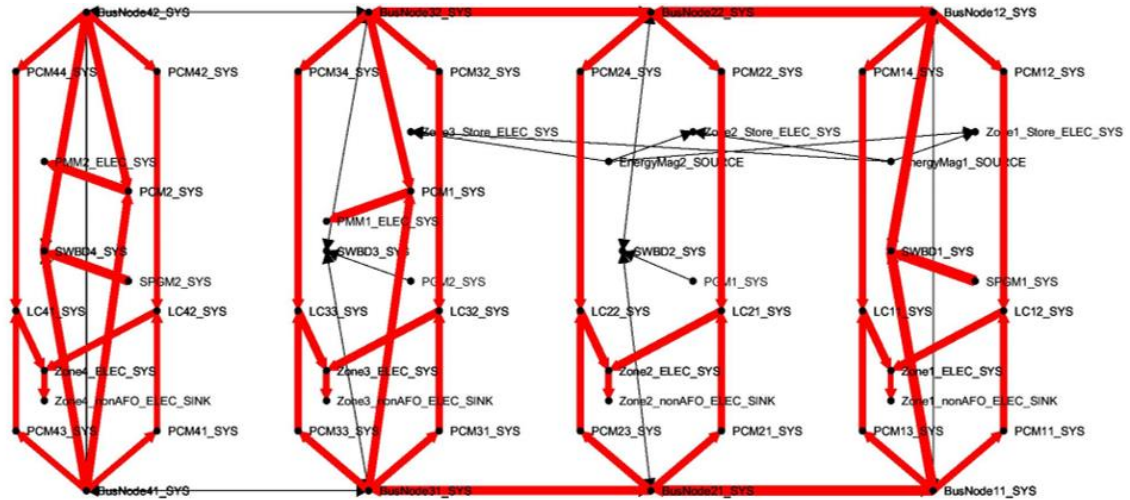


Figure 41. ELEC Plex Endurance System Response

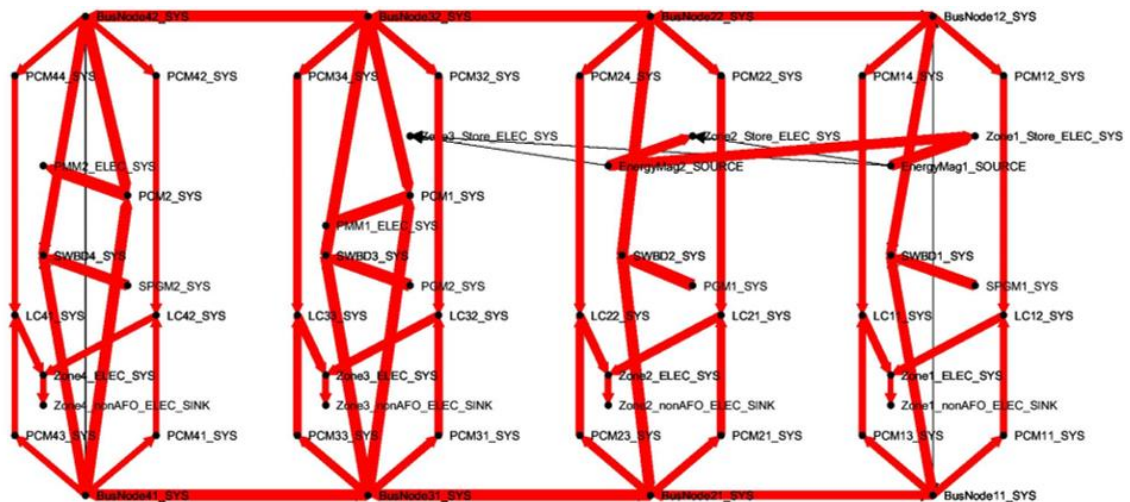


Figure 42. ELEC Plex Battle System Response

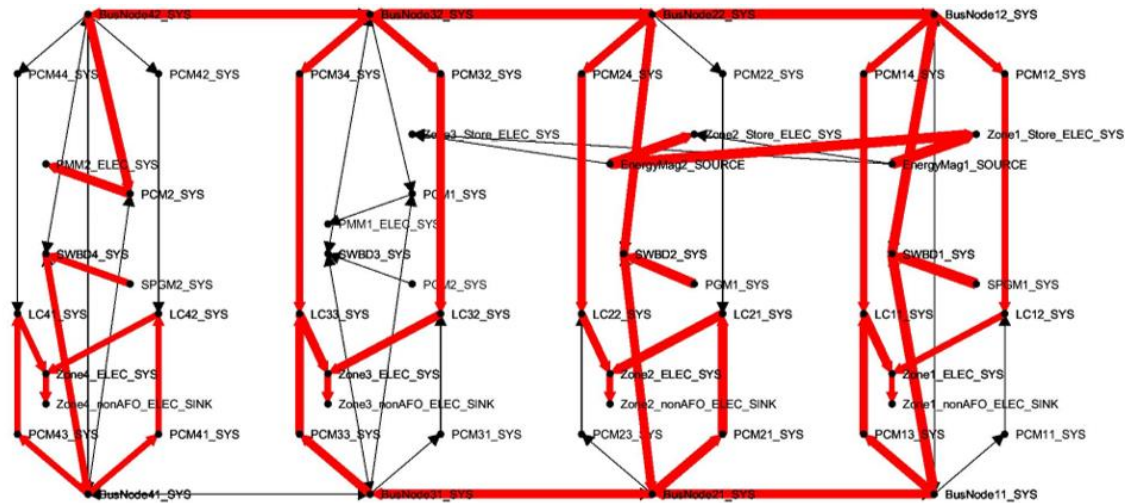


Figure 43. ELEC Plex Damaged MMR2 Lower System Response

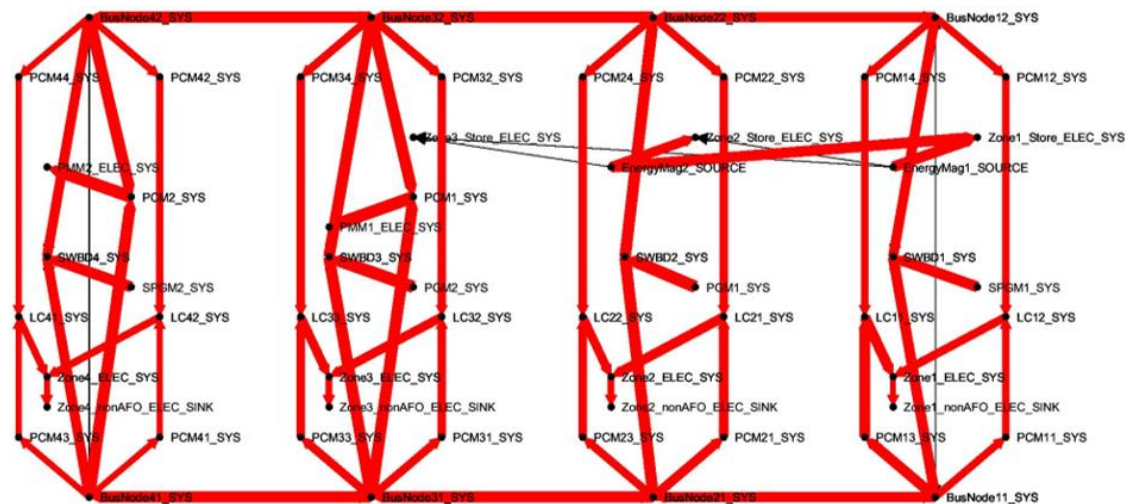


Figure 44. ELEC Plex Aggregate System Response

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.

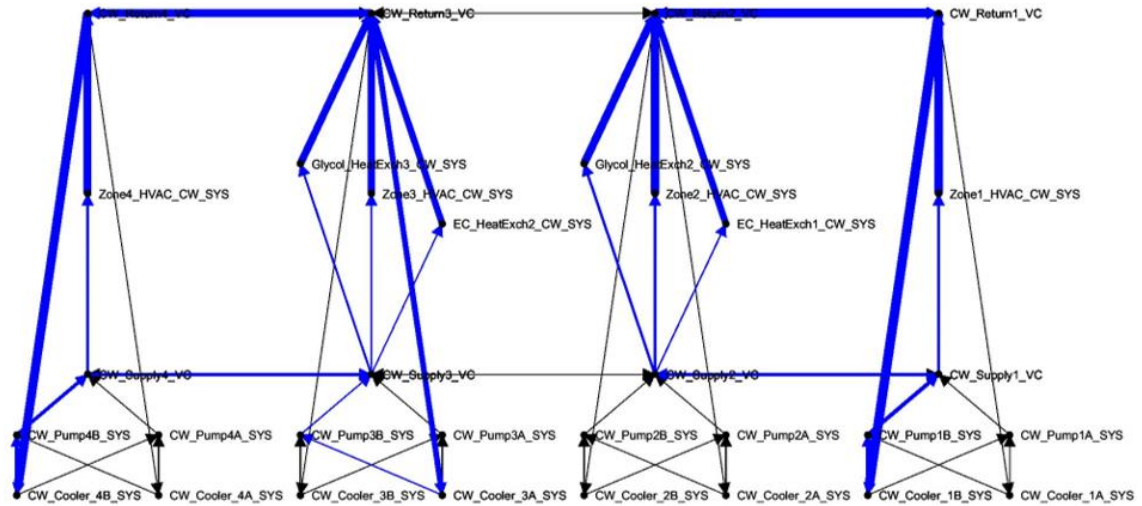


Figure 45. CW Plex Endurance System Response

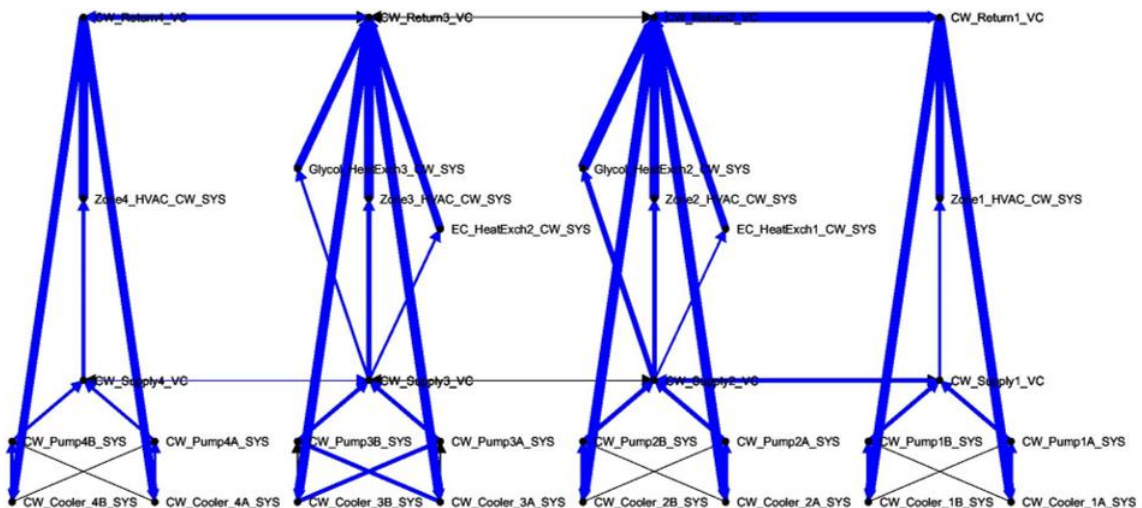


Figure 46. CW Plex Battle System Response

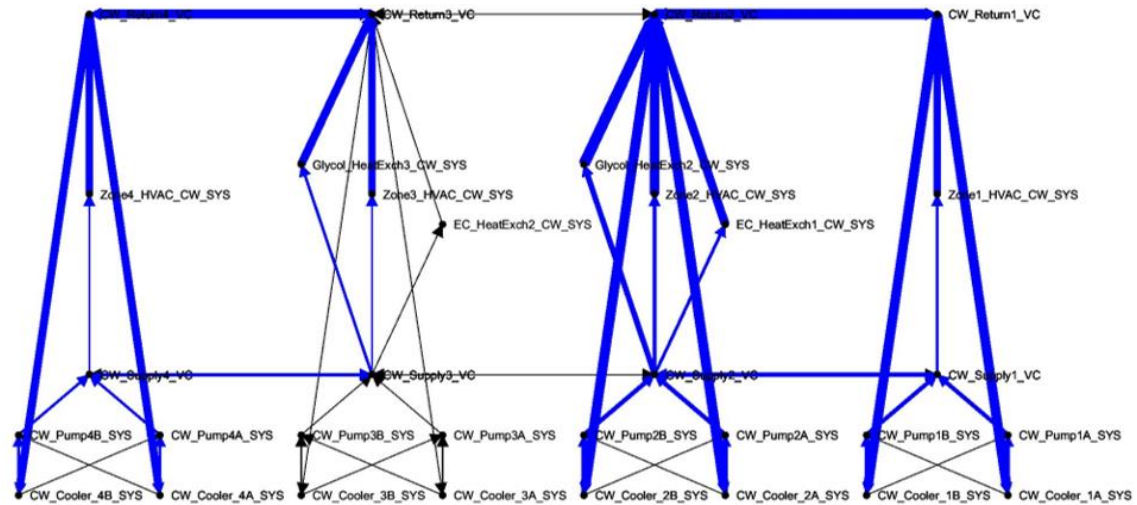


Figure 47. CW Plex Damaged MMR2 Lower System Response

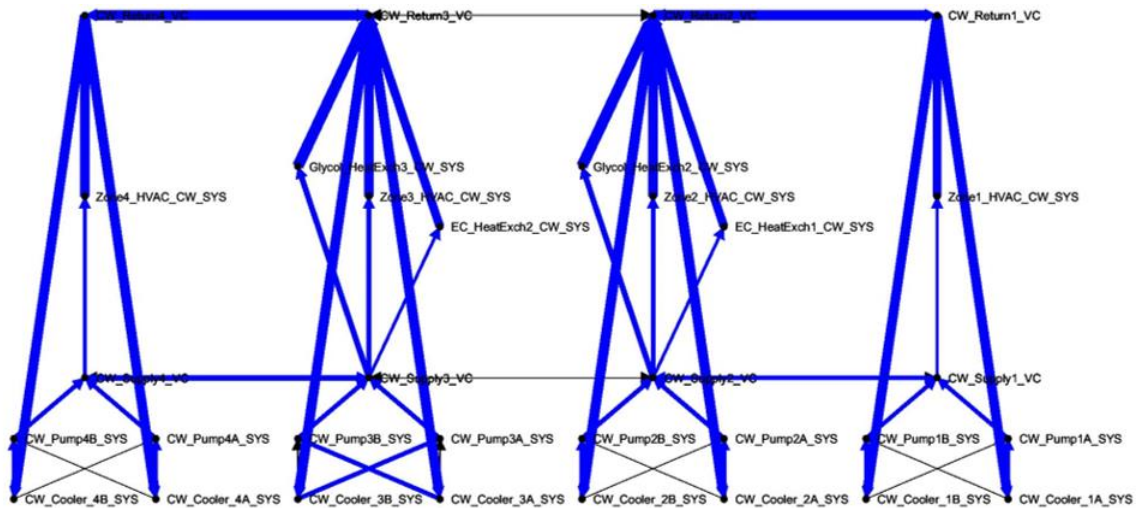


Figure 48. CW Plex Aggregate System Response

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 are 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 25. The PGMs are gas turbines while the SPGMs are diesel engines. The PGMs have a higher fuel

consumption and a higher power output. This is represented by the thicker arc flows. Figure 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).

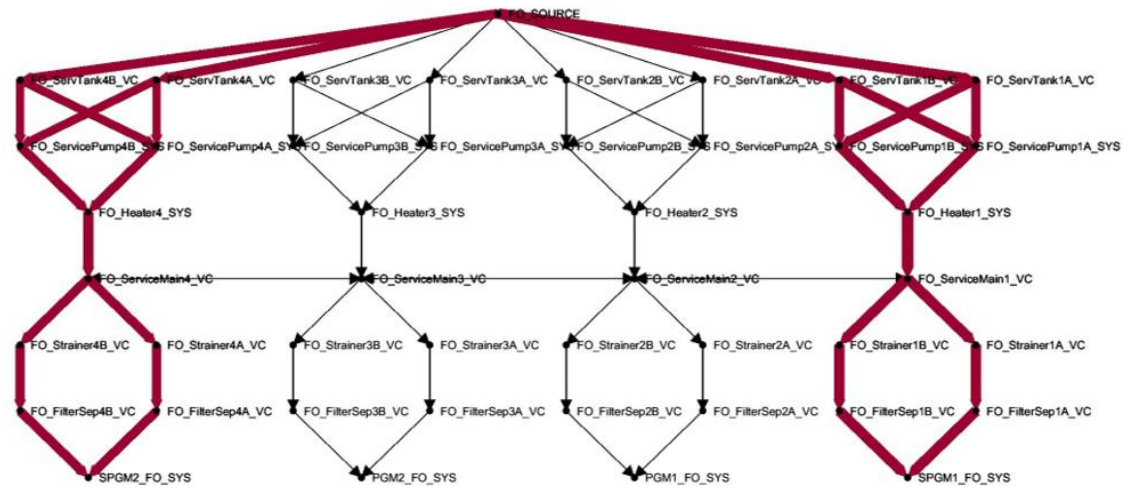


Figure 49. FO Plex Endurance System Response

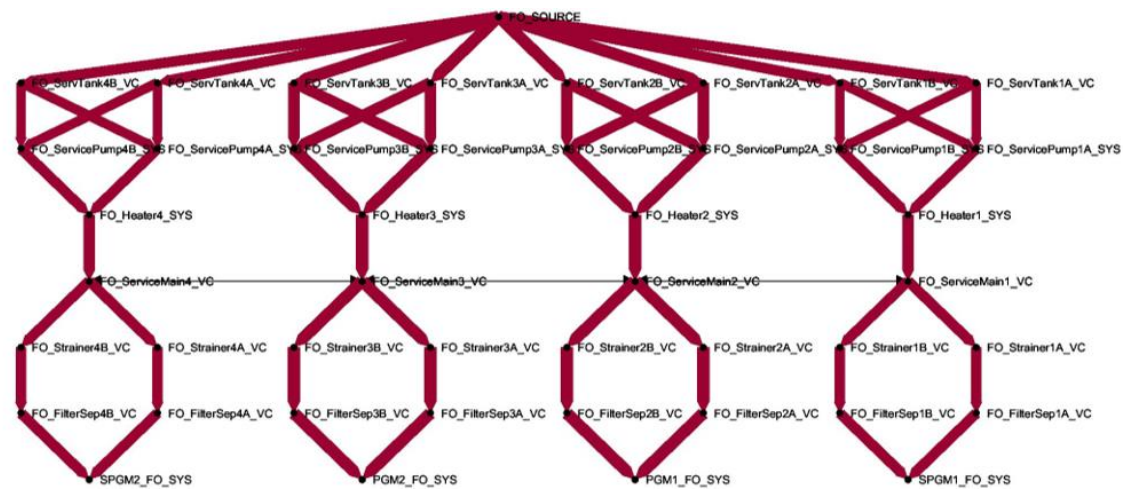


Figure 50. FO Plex Battle System Response

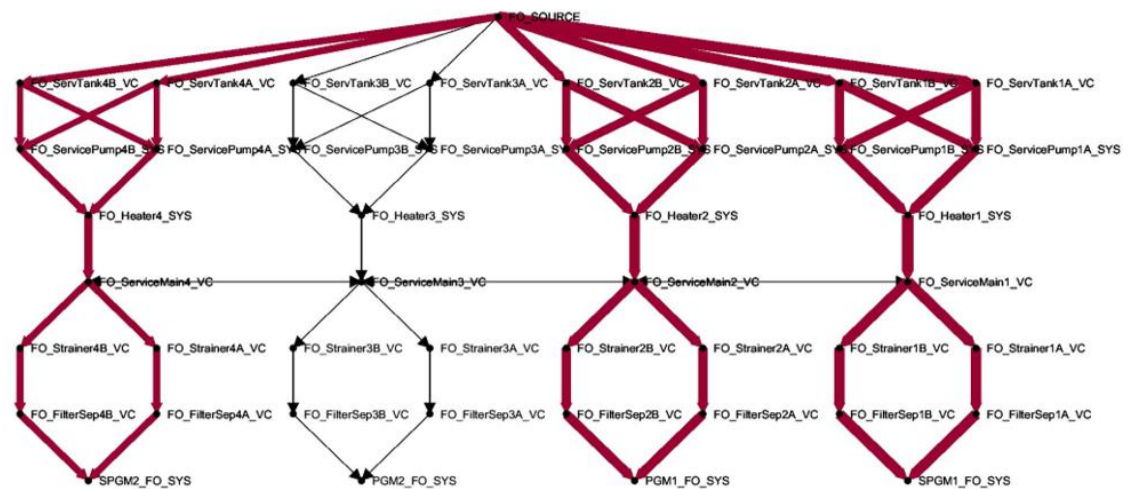


Figure 51. FO Plex Damaged MMR2 Lower System Response

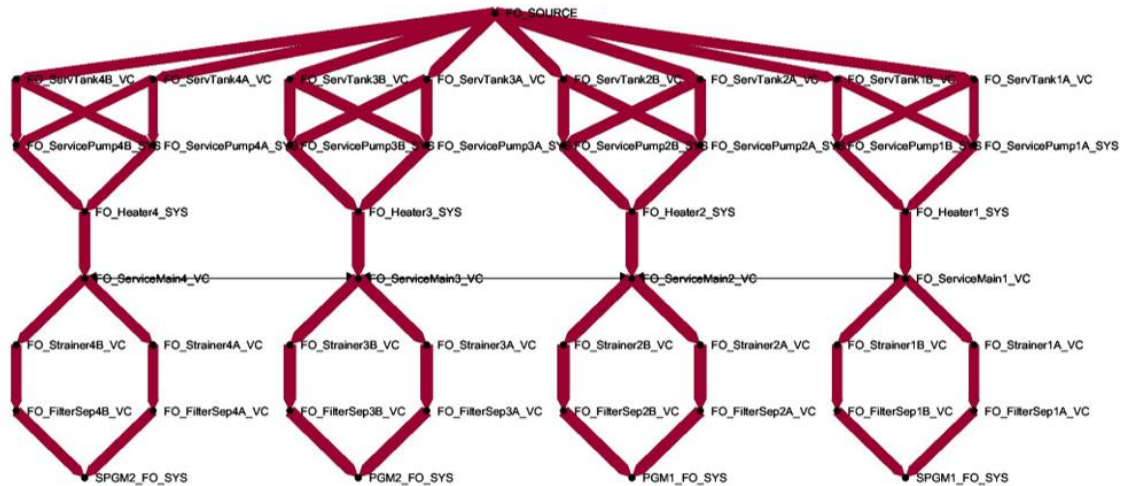


Figure 52. FO Plex Aggregate System Response

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 53, 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.

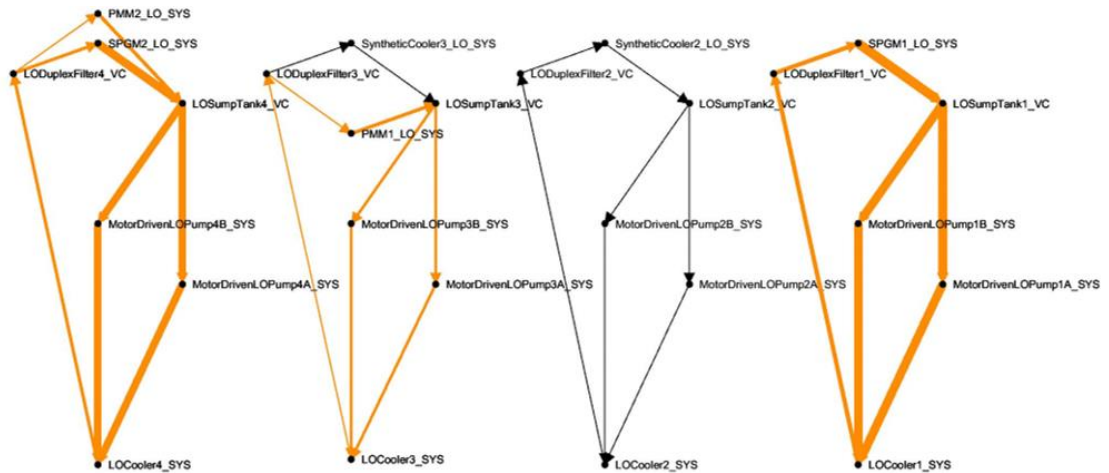


Figure 53. LO Plex Endurance System Response

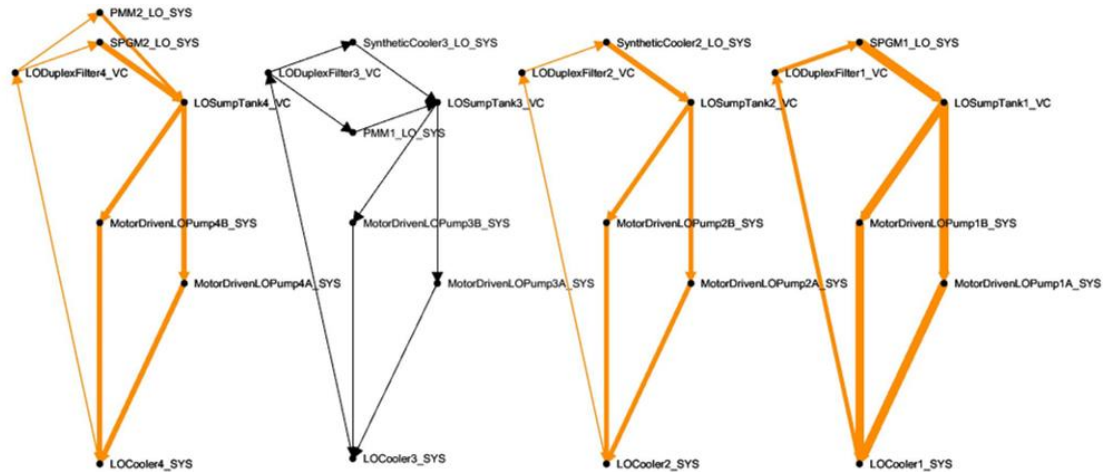


Figure 54. LO Plex Damaged MMR2 Lower System Response

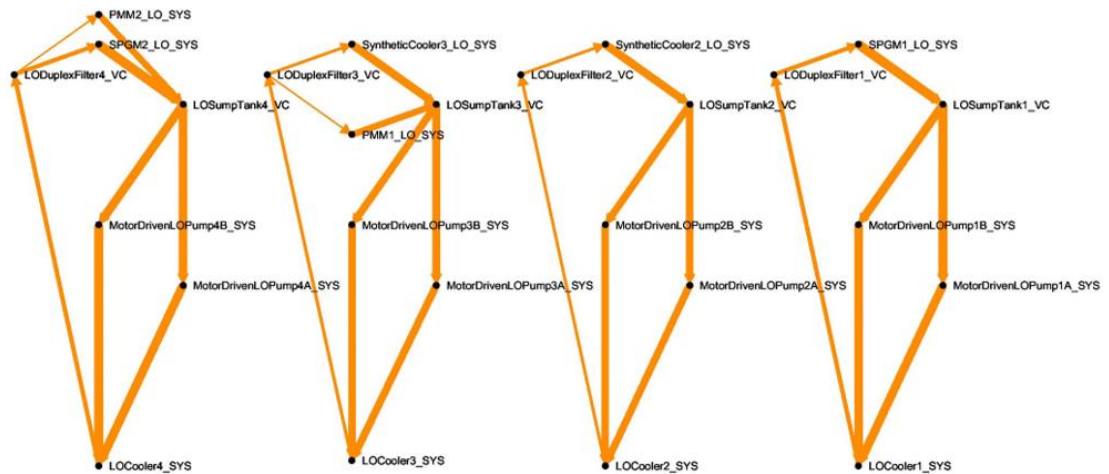


Figure 55. LO Plex Aggregate System Response

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.

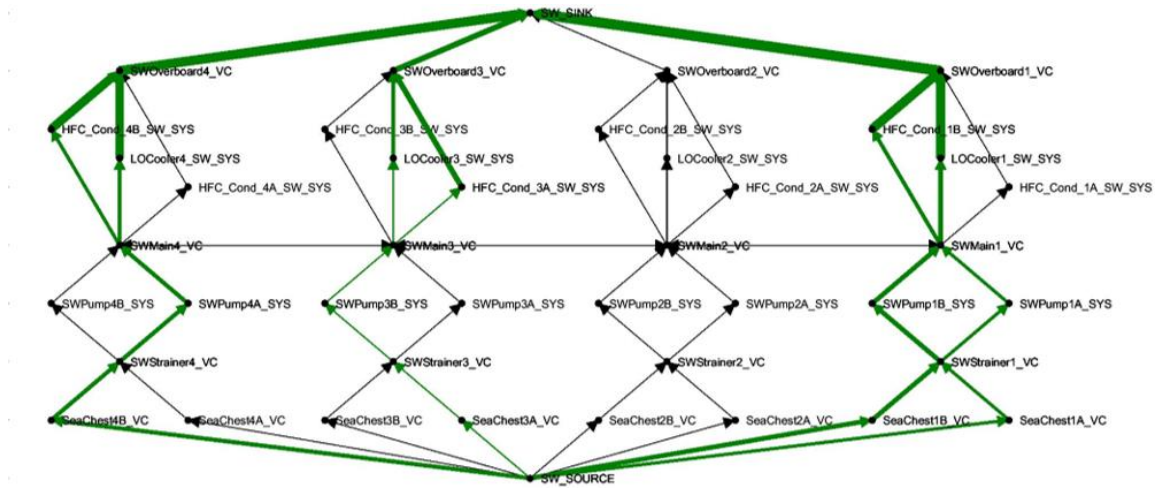


Figure 56. SW Plex Endurance System Response

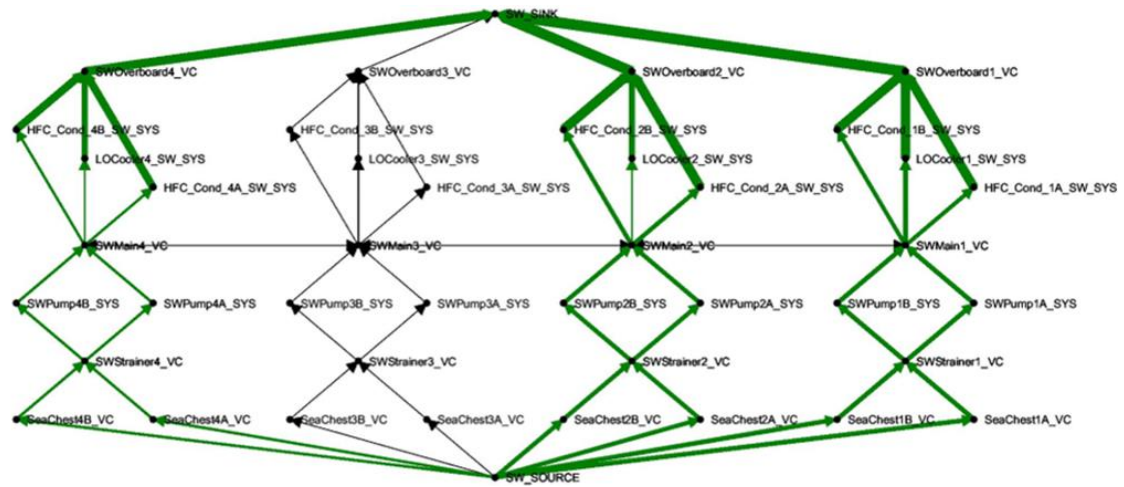


Figure 57. SW Plex Damaged MMR2 Lower System Response

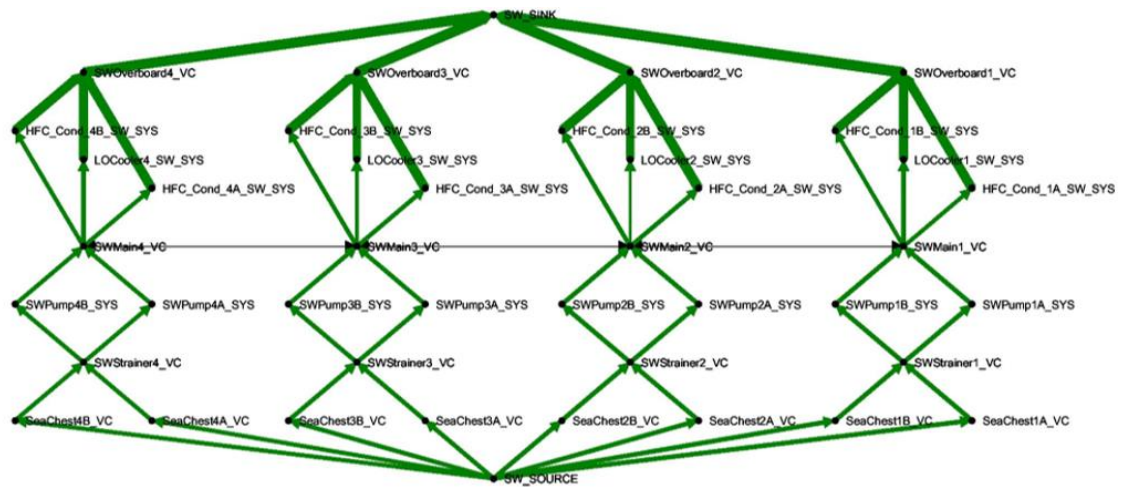


Figure 58. SW Plex Aggregate System Response

Conclusions and Future work

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

The authors would like to thank Ms. Kelly Cooper, ONR 331, for supporting this work under contract N00014-15-1-2476. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the Office of Naval Research. DCN# 43-5850-19.

References

- Andrews, D., "Choosing the Style of a New Design – The Key Ship Design Decision," *Transactions RINA, International J. Maritime Eng.*, 160 - Part A1, DOI No: 10.3940/rina.ijme.2018.a1.457, 2018.
- Brefort, D., C. Shields, A. Habben, E. Duchateau, R. Pawling, K. Droste, T. Jasper, M. Sypniewski, C. Goodrum, M. A. Parsons, M. Kara, M. Roth, D. J. Singer, D. Andrews, H. Hopman, A. J. Brown and A. Kana, "An architectural framework for distributed naval ship systems," *Ocean Engineering*, 147: 375–385, 2018.
- Brown, A.J, "Chapter 1: Design of Marine Engineering Systems in Ship Concept Design", *Marine Engineering*, edited by

- Michael G. Parsons, 4th ed., Society of Naval Architects and Marine Engineers, Alexandria VA, submitted for publication, 2020.
- Brown, A.J., Salcedo, J., "Multiple Objective Genetic Optimization In Naval Ship Design", *Naval Engineers Journal*, Vol. 115, No. 4, pp. 49-61, 2003.
- Brown, A.J., Thomas, M., "Reengineering the Naval Ship Concept Design Process", From Research to Reality in Ship Systems Engineering Symposium, ASNE, 1998, Tysons Corner, VA..
- Brown, A. and Waltham-Sajdak, J. 2015 Still reengineering the naval ship concept design processm, *Naval Engineers Journal*, 127(1), 49–61.
- Doerry, N. and Amy, J. 2016 Design considerations for a reference MVDC power system, *Proceedings, SNAME Maritime Convention 2016*, November 1–5, Bellevue, WA. Goodfriend, D. and A. J. Brown, "Exploration of System Vulnerability in Naval Ship Concept Design," *Journal of Ship Production and Design*, 34-1: 42-58.
- Robinson, K., "Modeling Distributed Naval Ship Systems using Architecture Flow Optimization," MS Thesis, Ocean Engineering, Virginia Tech, 2018.
- IBM, *IBM ILOG CPLEX Optimization Studio CPLEX User's Manual Version 12 Release 6*. USA: International Business machines Corp, 2014.
- McDonald, T., "A Library Based Approach for Exploring Style in Preliminary Ship Design," University College London, 2009.
- Parsons et al., "Application of a Distributed System Architecture Framework to Naval Ship Concept and Requirements Exploration (C&RE)," *Intelligent Ships Symposium, ANSE ISS 2019*, Philadelphia, PA, April 9-10, 2019.
- Robinson, K., "Modeling Distributed Naval Ship Systems using Architecture Flow Optimization," MS Thesis, Ocean Engineering, Virginia Tech, Blacksburg, VA, 2018.
- Stepanchick, J., Brown, A.J., "Revisiting DDGX/DDG-51 Concept Exploration", *Naval Engineers Journal*, Vol. 119, No. 3, 67-88, 2007.
- Strock, J., Brown, A.J., "Methods for Naval Ship Concept and Propulsion System Technology Exploration in a CGX Case Study", *Naval Engineers Journal*, Vol. 120, No. 4, pp. 95-122, 2008.
- Trapp, T., "Shipboard Integrated Engineering Plant Survivable Network Optimization," Ph.D. Dissertation, Massachusetts Institute of Technology, 2015.

Paper #3 – 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 feasibility 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. The AFO refinement discussion in this paper provides an overview of the continued AFO development to integrate this method with C&RE and a subsequent physics-based vital component sizing. It updates the modeling of trace flows, the cold-side flow in cooling auxiliary systems, to improve system usage across multiple zones. Results are discussed in the context of three notional surface ship representative designs.

Introduction

Mission 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" (Doerry & Amy 2016). 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 include the Design Building Block Approach (Andrews et al. 2012, McDonald 2009, Pawling 2007, Pawling et al. 2015) and Bin-Packing (Duchateau 2016, van Oers et al. 2010, van Oers 2011, van Oers et al. 2012). 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, Chalfant et al. 2017b). 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) updated a surface ship Concept & Requirements Exploration (C&RE) process developed over two decades at Virginia

¹ Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech

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. Survivability must be considered in these early decisions and in C&RE.

Goodfriend & Brown (2018); Snyder (2019); Snyder et al. (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.

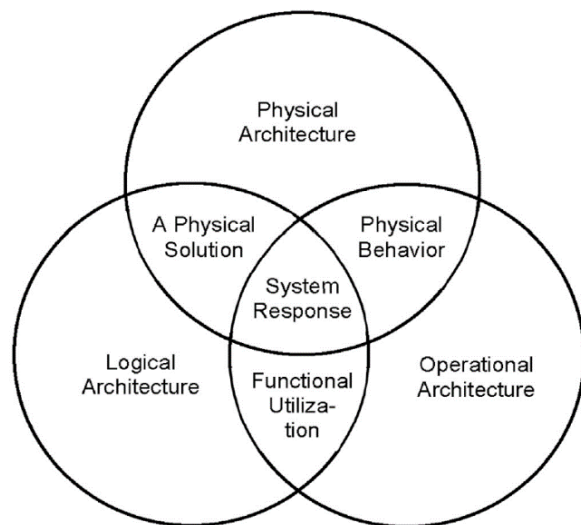


Figure 59. Architectural Framework for Distributed Ship Systems (Brefort et al., 2018)

Working in a Naval International Cooperative Opportunities in Science and Technology Program (NICOP), the authors began exploring the use of networks (Gillespie et al. 2012, Gillespie et al. 2013, Gillespie and Singer 2013) 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).

Concept & Requirements Exploration (C&RE)

The C&RE process, illustrated in Figure 2, 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.

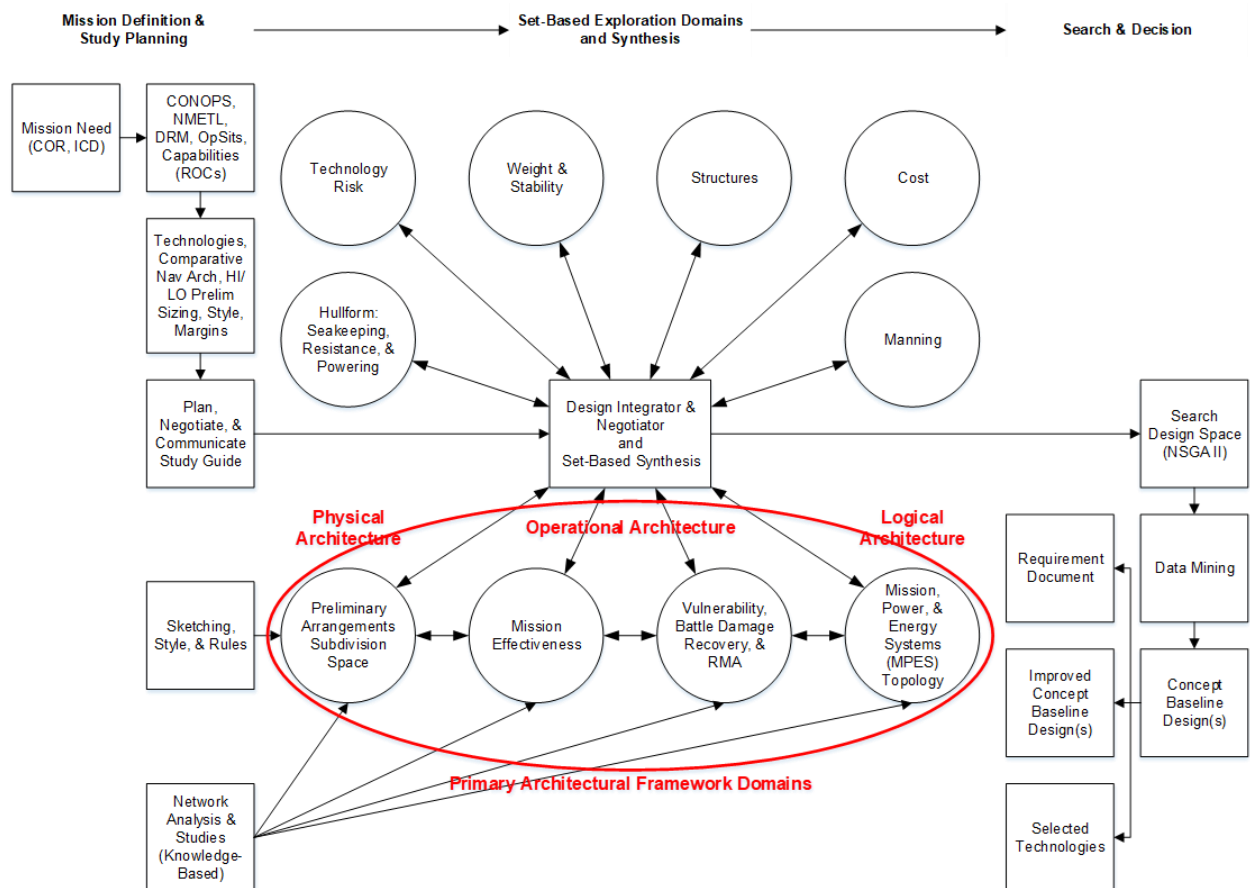


Figure 60. Surface Ship C&RE Process with Set-Based Domains and Architectural Framework (Parsons, et al., 2019)

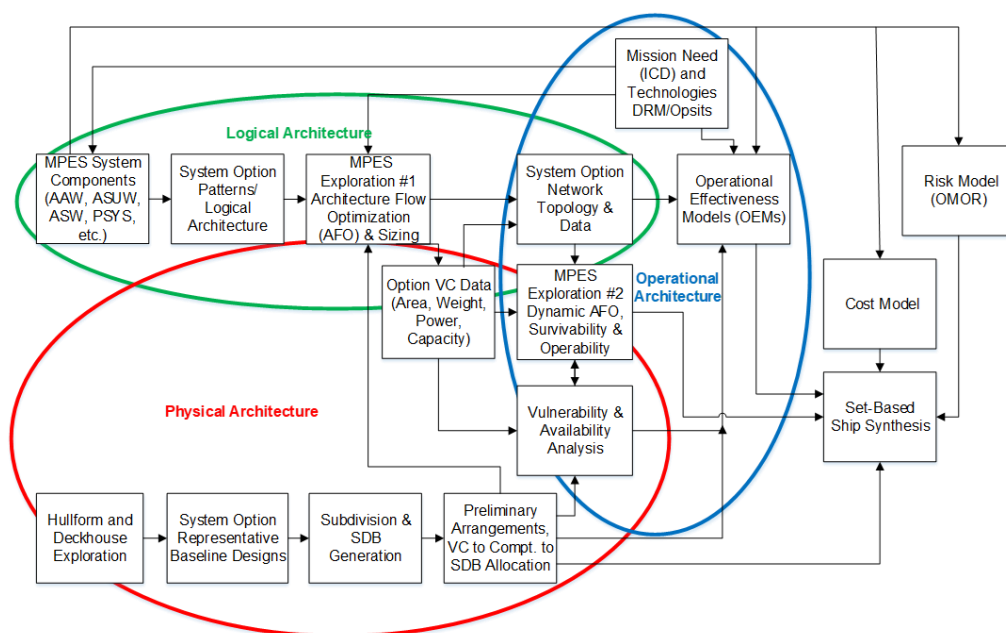


Figure 61. MPES Design Process Approximately Superimposed on the Architectural Framework (Parsons et al., 2021)

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. Deck spacing and transverse bulkhead locations are based on stack-up lengths, floodable length parametrics, average deck height and other “stylistic” design considerations are sought (Pawling et al. 2007, McDonald 2009, Andrews et al. 2012, Pawling et al. 2015, Andrews 2018). A single set of midrange hullform design variable (DV) values except length overall (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 61 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 61, 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 ongoing research and future papers which connect more closely with the Operational Architecture.

Architecture Flow Optimization (AFO)

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. 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 2020, Konak and Smith 2018). The 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. 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 S3D (Chalfant 2015).

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 result, plexes are similar to traditional marine engineering distributed systems (i.e. fuel oil service system, electrical distribution system, chilled water system, mission system 1/MS1) (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.

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)

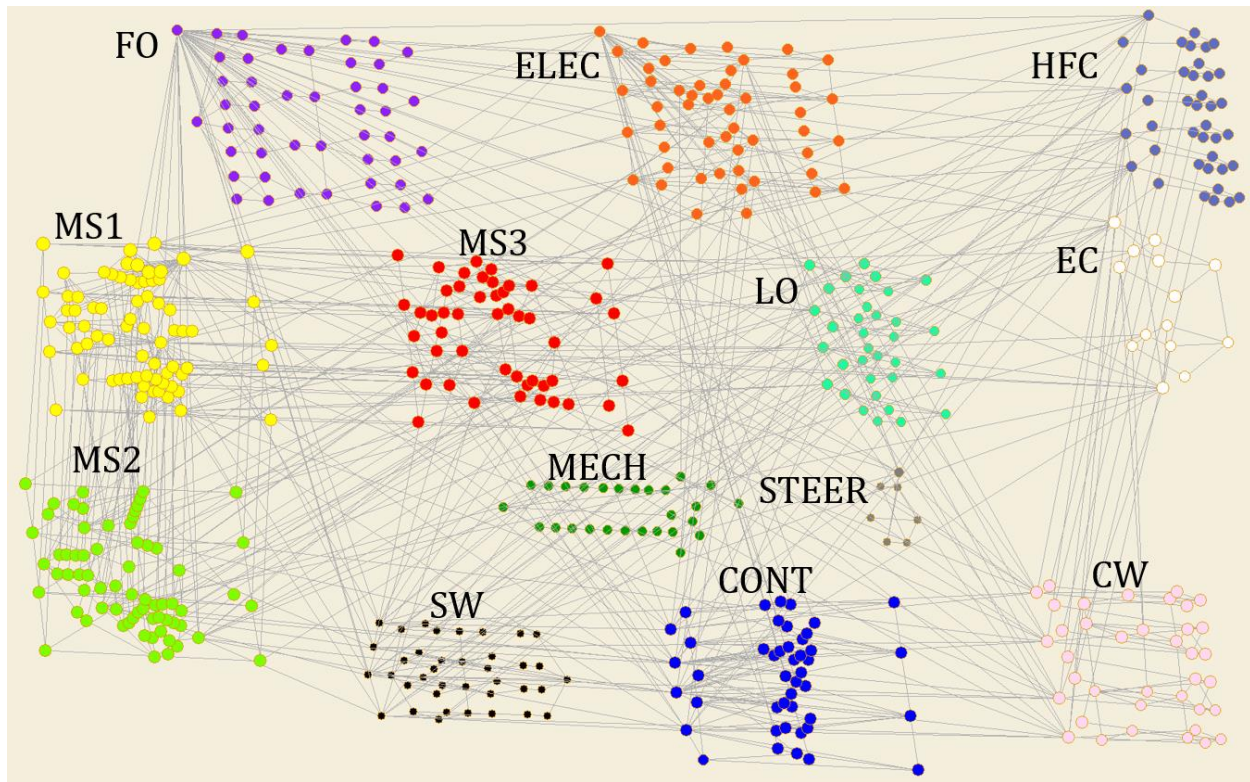


Figure 62. Notional Surface Ship Total-Ship Multiplex Logical Architecture

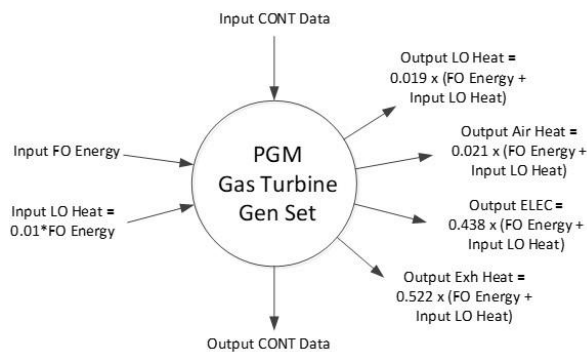


Figure 63. Nominal PGM (Gas Turbine and Generator Set Combination) Nodal Input and Output Coefficients

Figure 63 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 ($0.01 \times \text{FO Energy}$) 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 = 0.438). 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. The commodity flowing in these arcs is data/information and is used primarily by the CONT plex. CONT data is used for similar functions to data in the in MS1, MS2, and MS3 plexes, that is Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) functions.

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

Figure 64. Excerpt from MEL Equipment Input and Output Energy Coefficient Matrix

Energy coefficients are assigned to the input and output arcs of vital components based on these simple component models. Figure 64 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 64. Note the PGM coefficients are consistent with Figure 63.

This network approach has proven to be exceptionally capable and flexible for the C&RE application. As a result, the 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).

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 at Virginia Tech can be applied with additional component model characteristics and a power management objective. Robinson (2018) and Parsons et al. (2021) describe the incorporation of this Architecture Framework into an energy-based variation of Trapp's (2015) non-simultaneous multi-commodity which is called Architecture Flow Optimization (AFO). 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). AFO has become the primary method used in the 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 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.

AFO 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. (2021). 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
- mission system vital component heat dissipation

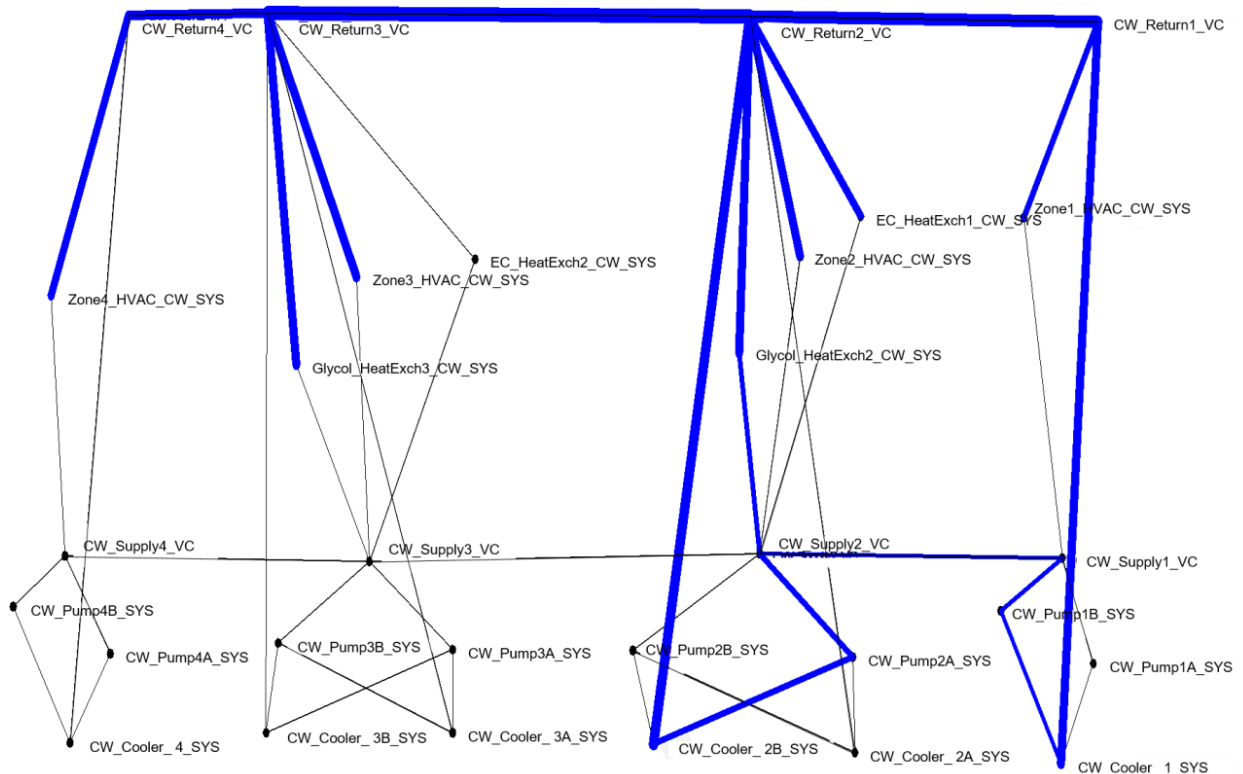


Figure 65. CW plex for sustained-speed-scenario flow in a previous surface ship application using original AFO formulation. Zones 1-4 are numbered from right to left. Cross-connecting arcs link each zone's supply and return respectively (Robinson, 2018).

Figure 65 shows a four-zone CW plex sustained-speed-scenario flow in a surface ship application generated using the 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 65). 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 65, 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 65). Similarly, the CW plex system flows generated using the original AFO formulation routed all heat in the CW plex 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	$\min \left(\sum_{(i,j) \in A} (\Pi_{i,j} B_{i,j} + \pi_{i,j} x_{i,j}) + \sum_{(n) \in N} (1 * 10^{12} * d_n) \right) \quad (20)$
Directed Arc Constraint	$x_{i,j}^s \geq 0 \quad (21)$
Sink Node Constraint	$e_n^s \geq \sum_{(i,n) \in A} x_{i,n}^s \quad (\text{e.g. Propulsion_SYS}) \quad (22)$
Scenario Arc Deactivation Flow Constraint	$x_{i,n}^s = \begin{cases} 0, & \text{if } b_{i,n}^s = 0 \\ x_{i,n}^s, & \text{if } b_{i,n}^s = 1 \end{cases} \quad \text{and} \quad x_{n,j}^s = \begin{cases} 0, & \text{if } b_{n,j}^s = 0 \\ x_{n,j}^s, & \text{if } b_{n,j}^s = 1 \end{cases} \quad (23)$
Scenario Arc Deactivation Binary Constraint	$b_{i,j}^s = \begin{cases} 0, & \text{if the edge is deactivated} \\ 1, & \text{if the edge available} \end{cases} \quad (24)$
Known Scenario Load Arc Flow Constraint	$x_{m,n}^s = e_n^s \quad (\text{e.g. MS1 VC electric load}) \quad (25)$
Known Scenario Heat Arc Flow Constraint	$x_{n,o}^s = e_n^s \quad (\text{e.g. MS1 VC heat load}) \quad (26)$
Scenario Arc In-Flow Capacity Constraint	$x_{m,n}^s \leq e_n^s \quad (\text{e.g. CW Cooler capacity}) \quad (27)$
Scenario Arc Out-Flow Capacity Constraint	$x_{n,o}^s \leq e_n^s \quad (\text{e.g. PGM power capacity}) \quad (28)$
Scenario Incoming Arc Flow Constraint	$x_{i,n}^s = C_n^{p(i)}(x_{m,n}^s) \quad (\text{applies VC In-flow coefficients}) \quad (29)$
Scenario Outgoing Arc Flow Constraint	$x_{n,j}^s = C_n^{p(j)} \sum_{(i,n) \in A} x_{i,n}^s \quad (\text{applies VC Out-flow coefficients}) \quad (30)$
Scenario Redundant VC Arc Flow Constraint	$x_{m,n_a}^s = x_{m,n_b}^s \quad (31)$
Scenario Continuity Constraint	$\sum_{(i,n) \in A} x_{i,n}^s - \sum_{(n,j) \in A} x_{n,j}^s - d_n^s = 0 \quad (32)$
Aggregate Arc Flow Constraint	$x_{i,j} = \max_{s \in S} (x_{i,j}^s) \quad (33)$
Aggregate Slack Variable Constraint	$d_n = \max_{s \in S} (d_n^s) \quad (34)$
Binary Arc Constraint	$B_{i,j} = \begin{cases} 0, & \text{if } x_{i,j} = 0 \\ 1, & \text{if } x_{i,j} > 0 \end{cases} \quad (\text{fixed-cost binary}) \quad (35)$

Where:

- 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 is the aggregate energy flow slack variable for node n
- d_n^s is the energy flow slack variable for node n in scenario s
- $C_n^{p(i)}$ is the coefficient of arcs to node n from the nodes in the p plex.
- $C_n^{p(j)}$ is the coefficient of arcs from node n to the nodes in the p plex.
- $b_{i,j}^s$ is a binary value associated with whether the flow through arc (i,j) is on or off for deactivation 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 6, 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 ensuring 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 (IBM 2014), 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 8 shows an example of a minor refinement to mission system vital component heat dissipation that 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 heat was removed by the VC's cooling system. The refined method models heat dissipated 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 environmental heat transfer. This refinement resulted in smaller and more realistic total ship system cooling loads. MS1 data commodity flows are not used in the energy model. They are used to facilitate C4ISR functionally in the MS1 plex.

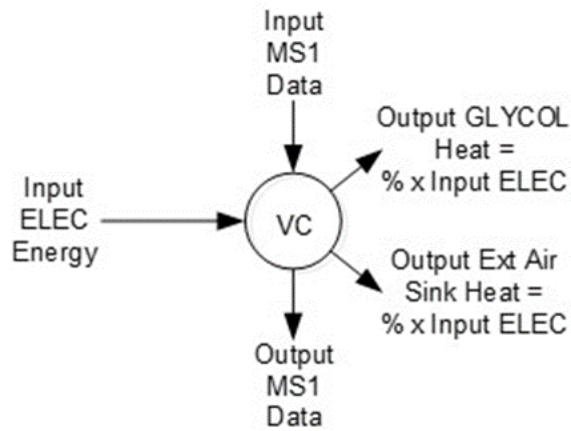


Figure 66. MS1 VC Energy Model

Surface Ship Case Study C&RE

The rest of this paper describes a surface ship case study that completes a C&RE and two

different methods for vital component sizing: parametric and AFO-based. This C&RE process is summarized in the first section of this paper and discussed in detail by Parsons, et al. (2019). A comparison of the results of these sizing methods is discussed.

Table 8 shows the design space of MPES design variables considered in the 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.

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

Table 8. Notional Surface Ship C&RE MPES Design Variable Options (Options not used are Omitted)

As a preliminary step to applying the 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 8. The MOGO's three objectives were cost (Cfola), effectiveness (OMOE), and risk (OMOR). The MOGO non-dominated frontier results are shown in Figure 67 through Figure 69.

Figure 67 shows cost, effectiveness and risk in one plot with risk indicated by colors blue to red (low to high). Figure 67 shows more effective designs (higher OMOE) in the design space are correlated with both more costly (higher Cfola) and have higher risk (lighter color). Figure 67 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, IPS technologies, laser, and anti-denial system technologies, and new radar technologies.

Figure 68 again shows effectiveness and cost on axes but replaces the color gradient with PSYS options: PSYS 6 (IPS) in blue, PSYS 7 (HED) in green, and PSYS 8 (CODAG) in red. PSYS 8 (CODAG) is correlated with cheaper, less effective designs. PSYS 6 (IPS) is correlated with more effective, more expensive designs. PSYS 7 provides a transition between PSYS 6 and PSYS 8 but generally aligns more closely with PSYS 6: the HED PSYS option provides a transition between IPS and CODAG in terms of effectiveness and cost, but generally has effectiveness and cost metrics aligned more closely with IPS.

Figure 69 again shows effectiveness and cost on axes but replaces the color gradient with Mission System 1 (MS1) options: Option 4 in blue, Option 5 in green, and option 6 in red. Option 4 is correlated with more effective, more expensive designs, Option 6 is correlated with cheaper, less effective designs, and Option 5 provides a gradual transition between Option 4 and Option 6. This result is expected due to the composition of MS1 Options 4, 5, and 6.

Three designs are labeled in the NDF plots. PSYS 8-1 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. PSYS 7-1 uses hybrid electric drive (HED, PSYS 7) which is medium risk, but still not quite able to support the high-end MS1 systems. PSYS 6-1 uses IPS power and propulsion which enables the high-end MS1 Option 4. A summary of these representative designs' system options are listed in Table 9. Representative designs based on the same system options as in PSYS 6-1, PSYS 7-1 and PSYS 8-1 are used in the surface ship case study comparison of parametric and AFO-based vital component sizing presented in Table 10 to demonstrate the impact of applying the new MPES Exploration process and AFO.

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

Table 9. Notional Surface Ship Representative Designs with Propulsion and Mission System Design Variable Options

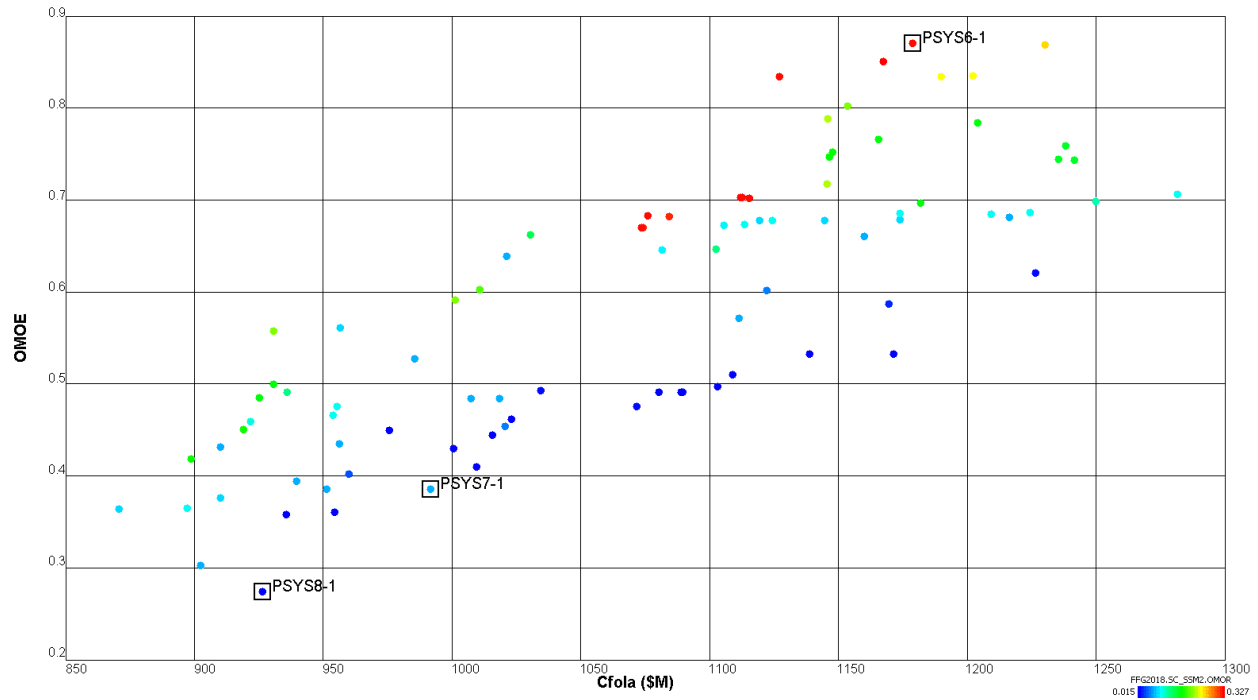


Figure 67. Surface Ship Non-Dominated Frontier.

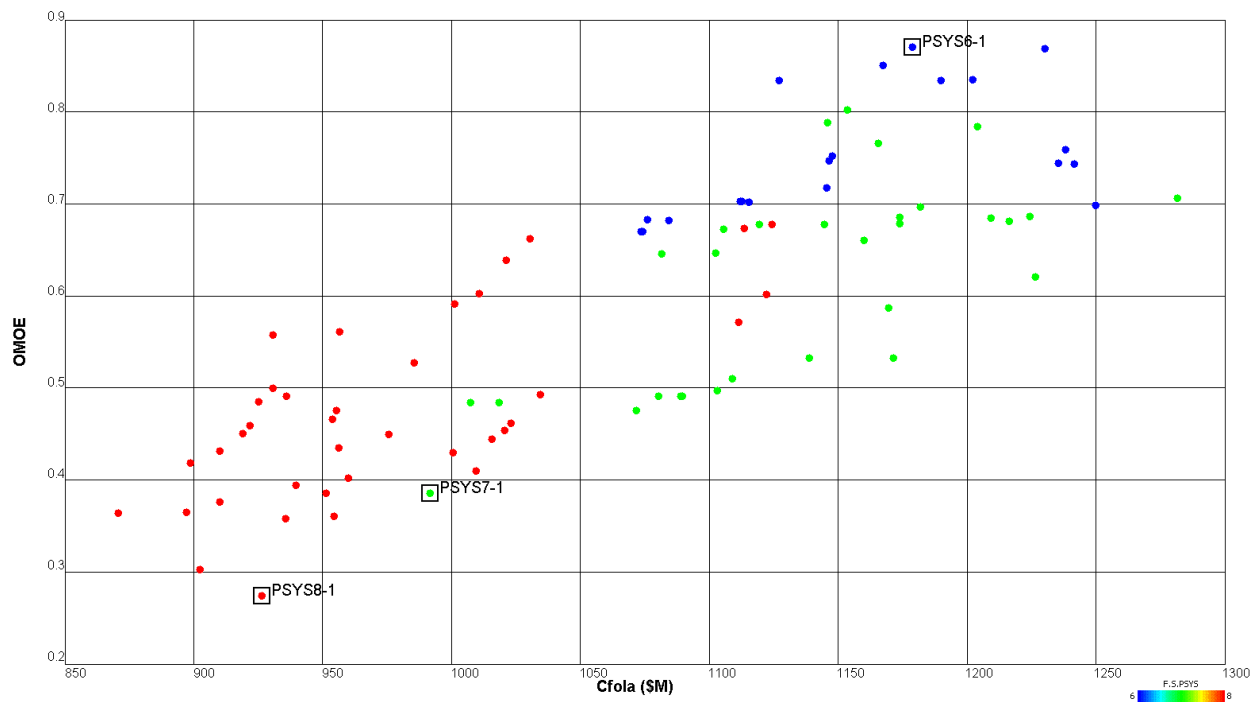


Figure 68. Surface Ship PSYS Option Non-Dominated Frontier.

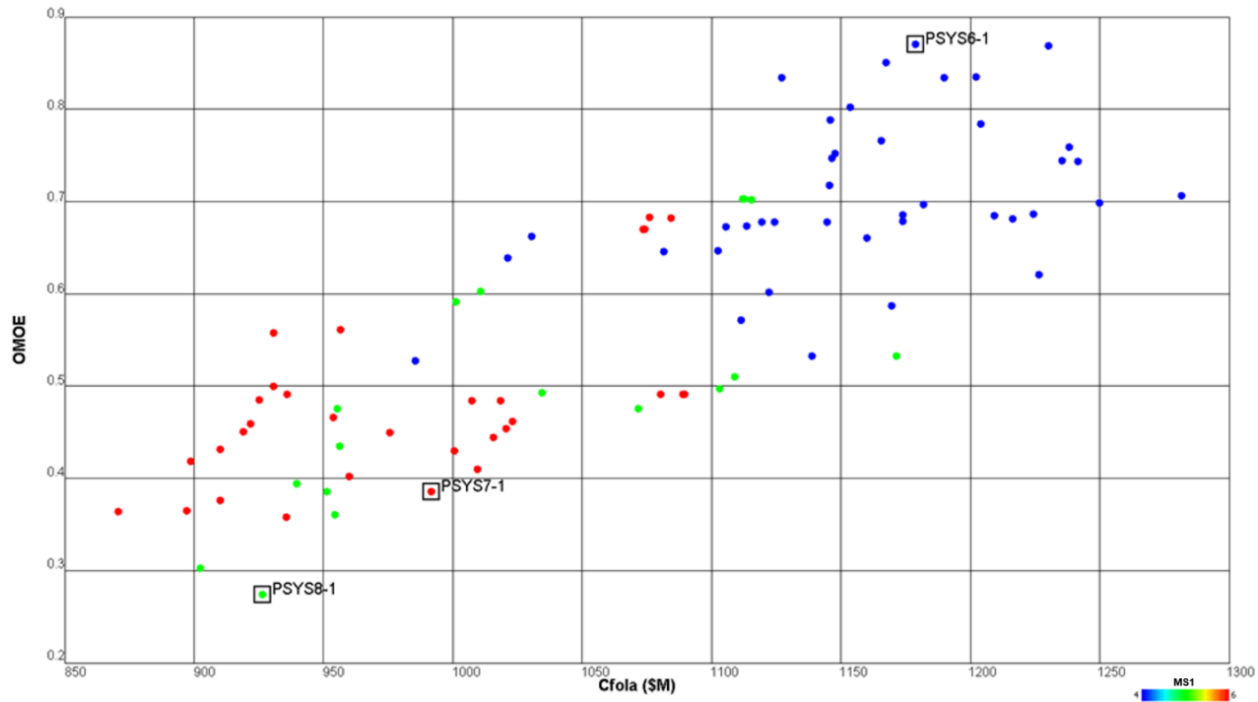


Figure 69. Surface Ship MS1 Option Non-Dominated Frontier.

The remainder of this section presents the representative designs described above (PSYS 6-1, PSYS 7-1, and PSYS 8-1) 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 (PSYS 6-2, PSYS 7-2, and PSYS 8-2). The second variant is an optimized design using power and energy components sized with the refined-AFO results (PSYS 6-3, PSYS 7-3, and PSYS 8-3). 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 10 presents the results of these nine designs. Several observations can be made about these results:

- The PSYS 6, 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 PSYS 7-3 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.

		PSYS6-1	PSYS6-2	PSYS6-3	PSYS7-1	PSYS7-2	PSYS7-3	PSYS8-1	PSYS8-2	PSYS8-3
LOA	[m]	149.0	143.5	142.8	142.0	135.3	139.1	142.0	133.3	135.5
LWL	[m]	139.6	137.7	136.0	133.0	128.8	132.9	133.0	129.0	129.4
BWL	[m]	18.1	18.1	18.1	17.2	17.7	16.9	17.2	16.1	16.3
T	[m]	6.6	6.2	6.5	6.3	6.0	5.8	6.3	5.6	5.9
GM _T	[m]	2.4	1.9	2.3	2.3	2.1	1.6	2.6	1.7	1.6
L / B	[-]	7.5	7.3	7.22	7.3	7.1	7.5	7.5	7.5	7.4
B / T	[-]	3.0	3.2	3.07	3.2	3.2	3.2	3.0	3.2	3.1
Min. Deckhouse Volume	[m ³]	2000	2000	2000	2143	2281	2447	2000	2000	2430
Stem Rake	[deg]	42.0	43.3	50	50.0	50.0	44.9	42.0	35.0	44.4
Longitudinal Prismatic Control	[0.1 - 0.4]	0.40	0.35	0.40	0.40	0.29	0.40	0.40	0.40	0.40
Deadrise Mid	[0.1 - 0.4]	0.39	0.10	0.12	0.15	0.10	0.22	0.39	0.26	0.10
Fullness Fwd	[0.3 - 0.6]	0.30	0.70	0.30	0.70	0.61	0.30	0.30	0.30	0.30
Section Tightness Mid	[0.4 - 0.99]	0.42	0.58	0.85	0.57	0.65	0.40	0.42	0.42	0.99
Manning & Automation Factor	[0.5 - 10.0]	8.00	7.31	7.00	7.00	7.00	7.00	8.00	7.00	7.00
Maintenance	[1 - 3]	3.00	2.00	2.00	2.00	2.00	2.00	3.00	2.00	2.00
Provisions Duration	[day]	60	60	60	60	60	60	60	60	60
PSYS	[6, 7, or 8]	6	6	6	7	7	7	8	8	8
MS1	[4, 5, or 6]	4	4	4	6	6	6	5	5	5
MS2	[4, 5, or 6]	4	4	4	5	5	5	6	6	6
MS3	[4, 5, or 6]	4	4	4	5	5	5	6	6	6
MPE/PGM	[1]	1	1	1	1	1	1	1	1	1
SPE/SPGM	[1 or 4]	1	1	1	1	1	1	4	4	4
SSG	[2 or 3]	3	3	3	2	2	2	3	3	3
ENER	[2]	2	2	2	2	2	2	2	2	2
Degaussing (DEGAUS)	[0 or 1]	1	1	1	1	1	1	1	1	1
CPS	[0, 1, or 2]	1	1	1	1	1	1	1	1	1
Δ	[mt]	9377	8717	8907	8122	7564	7756	8122	6738	6752
SWBS 100	[mt]	3270	3069	3030	2647	2643	2691	2763	2339	2440.99
SWBS 200	[mt]	1125	1125	1109	1038	1038	1108	815	813	1107
SWBS 300	[mt]	420	418	451	381	380	449	282	277	447
SWBS 400	[mt]	517	510	511	448	448	450	452	440	441
SWBS 500	[mt]	955	875	994	796	778	955	850	747	901
SWBS 600	[mt]	594	571	584	548	539	574	551	511	526
SWBS 700	[mt]	228	228	228	129	129	129	142	142	142
V _s	[kt]	28.2	28.9	28.1	28.7	29.2	29.0	29.3	30.0	29.4
V _{SBat}	[kt]	28.2	28.9	28.1	28.7	29.2	29.0	29.3	30.0	29.4
V _E	[kt]	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
Range	[nm]	6232	5088	5045	6547	5334	5190	9012	4515	4857
OMOE	[-]	0.759	0.759	0.759	0.393	0.394	0.393	0.379	0.377	0.377
OMOR	[-]	0.217	0.207	0.202	0.121	0.106	0.106	0.121	0.106	0.106
C _{fofa}	[\$ M]	\$ 1,272	\$ 1,228	\$ 1,227	\$ 1,085	\$ 1,042	\$ 1,056	\$ 1,012	\$ 950	\$ 958

Table 10. Notional Surface Ship Case Study Results.

Surface Ship Case Study with Refined AFO Results

This section discusses selected AFO system responses to show the results of the AFO refinement. A comparison of selected AFO system responses of the PSYS 6-3, PSYS 7-3, and PSYS 8-3 optimized baseline designs to show how these designs (with similar physical architectures but different logical architectures) respond differently to the same deactivation.

The surface ship refined-AFO flow results show that deficiencies in the previous surface ship flow results have been corrected. Figure 12 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 12, 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 shown in Figure 7 (Robinson 2018).

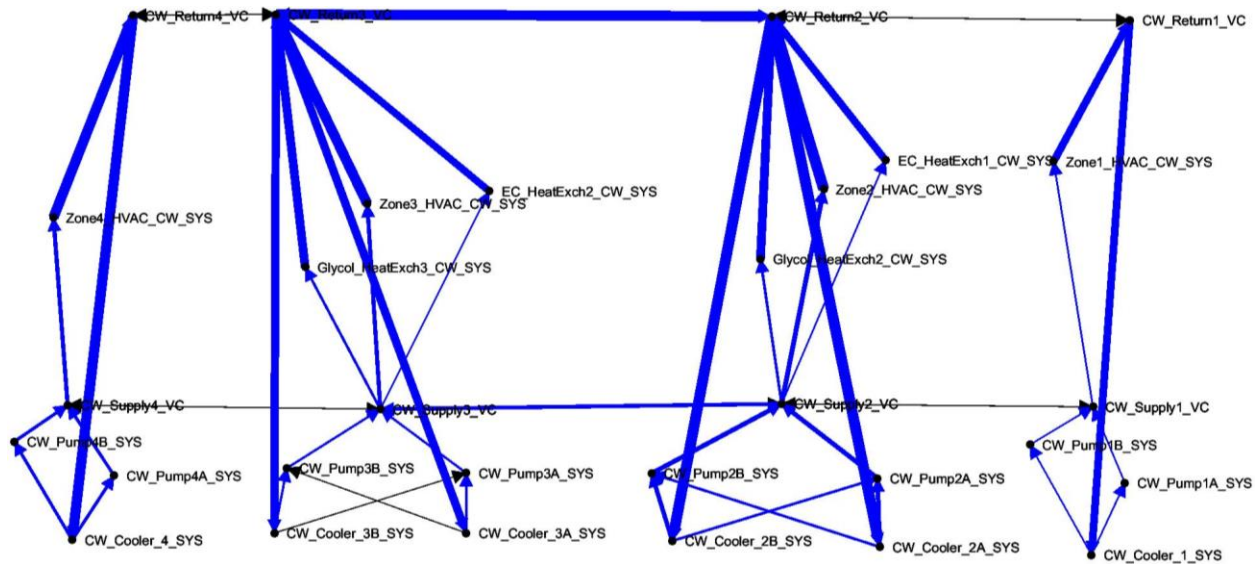


Figure 70. PSYS 8-3 Sustained Speed Scenario Chilled Water (CW) System Response. Energy flows are plotted using a logarithmic scale.

section compare the MECH and ELEC plex Main Machinery Room 2 (MMR2) Lower deactivation system response for each refined-AFO representative design. The energy flows in Figure 71 through Figure 76 are plotted using a logarithmic scale (as in Figure 70). 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 the deactivation scenarios, the designs are required to deliver half of the propulsion power required for endurance speed (20 kts), and the electric loads of all active mission system VCs are set to full load. These mission system loads represent a portion of the electric loads at the zonal ELEC nodes (Zone1_ELEC_SYS, Zone2_ELEC_SYS, Zone3_ELEC_SYS, and Zone4_ELEC_SYS). The remaining electric load at the zonal ELEC nodes represents the required power required for the VCs of the propulsion system plexes (e.g. CONT, CW, FO, HFC, LO, SW, EC, GLYCOL, and HVAC). Non vital loads are represented by zonal non-AFO sinks

(Zone1_nonAFO_ELEC_SINK, Zone2_nonAFO_ELEC_SINK, Zone3_nonAFO_ELEC_SINK, and Zone4_nonAFO_ELEC_SINK).

Figure 71 and Figure 72 show the MECH and ELEC system responses for PSYS 6-3. PSYS 6 is an IPS logical architecture. 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.

In the PSYS 6-3 deactivated MMR2 Lower system responses, power is generated by Secondary Power Generation Modules (SPGMs) in ELEC zones 1 and 4. Power is distributed via port and starboard buses to zonal ELEC nodes, zonal non-AFO nodes, and the port PMM (located in zone 4). Power at the PMM is then transferred from the ELEC plex to the MECH plex where it continues down the port shaft to the port propeller. MECH power is then sent to the Propulsion_SYS sink node representing power transmitted to the ocean during propulsion. The PMM in zone 3 is in MMR2 and therefore deactivated and cannot supply propulsion power to the starboard shaft.

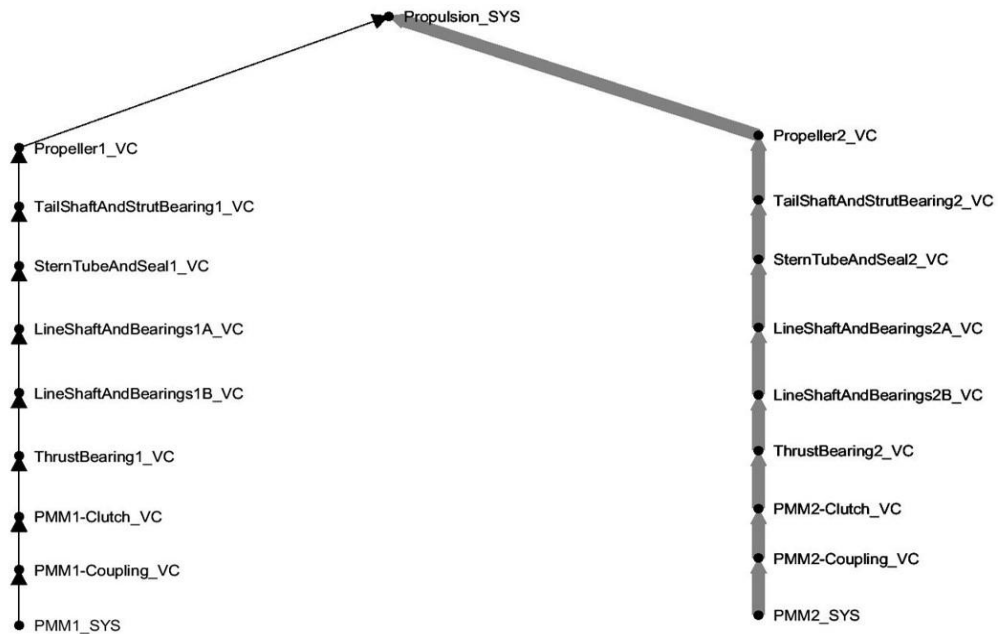


Figure 71. PSYS 6-3 MECH Plex Deactivated MMR2 Lower System Response

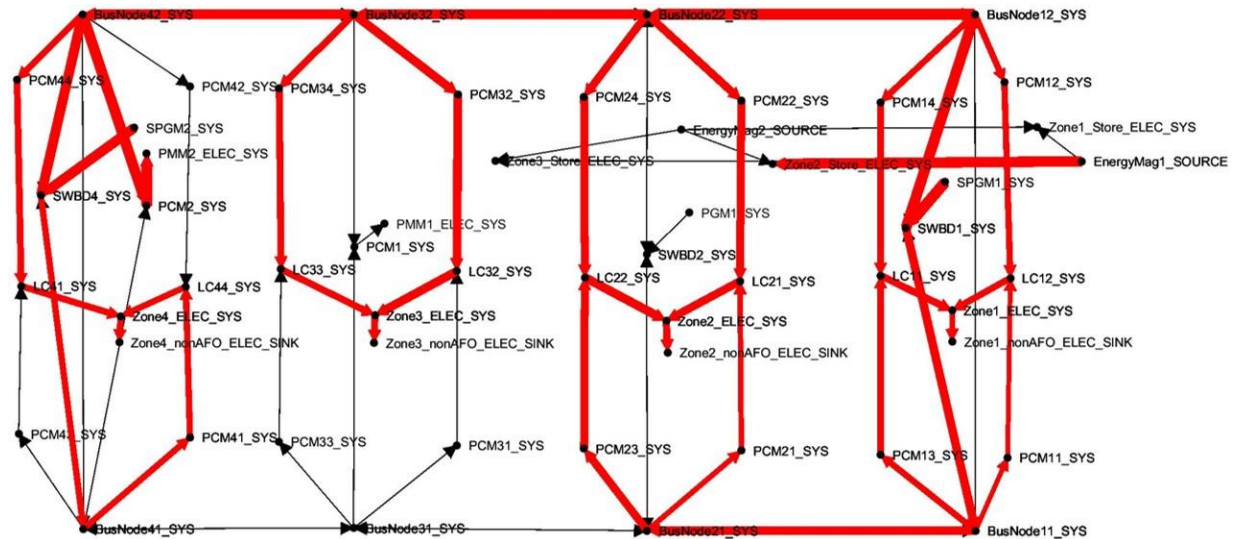


Figure 72. PSYS 6-3 ELEC Plex Deactivated MMR2 Lower System Response

Figure 73 and Figure 74 show the MECH and ELEC system responses for PSYS 7-3. PSYS 7 is a HED logical architecture. 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.

In the PSYS 7-3 deactivated MMR2 Lower system responses, power is generated by a SPGM in zone 2 and Ship Service Generators (SSGs) in zones 1 and 4. Power is distributed via port and

starboard buses to the zonal ELEC nodes, zonal non-AFO nodes, and the port PMM in zone 4. As in PSYS 6-3, power at the PMM is then transferred from the ELEC plex to the MECH plex where it continues down the port shaft to the port propeller and then to the Propulsion_SYS sink node. The Main Propulsion Engine (MPE) in the MECH plex, as well as the SPGM and PMM in ELEC zone 3 are all in MMR2. These VCs are deactivated and cannot supply propulsion power to the starboard shaft.

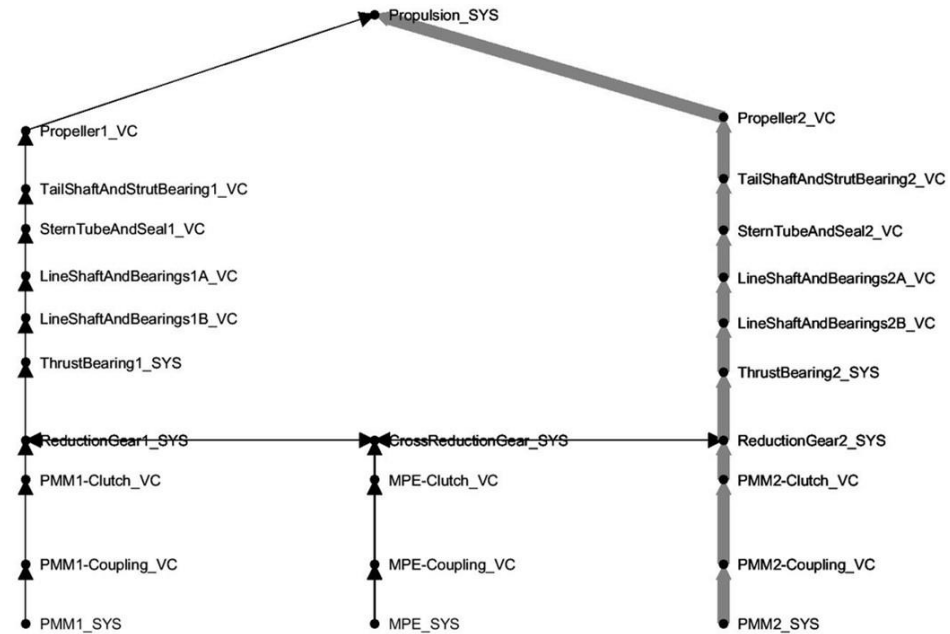


Figure 73. PSYS 7-3 MECH Plex Deactivated MMR2 Lower System Response.

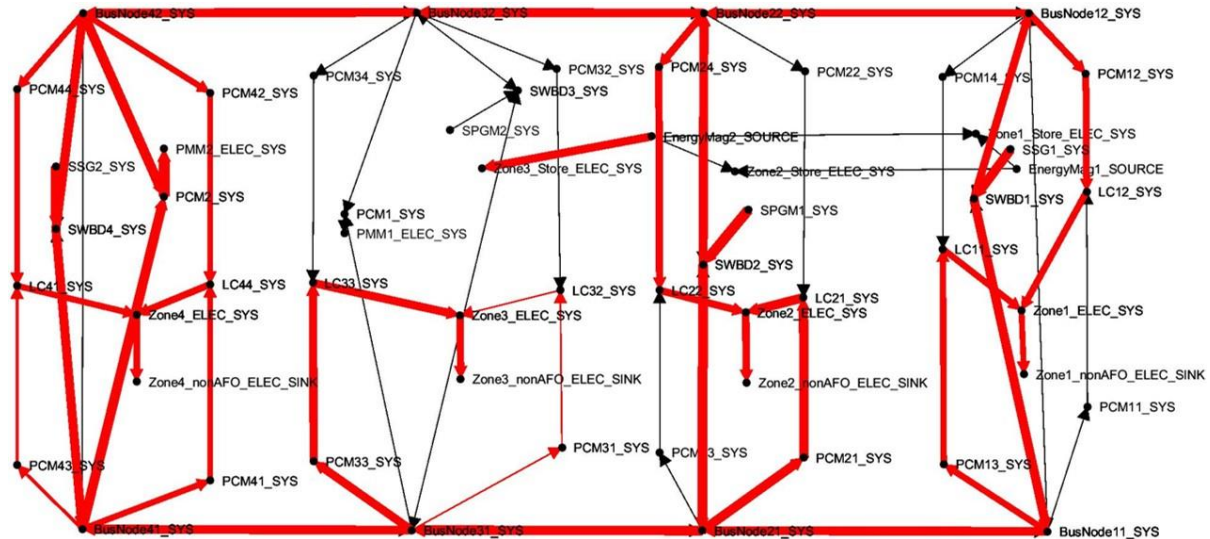


Figure 74. PSYS 7-3 ELEC Plex Deactivated MMR2 Lower System Response

Figure 75 and Figure 76 show the MECH and ELEC system responses of PSYS 8-3. PSYS 8 is a CODAG logical architecture. 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.

In the PSYS 8-3 deactivated MMR2 Lower system responses, power is generated by SSGs in zones 1, 2, and 4. Power is distributed via port

and starboard buses to the zonal ELEC nodes and zonal non-AFO nodes. There are no PMMs since PSYS 8-3 is a CODAG logical architecture. Power to the starboard shaft is supplied by Secondary Propulsion Engine (SPE) in MMR1 where it continues down the shaft to the port propeller and then to the Propulsion_SYS sink node. The MPE and Port SPE in the MECH plex, as well as the SSG ELEC zone 3 are all in MMR2. These VCs are deactivated and cannot supply propulsion power to the ELEC plex or port shaft.

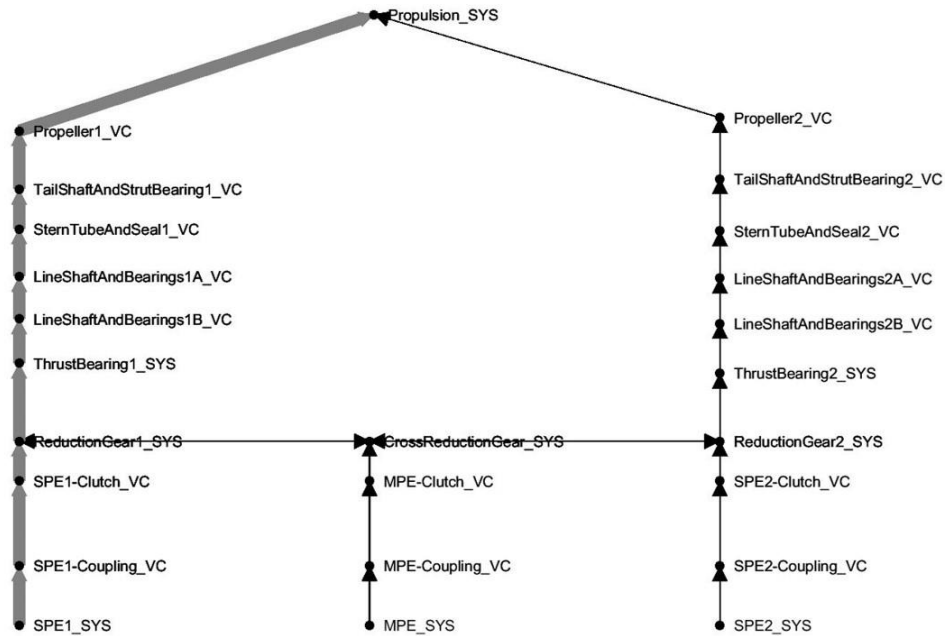


Figure 75. PSYS 8-3 MECH Plex Deactivated MMR2 Lower System Response.

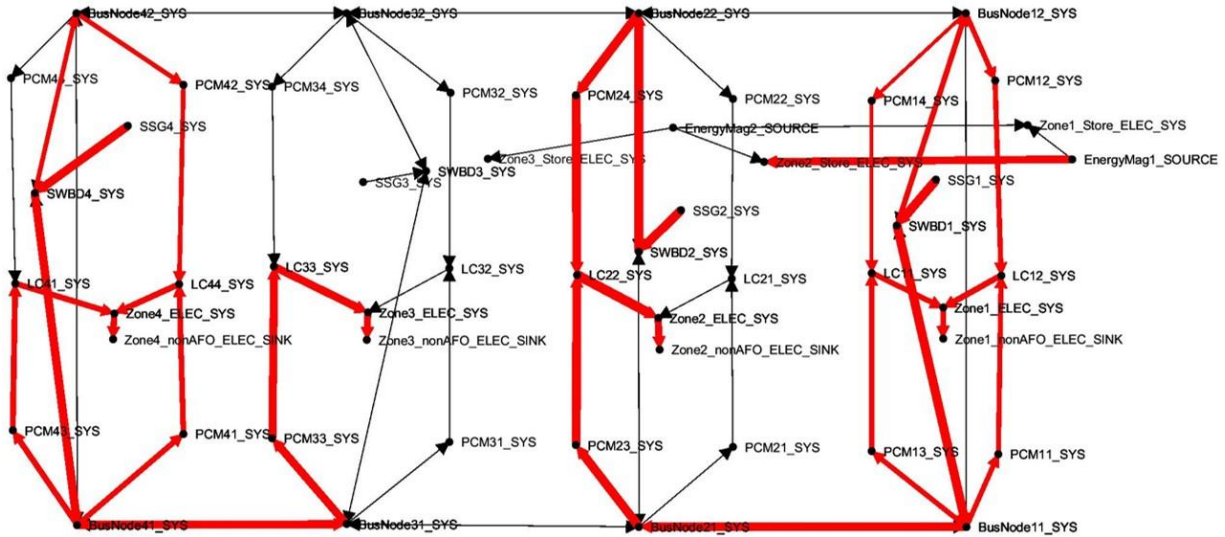


Figure 76. PSYS 8-3 ELEC Plex Deactivated MMR2 Lower System Response

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.

Architecture Flow Optimization (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 Concept & Requirements Exploration (C&RE) process, the MPES design process, system validation, commodity-based Vital Component

(VC) sizing, and vulnerability/survivability analysis.

This paper presents refinements to the AFO methodology and a surface ship case study. However, after multiple case studies (Robinson, 2018, Parsons et al., 2021, 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 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 underwater explosion (UNDEX) and UNDEX Shock Vulnerability Assessment criteria in addition to air explosion (AIREX).
- Development of time-based operational architecture methods and tools in the network architecture framework for surface ship 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
- Power Transition load analysis using a Dynamic Architecture Flow Optimization (DAFO). Recent work in this field, but only for electrical systems includes Stevens, Opila, Cramer, & Zivi, 2017 and Stevens, Opila, Oh, & Zivi, 2017.
- 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, & Stevens, 2019.

Acknowledgements

The authors would like to thank Ms. Kelly Cooper, ONR Code 331, for supporting this work under contract N00014-15-1-2476. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the Office of Naval Research. DCN# 43-5999-19.

Author Biographies

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. He researches network-based methods to assess surface ship distributed system vulnerability, survivability, and

deactivation recoverability in concept stage design. He received his M.S. in Ocean Engineering from Virginia Tech in 2019 and his B.S. in Naval Architecture and Marine Engineering from the University of New Orleans

in 2016. He is a student member of ASNE and SNAME.

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 surface ship distributed system vulnerability, survivability, and deactivation recoverability in concept stage design. He received his B.S. in Naval Architecture and Marine Engineering from the Turkish Naval Academy in 2006. He received his S.M. in Naval Architecture and Marine Engineering from MIT in 2010. He is a student

member of ASME and SNAME and alumni of MIT (Educational Counselor).

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 2015 recipient of the SNAME Webb Medal for Outstanding Contributions to NA&ME Education. 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.

References

- Andrews, D. J., Pawling, R., Gillespie, J. W., Singer, D. J., Duchateau, E., & Hopman, H. (2012). State of the Art Report: Design for Layout. International Marine Design Conference.
- Andrews, D. J. (2018). Choosing the Style of a New Design - The Key Ship Design Decision. International Journal of Maritime Engineering, Vol 160(A1).
<https://doi.org/10.3940/rina.ijme.2018.a1.457>
- Ashish, G. (2008a). Chapter 3 Linear Programs. <http://web.stanford.edu/~ashishg/msandde111/notes/chapter>
- Ashish, G. (2008b). Chapter 5 Network Flows. <http://web.stanford.edu/~ashishg/msandde111/notes/chapter>
- Brefort, Dorian, Shields, Colin, Habben Jansen, Agnieta, Duchateau, Etienne, Pawling, Rachel, Droste, Koen, Jasper, Ted, Sypniewski, Michael, Goodrum, Conner, Parsons, Mark A., Kara, Mustafa, Roth, Mark, Singer, David J., Andrews, David, Hopman, Hans, Brown Alan J., Kana, Austin (2018). An architectural framework for distributed naval ship systems. *Ocean Engineering*, 147, 375–385
- Brown, Alan J. (2020). Design of Marine Engineering Systems in Ship Concept Design. In M. G. Parsons (Ed.), *Marine Engineering* (4 Ed., pp. 1–39). SNAME .
- Brown, Alan, Salcedo, Juan. (2003). Multiple-Objective Genetic Optimization in Naval Ship Design, *Naval Engineers Journal*, 115(4), 49–61
- Brown, Alan J., Thomas, M. (1998). Reengineering the Naval Ship Concept Design Process" in *From Research to Reality in Ship Systems Engineering Symposium*, ASNE
- Brown, Alan J., Sajdak, John. (2015). Still Re-Engineering the Naval Ship Concept Process. *Naval Engineers Journal*, 127(1), 49–61
- Chalfant, Julie. (2015). Early-Stage Design for Electric Ship. Proceedings of the IEEE, 103(12), 2252–2266.
<https://doi.org/10.1109/JPROC.2015.2459672>
- Chalfant, Julie, Chrysostomidis, Chrys, Snyder, Daniel, Parsons, Mark A., Brown, Alan (2017a). Graph Theory Applications in FOCUS-Compliant Ship Designs, in *Electric Ship Technologies Symposium 2017*, Alexandria, VA: IEEE
- Chalfant, Julie, B. Langland, D. Rigterink, C. Sarles, P. McCauley, D. Woodward, A. J. Brown and R. Ames (2017b) Smart Ship System Design (S3D) Integration with the Leading Edge Architecture for Prototyping Systems (LEAPS), in *Electric Ship Technologies Symposium 2017*, Arlington, VA: IEEE
- Cramer, A. M., Chen, H., & Zivi, E. L. (2013). Shipboard electrical system modeling for early-stage design space exploration. 2013 IEEE Electric Ship Technologies Symposium, ESTS 2013, 128–134.
<https://doi.org/10.1109/ESTS.2013.6523723>
- Chinneck, J. (2020). Practical optimization: a gentle introduction. Practical Optimization: A

- Gentle Introduction.
<https://www.optimization101.org/>
- de Vos, P., Stapersma, D., Duchateau, E. A. E., & van Oers, B. (2018). Design Space Exploration for on-board Energy Distribution Systems - A New Case Study. Proc. of 17th Conference on Computer and IT Applications in the Maritime Industries (COMPIT).
- Duchateau, E. A. E. (2016). Interactive Evolutionary Concept Exploration in Preliminary Ship Design. In TU Delft University.
- Gillespie, J. W., Daniels, A. S., & Singer, D. J. (2012). Approaching ship arrangements from a non-spatial point of view using network theory. Proceedings of the 11th International Marine Design Conference (IMDC 2012).
- Gillespie, J. W., & Singer, D. J. (2013). Identifying drivers of general arrangements through the use of network measures of centrality and hierarchy. *Ocean Engineering*, 57, 230–239.
<https://doi.org/10.1016/j.oceaneng.2012.09.002>
- Gillespie, J. W., Daniels, A. S., & Singer, D. J. (2013). Generating functional complex-based ship arrangements using network partitioning and community preferences. *Ocean Engineering*, 72, 107–115.
<https://doi.org/10.1016/j.oceaneng.2013.05.007>
- Goodfriend, David, Brown, Alan J. (2018). Exploration of System Vulnerability in Naval Ship Concept Design, *Journal of Ship Production and Design*, 34(1), 42-58.
- IBM (2014), *IBM ILOG CPLEX Optimization Studio CPLEX User's Manual Version 12 Release 6*. USA: International Business machines Corp.
- Habben Jansen, Agnieta, de Vos, Peter, Duchateau, Etienne, Stapersma, Douwe, Hopman, Hans, van Oers, Bart, Kana, Austin A. (2019). A Framework for Vulnerability in Early Stage Design of Naval Ship Systems, in *Intelligent Ships Symposium 2019*, Philadelphia, PA: ASNE
- Habben Jansen, A.C., Duchateau, E.A.E., Kana, A.A. (2018). Towards a novel design perspective for system vulnerability using a Markov chain, in 14th International Naval Engineering Conference, Glasgow, Scotland: IMarEST
- Habben Jansen, A.C., Duchateau E.A.E., Kana, A.A., Hopman, J.J. (2019). Assessing complex failure scenarios of on-board distributed systems using a Markov chain. *Journal of Marine Engineering and Technology*,
<https://doi.org/10.1080/20464177.2019.1673032>
- Habben Jansen, A.C., Kana, A.A., Hopman, J.J. (2018). An approach for an operational vulnerability assessment for naval ships using a Markov model, in 13th International Marine Design Conference, Helsinki, Finland.
- Habben Jansen, A.C., Kana, A.A., Hopman, J.J. (2019). A Markov-based vulnerability assessment for the design of on-board distributed systems in the concept phase. *Ocean Engineering*, 190
- Konak, A., & Smith, A. E. (2018). Network Reliability Optimization. In Handbook of Optimization in Telecommunications (pp. 735–760). by M. G. C. Pardalos and P. Resende.
- McDonald, T. P. (2010). A Library Based Approach for Exploring Style in Preliminary Ship Design. In Department of Mechanical Engineering. UCL (University College London).
- Parsons, M. A., Kara, M. Y., Robinson, K. M., Stinson, N. T., & Brown, A. J. (2021). Early-Stage Naval Ship Distributed System Design Using Architecture Flow Optimization. *Journal of Ship Production and Design*, 37(02), 78–96.
<https://doi.org/10.5957/JSPD.10190058>
- Parsons, Mark A., Robinson, Kevin, Kara, M. Y., Stinson, Nick, Snyder, Dan, Woodward, David, Brown, Alan J., (2019). Application of a Distributed System Architecture Framework to Naval Ship Concept and Requirements Exploration (C&RE), in *Intelligent Ships Symposium 2019*, Philadelphia, PA: ASNE
- Pawling, Richard. (2007). The application of the design building block approach to innovative ship design. Pawling, Rachel, Piperakis, A., & Andrews, D. J. (2015). Developing Architecturally Oriented Concept Ship Design Tools for Research and Education. Proceedings of the 12th International Marine Design Conference.

- Robinson, Kevin M. (2018). *Modeling Distributed Naval Ship Systems using Architecture Flow Optimization* (thesis), Virginia Polytechnic Institute and State University, Blacksburg, VA
- Stevens, John D., Opila, Daniel F., Cramer, Aaron M., Zivi, Edwin L. (2017). Operational Vignette-based Electric Warship Load Demand, in *Electric Ship Technologies Symposium 2017*, Arlington, VA: IEEE
- Stevens, John D., Opila, Daniel F., Oh, Eun S., Zivi, Edwin L. (2017). All-Electric Warship Load Demand Model for Power and Energy System Analysis Using Exogenously Initiated Threats, in *Electric Ship Technologies Symposium 2017*, Arlington, VA: IEEE
- Sinsely, Gregory L., Opila, Daniel F., Stevens, John (2019). Dynamically Coupled Process Control and Power Management for Shipboard Power and Energy System Applications, in *Electric Ship Technologies Symposium 2017*, Arlington, VA: IEEE
- Stepanchick, Justin, Brown, Alan. (2007). Revisiting DDGX/DDG-51 Concept Exploration. *Naval Engineers Journal*, 119(3), 67-88
- Stinson, Nicholas T. (2019). *Refinement of Surface Combatant Ship Synthesis Model for Network-Based System Design* (thesis), Virginia Polytechnic Institute and State University, Blacksburg, VA
- Stinson, Nicholas T., and Brown, Alan J. (2019). Ship Distributed System Design and Synthesis Using Architecture Framework, in *SNAME Maritime Convention 2019*, Tacoma, WA: SNAME
- Strock, Justin, Brown, Alan. (2008). Methods for Naval Ship Concept and Propulsion System Technology Exploration in a CGX Case Study. *Naval Engineers Journal*, 120(4), 95-122
- Snyder, Daniel J. (2019). *Deactivation Diagram Development for Naval Ship System Vulnerability Analysis* (thesis), Virginia Polytechnic Institute and State University, Blacksburg, VA
- Snyder, Daniel J., Parsons, Mark A., Brown, Alan J., Chalfant, Julie. (2019). Network Architecture Framework Applications with FOCUS-compliant Ship Designs, in *Electric Ship Technologies Symposium 2019*, Alexandria, VA: IEEE
- Trapp, Thomas A. (2015). *Shipboard Integrated Engineering Plant Survivable Network Optimization* (dissertation), Massachusetts Institute of Technology, Cambridge, MA
- van Oers, B., & Hopman, H. (2010). A 3D Packing Approach for the Early Stage Configuration Design of Ships. COMPIT 2010.
- van Oers, B. (2011). A Packing Approach for the Early Stage Design of Service Vessels.
- van Oers, B., Stapersma, D., & van Ingen, G. (2012). An integrated approach to design, route and evaluation of resilient ship service systems. International Naval Engineering Conference and Exhibition (INEC).

The Force Behind the Fleet
–Naval Sea Systems Command

Paper #4 – Operational Architecture and Framework for Assessing Mission Effectiveness in Surface Ship Concept and Requirements Exploration

Alan Shane¹, Mark A. Parsons¹, David J. Berrow¹, Mustafa Y. Kara¹, and Alan J. Brown¹

Abstract

This paper proposes and demonstrates a framework and surface ship Operational Architecture (OA) for assessing ship system designs using a Design Reference Mission (DRM) in surface ship Concept and Requirements Exploration (C&RE). It applies a Mission Means Framework (MMF) approach to decompose missions, tasks, and capabilities in a Mission, Power, and Energy System (MPES) Dynamic Architecture Flow Optimization (DAFO). Interaction with other agents in the warfighting environment is modeled as a discrete event operational simulation based on the DRM. The DAFO is used to optimize system alignment and recoverability at each time-step in response to the operational model and damage. Mission effectiveness is assessed and optimized in the time domain to support ship and ship system assessment and development within a Model Based Systems Engineering (MBSE) and Digital Engineering (DE) approach. This provides the foundation to assess the total ship system design impact on an integrated future fighting force.

Introduction

Mission, Power and Energy Systems (MPES) are fundamental to the design, mission, and operation of surface ships. MPES design and architecture are critical in 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 Vital Components (VCs) distributed throughout a ship that are connected to work together. This includes mission systems. 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. (2020) describe 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, Kerns, et al., 2011a, Kerns, et al., 2011b, Brown & Sajdak, 2015, and Parsons et al. 2019). Goodfriend & Brown (2018) describe 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. Survivability must be considered in C&RE.

Goodfriend & Brown (2018); Snyder (2019); Snyder et al. (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. Recoverability is not considered. Stevens et al (2017) consider power, but only electrical power. The total ship system is not modeled.

¹ Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech

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 77 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).

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). Developing and understanding the relationships between the systems and the mission provides the linkage to see how individual systems affect the overall effectiveness and relative effectiveness between systems.

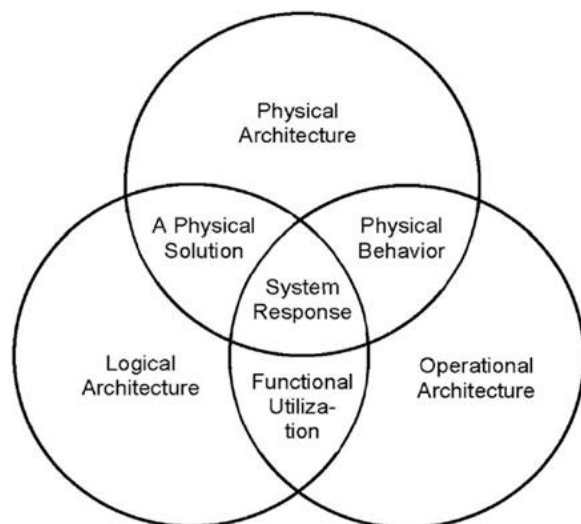


Figure 77. Architectural Framework for Distributed Ship Systems (Brefort et al., 2018)

Figure 78 shows examples of these architectures and their relationships. In early-stage design, physical architecture must be kept as simple as possible to support concept exploration. The physical architecture has two important classes of information: (1) the constraining architecture defined by the ship arrangement and relationships with compartments and subdivision, as illustrated at the top of Figure 78; 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 ship logical architecture is a network of nodes representing multiple system vital components, and arcs indicating their connectivity and relationships as shown in the lower left corner of Figure 2 for an electrical subsystem or plex. The interface between the logical architecture and the operational architecture is at capability nodes in the logical architecture. These capability nodes also reside in the “Functional Utilization” intersection shown in Figure 77. The operational architecture is illustrated in the lower right corner of Figure 78 and its development and application are presented in the remainder of this paper.

The simplified operational architecture, warfighting model, and mission system vital component models presented in this paper are for academic purposes only, adapted from content provided by Friedman (2006), Payne (2010), Hughes & Girrier (2018), and Appleget, et al. (2020) to a level of detail sufficient for fundamental research and the development of new methods, processes and system framework.

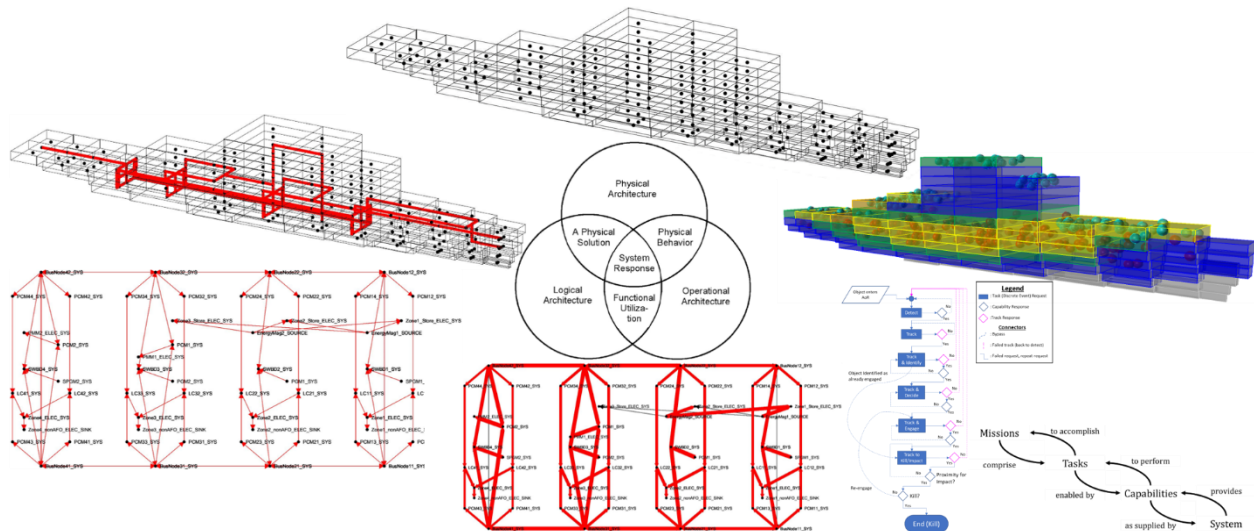


Figure 78. Virginia Tech Ship Architectural Framework

Ship System Behavior Models and Architecture for Missions

Lexicon and Identification

The following sub-sections detail the language and conventions used to describe the ship system operational architecture, operational model, warfighting model, and warfighting environment.

Identification/Naming

- **Library:** Generic source information. Agents and their associated characteristics are described in the Library.
- **Agent:** An intelligent operating vehicle, aircraft, missile, ship, boat, land base, etc. in the warfighting model.
- **Blue Ship:** “own” ship system of systems represented in the logical and physical architectures. The blue ship is also an agent, in the context of the warfighting environment.
- **Object:** an individual green, red, or gray agent viewed from the perspective of the blue ship.
- **Threat:** an individual red object (or green/gray object prior to identification) that is being analyzed or acted upon.
- **Team Colors:**
 - Green: applied to allied objects
 - Red: applied to enemy objects
 - Gray: applied to neutral objects

Mission Means Framework (MMF)

The definitions for terms in this framework are taken primarily from the DOD Dictionary of Military and Associated Terms (2020).

- **Mission** – a task and an operational objective assigned to a system or system of systems.
- **Task** – a clearly defined action or activity performed by a system which requires system capabilities, resources and/or information. Tasks may be decomposed into subtasks.
- **Capability** – a state of system function having sufficient system resources and/or information to perform a task.
- **System** – a functional (logical architecture), physical (physical architecture), and/or behavioral (operational architecture) group of related interacting/interdependent components. Systems may be decomposed into subsystems.

Models

- **Warfighting Model (WM):** the agent-based behavior model for determining how agents move and interact with each other (events) in the warfighting environment.
- **Ship Operational Model (OM):** the behavior model of a ship’s operational architecture (i.e. temporal relationships/discrete event formulation).

- Ship Capability Model (CM): the behavior model of the capability nodes in the logical architecture.
- Ship Dynamic Architecture Flow Optimization (DAFO) Model: the behavior model of the ship's distributed systems.

Warfighting Environment Areas

- Wargame Area (Total Warfighting Environment): Covers all areas, including all local warfighting environments (outside the scope of this paper).
- Operational Area (Local Warfighting Environment): Area in which operations take place.
- Area of Responsibility (Radius): The observable radius around and relative to the blue ship.

Mission Means Framework (MMF)

Figure 79 shows the Purdy (2004) MMF, a modified systems-engineering V-model, that illustrates the relationships between necessary elements in a system's operational architecture.

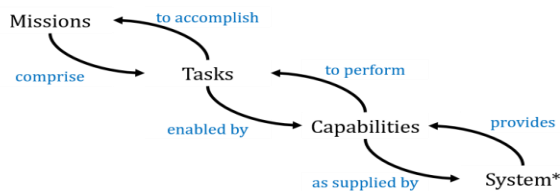


Figure 79. Modified Mission-Means Framework (Purdy, 2004)

A mission is comprised of and accomplished by tasks, the clearly defined actions or activities of a system which require system capabilities, resources and/or information to be performed. Each mission is assigned a measure of effectiveness (MOE), a quantitative or qualitative metric for how well a mission is accomplished by its comprised tasks. Each system capability is assigned measures of performance (MOPs), quantitative or qualitative metrics describing how well a task is performed by the capability that enables it. Both MOPs and MOEs can change with respect to time, system configuration, and availability of resources/information. The necessary and accomplished time-dependent relationships between one system state and the next comprise

the operational architecture. This state-based approach to modeling an operational architecture is similar to Stevens et al (2017).

Ship Behavior and Interaction Models

The Ship Behavior and Interaction Models (SBIMs) implement the MMF to accomplish mission(s) and perform tasks(s) specified by the DRM as system responses in a discrete event simulation. The SBIMs include three behavior models represented in Figure 4.

- Ship Agent Operational Model (OM)
- Ship Capabilities Model (CM)
- Ship Dynamic Architecture Flow Optimization (DAFO) Model

Figure 80 is an application and refinement of Figure 79 where the (blue) ship agent operational model requests capabilities from the capabilities model. Following this query, the capabilities model assesses the ability of the ship to provide the capabilities if supported by the MPES.

The OM is the blue ship mission/task behavior model implementing the blue ship's Operational Architecture and serves as the interface between the blue ship CM and the WM. It interacts with the CM through capability requests and responses, as shown in Figure 80. As an example, capability requests from the OM to the Anti-Air Warfare (AAW) system or plex are modeled and managed by the capability nodes in the logical architecture shown in Figure 81. The outcome of the execution of a task defined in the OM is determined by whether or not the ship possesses capability to perform the task. If the necessary capability is available, the task can be successfully performed.

The CM interfaces with the OM and the DAFO model to answer queries at each time step as described by Berrow, et al. (2021). The specific query being requested is specified by the OM based on the operational mode of the blue ship which determines decision capability logic and mission doctrine. The operational mode of an agent is selected during setup based on the OPSIT. The available operational modes are loitering, self-defense, offense, and attack. Both the offense and attack operational modes allow an agent to engage other agents. The attack mode is reserved for agents that require an intercept course to engage another agent such as an Anti-Ship Missile

(ASM). Berrow, et al. (2021) provides a further description of operational modes. A system response objective function in the DAFO model is

updated at each time step based on priorities specified by the OM and consistent with the operational architecture.

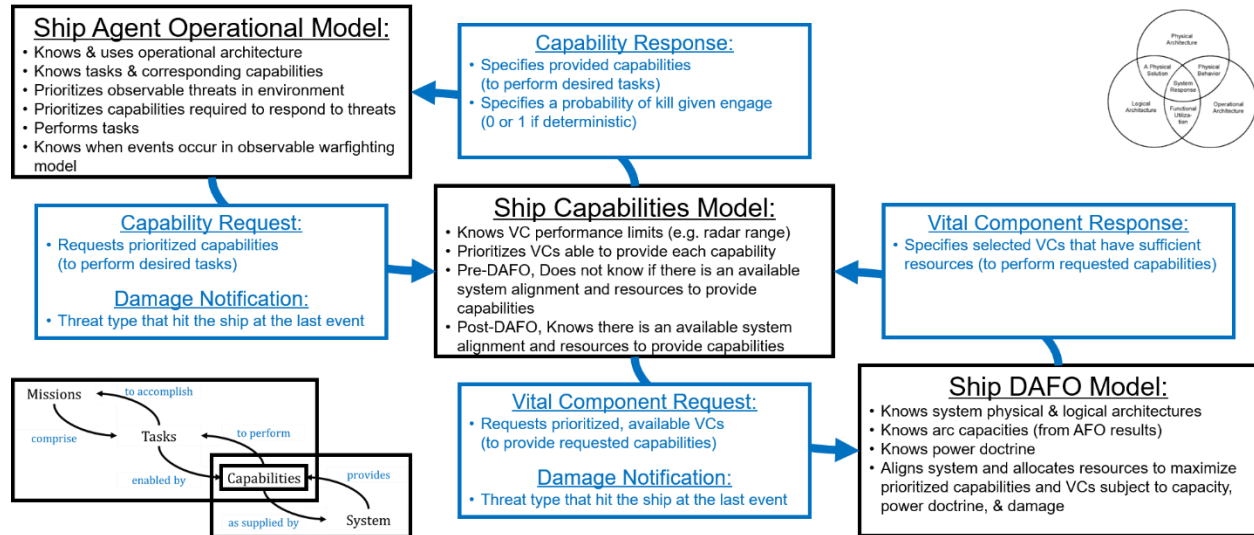


Figure 80. Ship Behavior and Interaction Models (SBIMs)

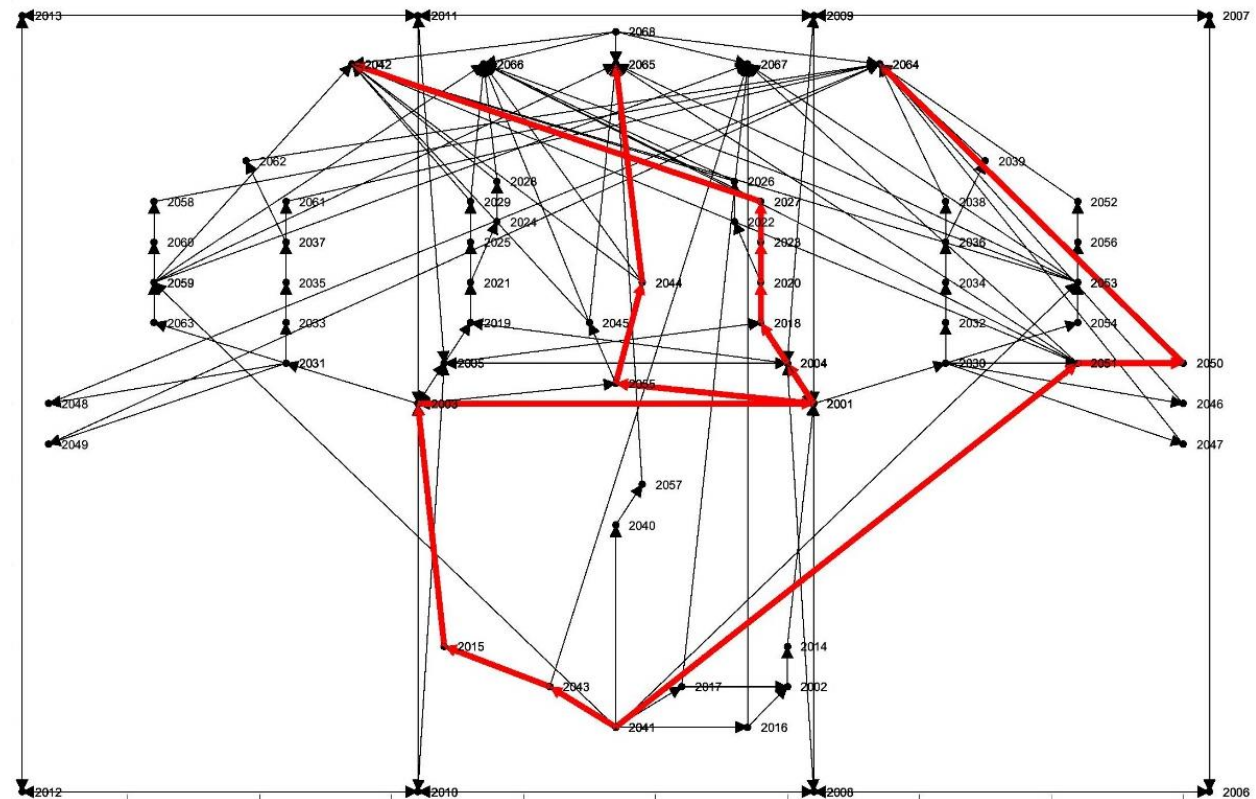


Figure 81. Notional Mission System Vital Components and Capability Nodes with Data Commodity Flows (adapted from Friedman, 2006, p 105 and Chalfant et. al, 2017)

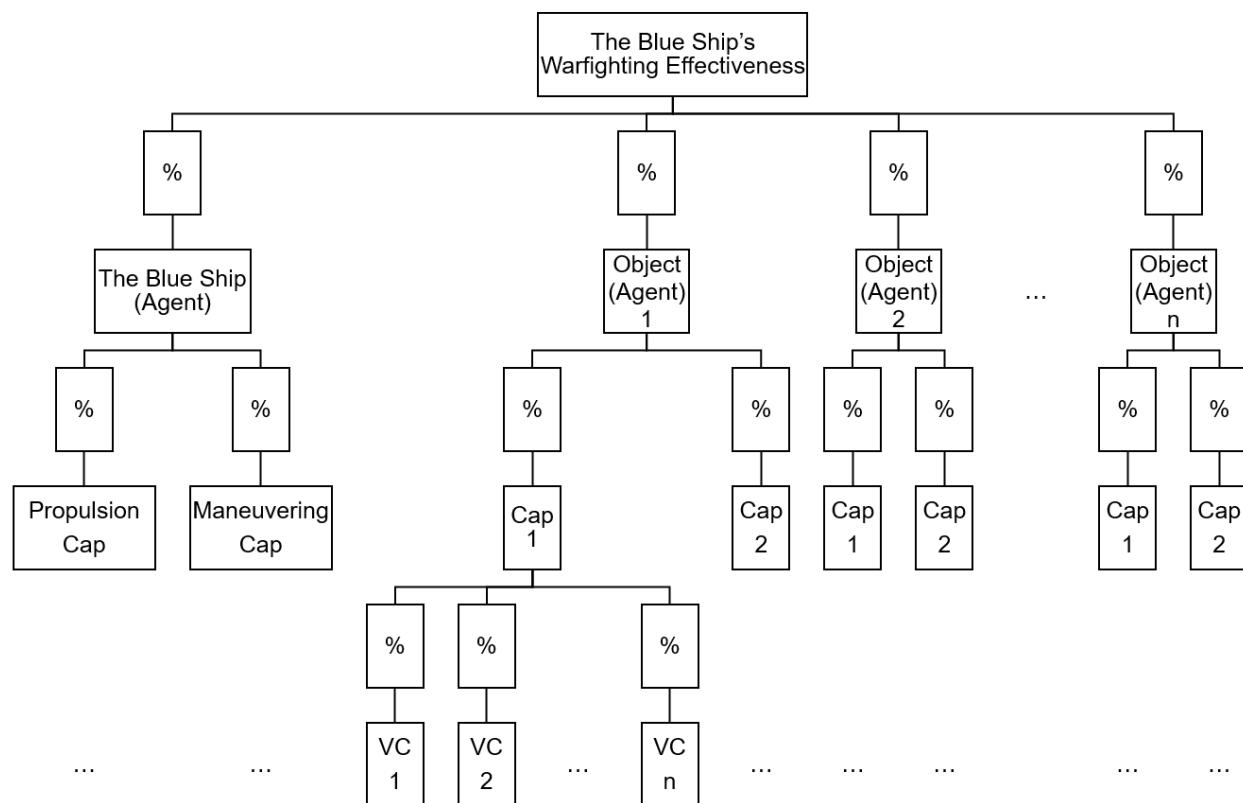


Figure 82. Effectiveness Hierarchy

The DAFO model uses both an energy formulation and a mission system data formulation to support and interface with the CM and OM as shown in Figure 80. The DAFO model determines the optimum energy flow and mission system data flow (0, 1) through the logical architecture to support the capability pull, translated by the CM, from the operational architecture at each time step. This data flow is a DAFO commodity in addition to the energy flow used to model a functional mission system as shown in Figure 82. Each of the AAW VCs in Figure 82 requires electric power and cooling which must be provided in the energy solution. The power and energy formulation and the basic AFO is described by Parsons et al. (2019), Brown (2020) and Parsons et al. (2021b). The DAFO model determines the mission system usage, data and energy flow using the prioritized capability pulls on the system to determine which Vital Components (VCs) are active during the discrete event.

At each time step, the mission effectiveness for the blue ship system is maximized in the DAFO model using the hierarchy shown in Figure 82, with priorities provided by the OM and CM.

Objects approaching the blue ship area of responsibility are assigned a priority between 0 and 1 by the OM based on:

- Time to impact the ship (or not)
- Potential damage to the ship (i.e. warhead kg TNT)

Threats reaching an engage task capability request are prioritized above all other threats. Object priorities are normalized to sum to 1 for all detectable objects/threats in the warfighting environment.

Warfighting tasks in the OA and their corresponding capability requests are structured according the steps in the kill chain (adapted from Payne, 2010; Office of the Chief of Naval Operations, 2007; and Office of the Chief of Naval Operations, 2014):

1. **Detect:** Detect
2. **Track:** Track
3. **Identify:** Track and Identify
4. **Decide:** Track and Decide
5. **Engage:** Track and Engage

Capabilities are prioritized and sum to 1 for each object. This basic series of tasks is also used as a simple and generic warfighting operational architecture as discussed and illustrated later in Figure 85. The temporal implementation of these generic tasks is more completely specified and described by the WM and OM consistent with the OA. System VCs provide capabilities, but more than one VC may be able to provide a single capability. To determine which VCs are best suited to provide each capability, capability MOPs are calculated for each VC. Based on these MOPs, VCs are prioritized between 0 and 1, and normalized to sum to 1 for each capability. For example, the engage capability may be requested for a threat, and may be provided by VC 1 or VC 2. For engage, the MOP used is the Probability of Kill (PKill), so the PKill against the threat is calculated for VC 1 and VC 2. In this example, if PKill for VC 1 is assessed as being two times greater than for VC 2, then VC 1 would receive a priority of 0.67 and VC 2 would receive a priority of 0.33.

The priorities associated with each VC are used in the DAFO objective function. The DAFO model maximizes effectiveness by selecting VCs to provide the optimum combination of successful capabilities as responses against the objects/threats, as described in Parsons, et. al (2021a).

SBIM Application

This paper focuses on the framework, architecture and methods necessary for the operational effectiveness assessment of an individual ship design being considered in C&RE. Previously, the C&RE evaluation was performed based on relative effectiveness by comparing ship designs to each other, rather than modeling the ship design in an operational scenario to determine its effectiveness. This research seeks to improve the assessment process by explicitly considering the ship's effectiveness to perform a DRM. Ultimately, this design overall measure of effectiveness (OMOE) will be used to compare designs

The SBIMs are developed to be universal for any specific Operational Situation (OPSIT) within a DRM, which is made possible by the MMF decomposition. This allows a system to be analyzed in a series of OPSITs within each DRM

using the same SBIM model formulation and also enables a broader application above the single ship system of system (SoS) level.

A single DRM was chosen as the test case and proof of concept for this paper. The DRM modeled for this paper is a blue ship in the self-defense operational mode (i.e. the blue ship engages all threats that are in offense or attack operational modes engaging or attacking the blue ship) with Anti-Air Warfare (AAW) and Anti-Surface Warfare (ASUW) warfighting areas. Each OPSIT is modeled independently in the WM as its own discrete event simulation. The OPSITs chosen are designed to test specific components of the SBIMs within a single DRM. Validating the process and its functionality with this limited scope allows the future application to additional DRMs and OPSITs within them including additional warfighting areas and higher numbers of threats. The three OPSITs chosen are listed below and described in detail in later sections:

- Attack by enemy ASM with allied ship, & neutral ship nearby.
- Attack by enemy ship & enemy aircraft using ASMs.
- Attack by enemy ship using multiple ASMs. Every 3rd ASM is programmed to hit the blue ship, i.e. not capable of being intercepted. This ensures damage to the blue ship and forces recoverability reconfiguration by the DAFO.

In its current configuration, the OPSIT is modeled as a discrete event simulation in the OM where the actions of all other objects are prescribed rather than being self-aware and reactive to other stimuli within the warfighting environment. Modeling the overall OPSIT and interactions as deterministic reduces the complexity and increases repeatability of an individual OPSIT. Additionally, by fixing the scenario seen by the blue ship, it allows for a more direct comparison between ship designs.

The overall process flow is expandable into a fully agent-based probabilistic simulation where each agent has its own system models reacting to and interacting with other agents. This is discussed in the future work section.

Because of the MMF decomposition and generic SBIMs, the same framework can also be

extended to higher SoS levels. Figure 7 shows a systems engineering design V for an integrated force/fleet decomposition and synthesis with assessment. Each level in this model (fleet, force, group, ship) down to the components represents a system of systems (SoS) of its lower levels. Utilizing the MMF methodology for the OA within each level, for each system model, would make it easier to assemble an overall model and determine traceability from the highest levels down to the lowest.

This extension of the single blue ship application would be an important step towards a more detailed and integrated MBSE approach by integrating both sides of the Figure 83 design V together to assess how the model performs the mission(s) and how this is impacted at each level. The current SBIM, identified by the circled area in Figure 83, only models the response of individual blue ship distributed systems (modeled with the DAFO model) required to accomplish mission(s) specified by the DRM.

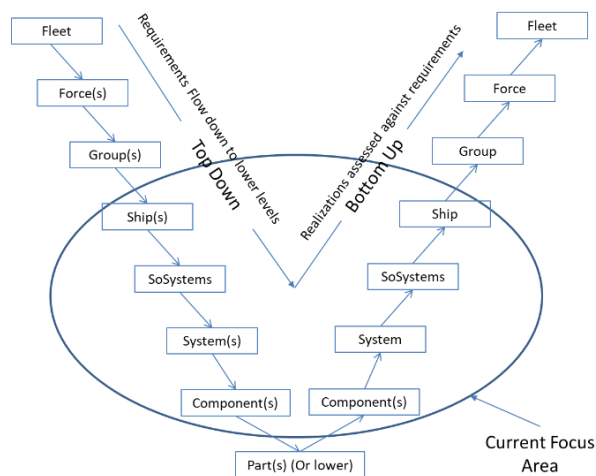


Figure 83. Ship Design Development Methodology & Force/Fleet Interfaces

Warfighting Model (WM)

The agent-based warfighting behavior model describes how agents move and interact with each other (events) in the warfighting environment and can be very complex, but this is necessary to correctly simulate specific OPSITs in a DRM. It is also necessary to filter all the complex object actions and behaviors going on in the WM to the perspective of the blue ship system model consistent with the system framework, logical and

physical architectures. The operational architecture (OA) provides a basic temporal task structure for viewing and specifying the blue ship operational interface and the operational model (OM) provides additional details about the blue ship operational behavior necessary for interfacing with and providing an operational pull on the capability nodes and capability model (CM). The whole process begins with the DRM and the WM.

Warfighting operations are modeled in 3-D model-based simulations of the individual OPSITs specified in the DRM. Every agent has its location and speed tracked and its relative distances to other agents calculated at each time step until it is destroyed or identified as friendly. The relative distances are used to make a determination if agents are hit during an engagement.

The simulation is also designed to allow the allocation of individual local warfighting environments around individual agents based on their operational area and/or Area of Responsibility (AoR). In its current configuration only the AoR is used, but this could be expanded to include additional parameters to further define the warfighting environment and associated mission doctrine for each agent.

The AoR provides the distance at which the kill chain begins for an object relative to the agent. This AoR acts as the filter and translator between the list of agents at the WM level down to the list of objects relative to the blue ship.

The WM includes all agents that exist and processes their metadata to one that can be processed by a single agent Operational Architecture. Having fixed interfaces between the warfighting environment and the agent SBIM, through the OM, makes its integration into the warfighting environment relatively simple. The integration and interactions with other agents is more difficult.

In its current test configuration, the WM only parses information and the OM of the blue ship only reacts to changes in the warfighting environment. Developing the methodology for a DRM where the blue ship operates alone is a first step to show the process of implementing MMF for a simple and more manageable scenario. In reality, agents operate as more of a network, sharing resources and capabilities to complete missions. The MMF provides an excellent structure for allocation within a single agent, but

the same framework would also apply when trying to integrate across multiple agents.

The WM controls and maintains where the agents are in space, translates responses from the agents into the creation of new agents (e.g. firing of missiles) and executes the movements for each agent. From an integration perspective, the model being used to develop the responses is irrelevant as long as it can use the same interfaces, and the blue ship OM is one of those interfaces. This independence allows for agents to be modeled in a variety of different ways. For the OPSITs run, each agent that is not the blue ship operates based on a fixed preprogrammed set of actions that are selected during the initialization as described above.

Agent Movement

The process for moving agents within the Air, Surface, Sub-Surface domains is the same, where each agent has a physical point in space that it is moving towards. For some agents that point may be another agent that it is trying to hit, or it could just be a way-point in space.

All movement at this stage is a point to point progression where the agent moves in steps based on its speed and the duration between time steps. Agents that are specifically targeting an agent are the only ones that can change their trajectory by updating their target point based on the movements of the agent that is being targeted.

Energy weapon intercepts are tracked as an agent that is being used to engage another object, but there is no actual agent modeled. Decoys are modeled and tracked as physical objects in space but their creation and addition to the warfighting environment is unique. Rather than being immediately brought into the wargame, they are modeled as coming into existence just when a target threat is engaged.

Kill/Impact Resolution and Damage

Checks for an impact between two agents are based on their proximity to each other and the amount of space that they would move in the current time step. If they would occupy the same physical space within that time step, an impact check is initiated. The impact check is based on the probability of hit for the agent relative to whatever it is hitting using an approach similar to Appleget et al. (2020, p. 111).

This proximity check is done for all agents except those classified as energy. For energy, rather than a proximity calculation, a check on dwell time is performed. If the energy engagement is maintained for the entire dwell time required, it is considered an impact.

When an impact is determined, the agent that is hit is assessed against its damage tolerance to determine if it is killed and therefore removed from the scenario. Currently, all agents use notional thresholds. These thresholds are set based on the number of hits and/or the total amount of theoretical damage that they can sustain. Temporarily, for this OPSIT, the blue ship has a damage tolerance equal to a predefined cumulative total of kg TNT using an approach adapted from Hughes & Girrier (2018, p. 152). Once the capability interface and DAFO have been fully tested, the blue ship damage extent calculation developed by Stark (2016) in the physical model (PM) will be implemented using the Physical Architecture / OA interface.

The OPSIT is currently set to run until either the blue ship exceeds its damage tolerance, all enemy objects are destroyed, or the run time of the scenario has expired.

Limitations and Assumptions

In the DRM and OPSITs chosen, only surface and aerial objects are currently modeled. The process is setup to support undersea agents as well but it was not modeled as a part of this paper's effort.

There is currently no capability to model multi-domain movement, air/surface to sub-surface or vice versa. There are no OPSITs with sub-surface agents so this is not an issue for this paper.

For tracking and targeting information, the process does not currently support the use of offboard sensors or network data. The DRM and OPSITs are developed such that there are no other resources that can provide that data, but adding this capability is planned for future work.

There is also no current ability to prioritize between warfare areas and share missions between agents. Engagements and intercepts on other agents are only launched one at a time. Upon resolution of an impact, another engagement or intercept is launched if the target is not destroyed.

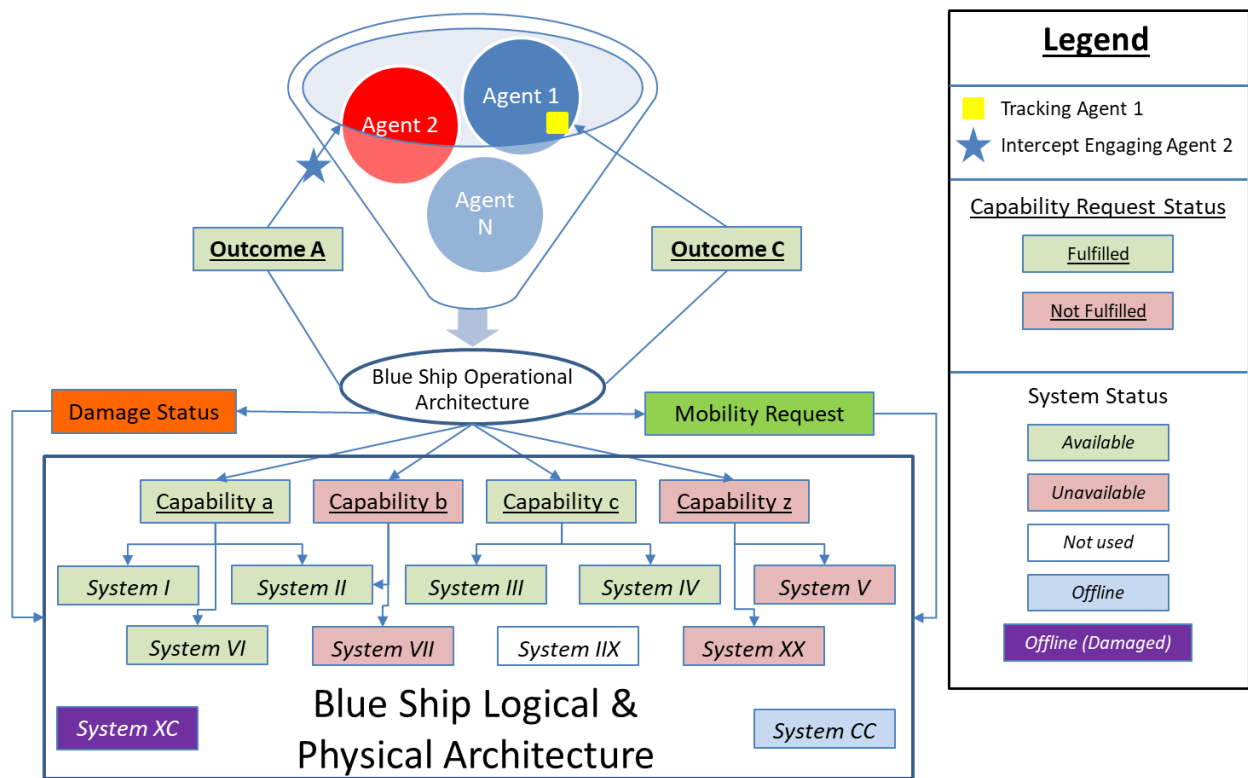


Figure 84. Warfighting Model and System Interface

Operational Architecture (OA) and the Operational Model (OM)

The Operational Architecture described in this paper was developed to be agent independent, but is intended specifically for the blue ship. The blue ship's OM supports its OA and interfaces with the WM and other objects in it. Figure 84 shows a notional process of how the OM works and how the responses to capability requests are determined.

The OM is represented as a funnel to ingest, filter, and analyze the warfighting environment, and all objects in it, to create an operating picture for the blue ship consistent with its OA and to translate any actions/tasks completed by the blue ship back into the warfighting environment. The OM also serves as a filter and processor to determine the appropriate capability requests when decomposing the operating picture into prioritized capability requests that align with the 5 step kill chain.

The objects are prioritized by their relative importance calculated as a combination of the

damage that an object can do to the blue ship and how long it would take for it to impact. Until the object has been identified, notional damage and speed are assigned based on the object class defined by its warfighting area and size. Time to impact is calculated assuming the object is targeting the blue ship using its current range and notional speed. After the object has been identified, actual values for damage and time for the object to hit its target are used for prioritization. The weighting of these two factors is currently set to the following levels:

- Damage: 30%
- Time to Impact: 70%

An exception to this rule for prioritization is when an "Engage" request is made. When an "Engage" request is made, the priority of the object(s) that is being engaged is inflated to ensure that it gets priority above any other objects that are not being engaged. The weighting is done such that any object(s) being engaged split the engage priority amongst them according to their relative

importance, and all other objects split the remainder.

- “Engage” objects priority: 95%
- Other objects (remainder): 5%

This combination of relative importance with the specific engage prioritization creates a notional priority weighting that is then used to assign a priority for each object that cumulatively sum to 1 for all objects. For example, if two equally weighted objects (A,B) are requested to be engaged and two other equally weighed objects (C,D) are requested to be tracked, A and B would each receive a 47.5% weight, and C and D would each receive 2.5%.

The blue ship must effectively continue to “Track” during the kill chain steps that follow it: Identify, Decide, and Engage. These requests are treated as combination requests (i.e. Identify and Track, Decide and Track, Engage and Track). In a combination request, track is weighted higher than the accompanying request (e.g. Identify, Decide, or Engage) This is done because if the track is lost for an object it must restart the kill chain at Detect. If Track is lost, it does not lose the metadata associated with the object which includes any decision already made or engagements that have been launched. These are re-associated with the object after it is re-identified. The relative priorities between capability request for each step are shown in Table 11. These align with the requests made in each step shown in Figure 85.

Figure 85 shows the operational architecture and capability request logic associated with the discrete events taking place for each object. This is how the OM develops and progresses between the capabilities being requested.

Responses to the capability requests are determined based on the availability of the systems required to provide it, as shown in Figure 84. A response to a capability request is only successful if all of the systems and resources (energy, cooling and data) required to provide it are online and available. Conversely, a capability request is unsuccessful if the systems and resources required are not available. Based on the responses, the OM will update the status, and send any physical outcome to the WM. The response is stored as the status for the step within the kill chain, for each object.

		Capability Request				
		Detect	Track	Identify	Decide	Engage
Kill Chain Step	Detect	100%	0%	0%	0%	0%
	Track	0%	100%	0%	0%	0%
	Identify	0%	60%	40%	0%	0%
	Decide	0%	60%	0%	40%	0%
	Engage	0%	60%	0%	0%	40%

Table 11. Capability Request Prioritization

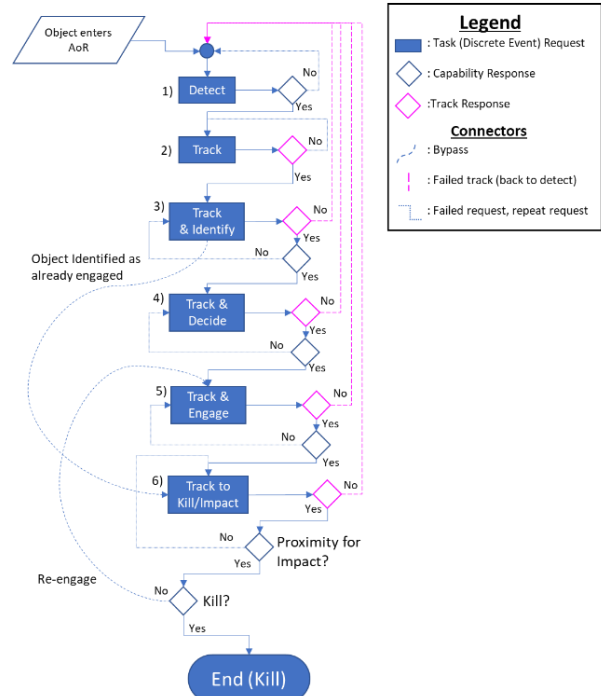


Figure 85. Kill Chain Operational Architecture

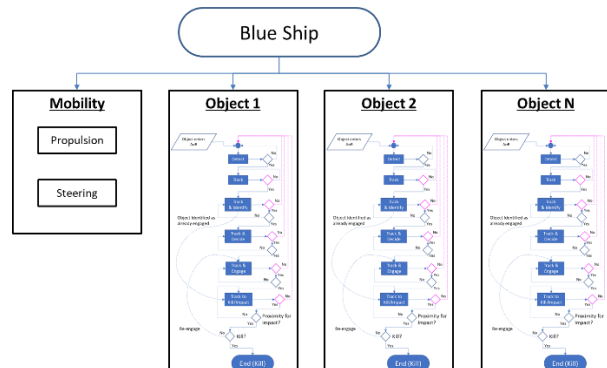


Figure 86. Ship Operational Architecture

Figure 86 is an extension of Figure 85 and shows a top down look from within the blue ship of the potential capability requests. This shows the kill chains associated with each individual object, that can be at any step within it at a given

time-step, as well as the mobility request that would accompany them at each time-step. The mobility requests are important to identify because the ability to fulfill these requests may be impacted by the power demands of other capability requests for objects in the warfighting environment.

While Figure 86 is generic, it aligns with the overall tactical picture shown in Figure 87, and shows how the steps within the kill chain progress for each object. Figure 87 specifically shows the overall tactical picture for OPSIT 1, including enemy aircraft, allied ship, and neutral ship, and how each object progresses through the kill chain within that OPSIT. The figure shows the relative positions of the other objects relative to the blue ship, but does not show the passing of time, or the movement of the blue ship which are calculated and retained.

The numbering scheme correlates to the 5 steps in the kill chain. Step 0 denotes when the object is too far away to be detected by any shipboard systems and therefore has not begun its

progression through the kill chain and Step 6 denotes the Kill/Impact step in Figure 85.

Each number represents the step within the kill chain for the object at that physical location. The kill chain starts once the object enters into the Area of Responsibility and a detect request is made, step 1. From there the progression follows the kill chain and request logic in Figure 85. The logic for each Decision, step 4, is based on a pre-determined mission doctrine that assesses the intent of the target object relative to the blue ship mission and what team it is on to determine if it should be engaged or not. For the purposes of this research the blue ship is set to engage all objects of the opposing team that are threatening the blue ship and not to engage allied objects or neutral objects.

As seen above, Object A is on a different team than the blue ship so the blue ship decided to engage it, which correlates to step 5. The decisions for Objects B and C are to track only rather than engage, as shown by them not progressing to the Engage step (5) after completing the Decide step (4).

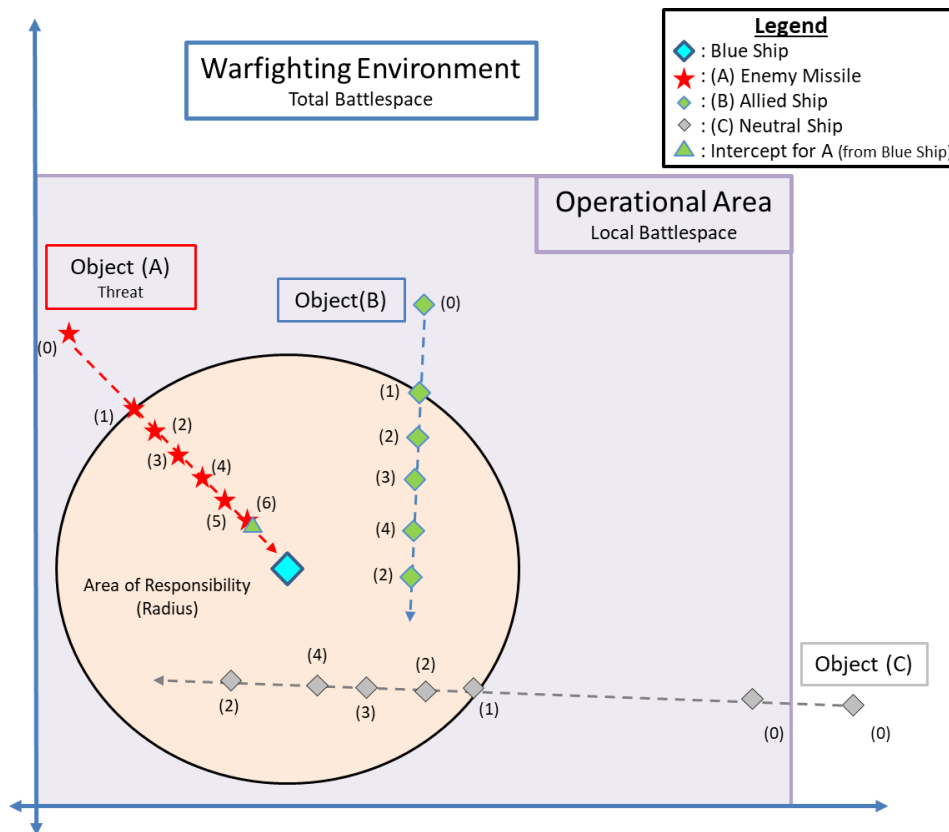


Figure 87. OPSIT 1 – Tactical Picture and Kill Chain Progression

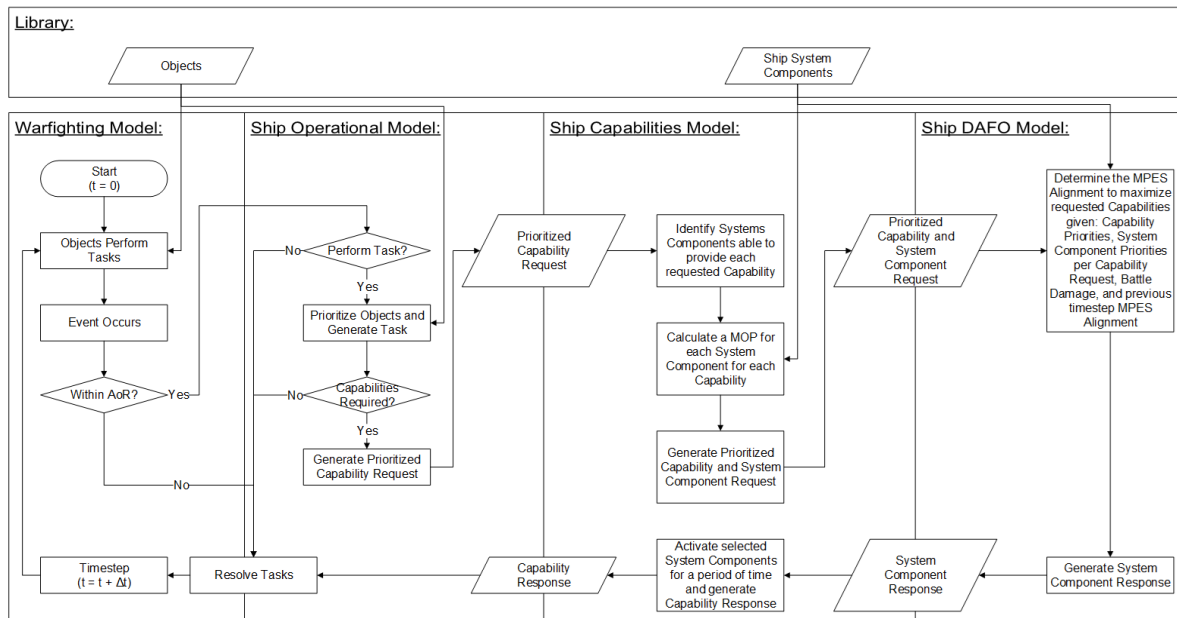


Figure 88. SBIM Execution Process

In developing the OM for the blue ship there was a specific intent to make the OM agent independent and universal. Every agent operates the same way within the warfighting environment because they all utilize the same interfaces that are fixed within the wargame environment. Each agent has its own AF, and its own MMF, but they can still be easily integrated into the OPSIT because they follow the same framework as the blue ship. This will allow the use of the OM developed for the blue ship to integrate other agents into the OPSIT.

Having this agent-independent OM provides the means to interface agents modeled by other means and at different levels of fidelity into the blue OPSIT or future OPSITs. For the purposes of this exercise, the interaction is turned off for objects (agents that are not the blue ship) to minimize computation time, but has been tested successfully and is discussed further under future work.

Upon initialization, the WM ingests, processes, filters and distributes the metadata of each agent to each agent as appropriate based on its observable warfighting environment. From this list of pre-processed data, the agent OM analyzes the characteristics and status of each object to determine the appropriate capability requests as described above. That execution process, from the perspective of the blue ship, is shown below in Figure 88.

The Capability Model then assesses and responds to the capability request considering the appropriate systems that can fulfill the request and input from the DAFO model. Based on this response, the status of the object is updated in OM and translates any engagement actions into the warfighting environment through the WM.

Scenarios Modeled and Results

Three OPSITs in the self-defense DRM are modeled to exercise the WM/OM/CM function and interfaces as test cases. These do not include any sub-surface or multi-domain agents and are intended to exercise primarily the Anti-Air Warfare and Anti-Surface Warfare areas. The next step will be to couple the WM/OM/CM with the DAFO and PM to test and assess the blue ship system response to the OPSITs and to damage from weapon hits. This will be the subject of future papers.

OPSIT 1: Enemy Aircraft, Allied Ship, & Neutral Ship

This OPSIT contains one enemy missile in attack mode that is engaging the blue ship, an allied ship, and a neutral ship. The intended outcome is that the blue ship successfully engages only the incoming missile. This OPSIT is selected to exercise self-defense against a single AAW threat, and to show that allied and neutral objects do not get engaged.

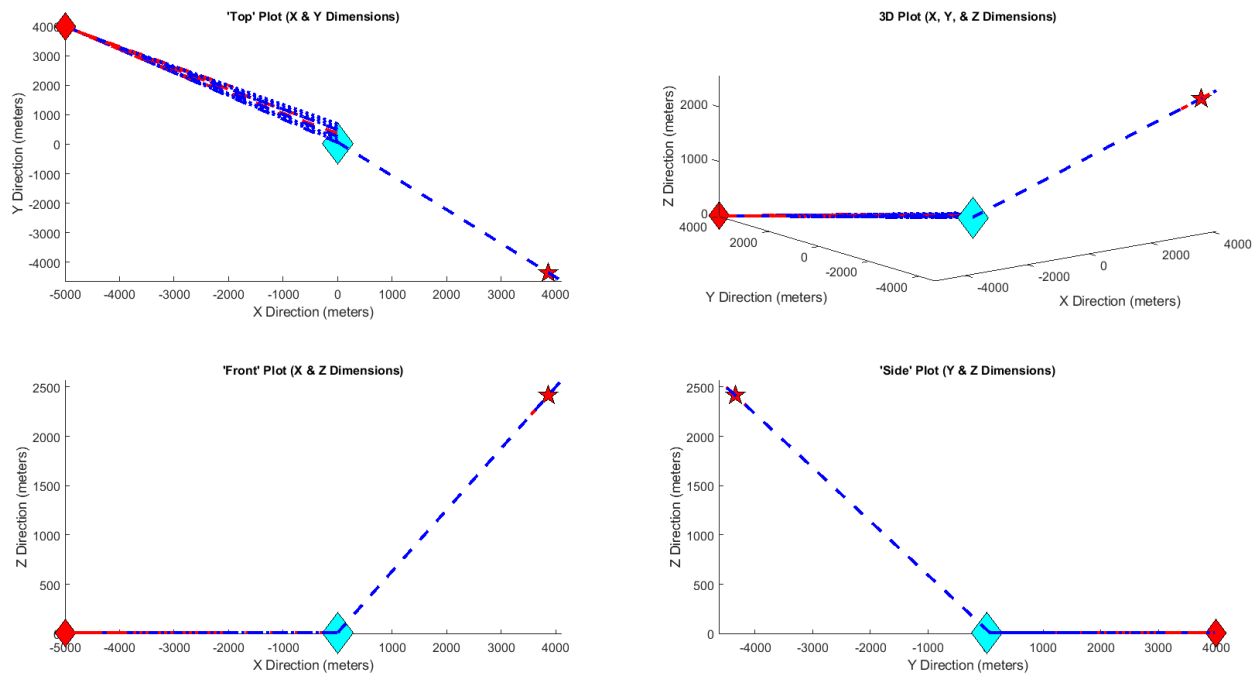


Figure 89. OPSIT 2 3D View at Time=10.5 seconds

OPSIT 2: Enemy Ship & Enemy Aircraft

This OPSIT contains an enemy ship and enemy aircraft that are both in offense mode and launching Anti-Ship Missiles (ASMs) that are attacking the blue ship. The intended outcome is that the blue ship intercepts the ASMs launched at the blue ship and executes retaliatory engagements on all red objects, ship and aircraft. This OPSIT exercises self-defense against multiple threats, and self-defense by shooting the archer that is launching attacks at the blue ship.

OPSIT 3: Enemy Ship with Special Anti-Ship Missiles (ASMs)

This OPSIT contains an enemy ship in offense model that is launching special ASMs in attack mode. The ship will be programmed such that

every 3rd missile launched is invulnerable to all intercept attempts. The intended outcome is that the blue ship will intercept the missiles it is able to, while continually attempting to intercept the ones that it cannot, and execute a retaliatory engagement on the ship that is firing at the blue ship. This OPSIT is intended to force the blue ship to exercise multiple layers of defense at different ranges, to be hit and be damaged, and to ensure that the blue ship's DAFO damage reconfiguration works.

The figures below show the progression of this OPSIT. The blue diamond is the Blue Ship and the red Diamond is the enemy ship. The stars represent air threats, green is friendly, red is hostile. The triangle seen in Figure 91 and Figure 92 is an intercept launched by the blue ship.

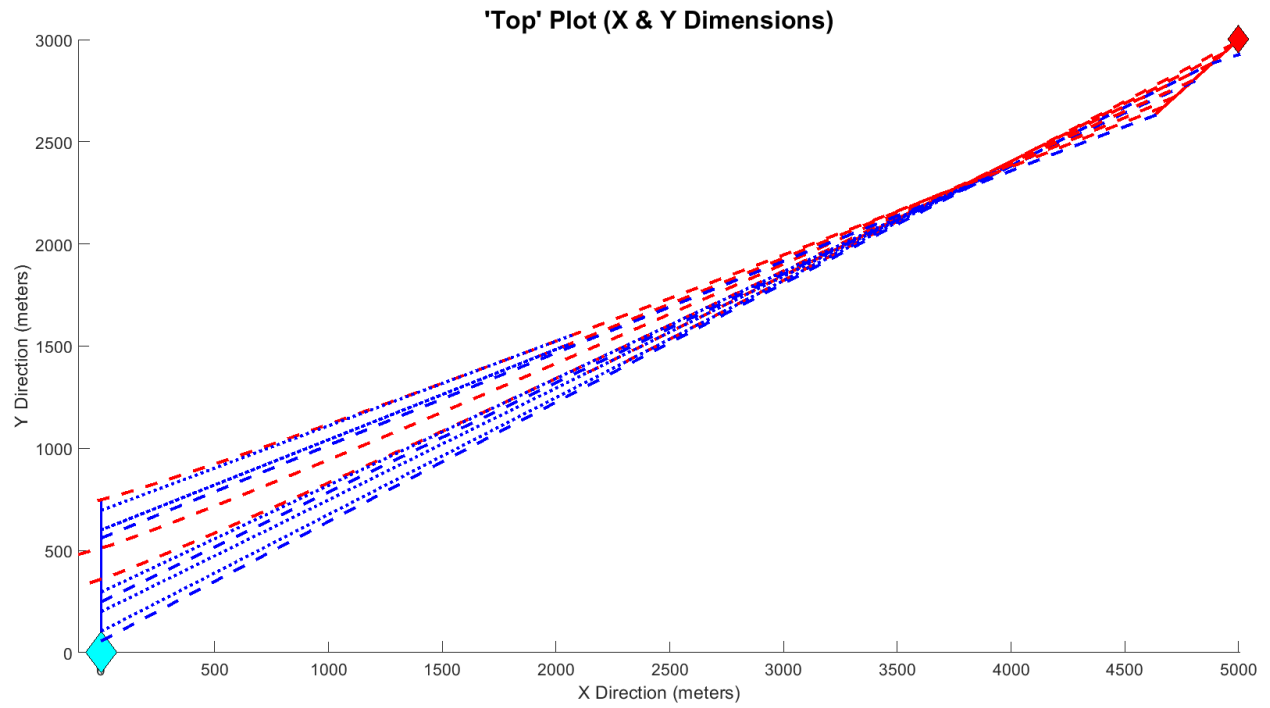


Figure 90. OPSIT 3 Aerial View at Time=0

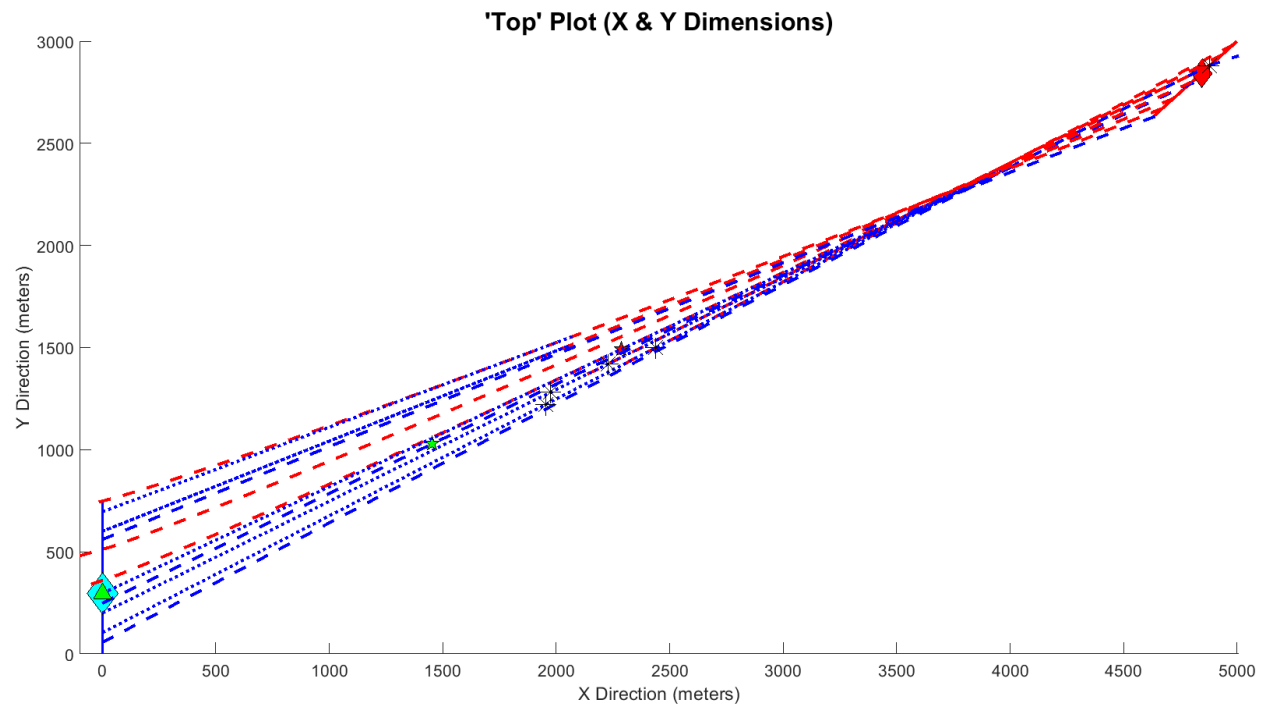


Figure 91. OPSIT 3 Aerial View Time=38 seconds

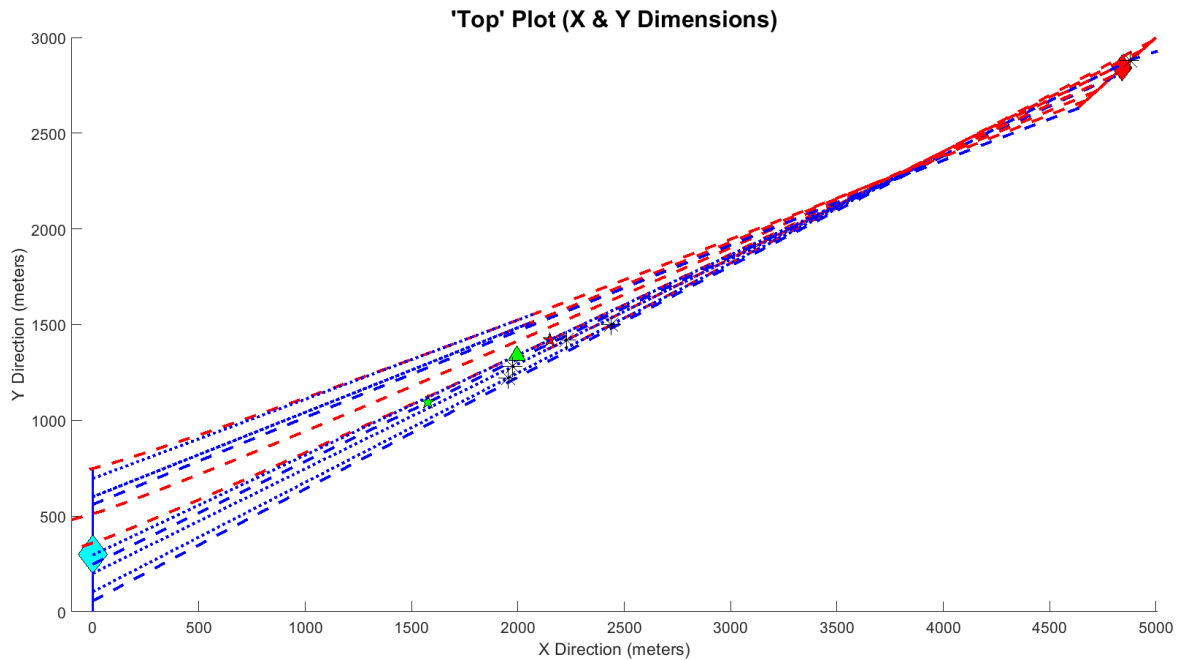


Figure 92. OPSIT 3 Aerial View Time=38.5 seconds

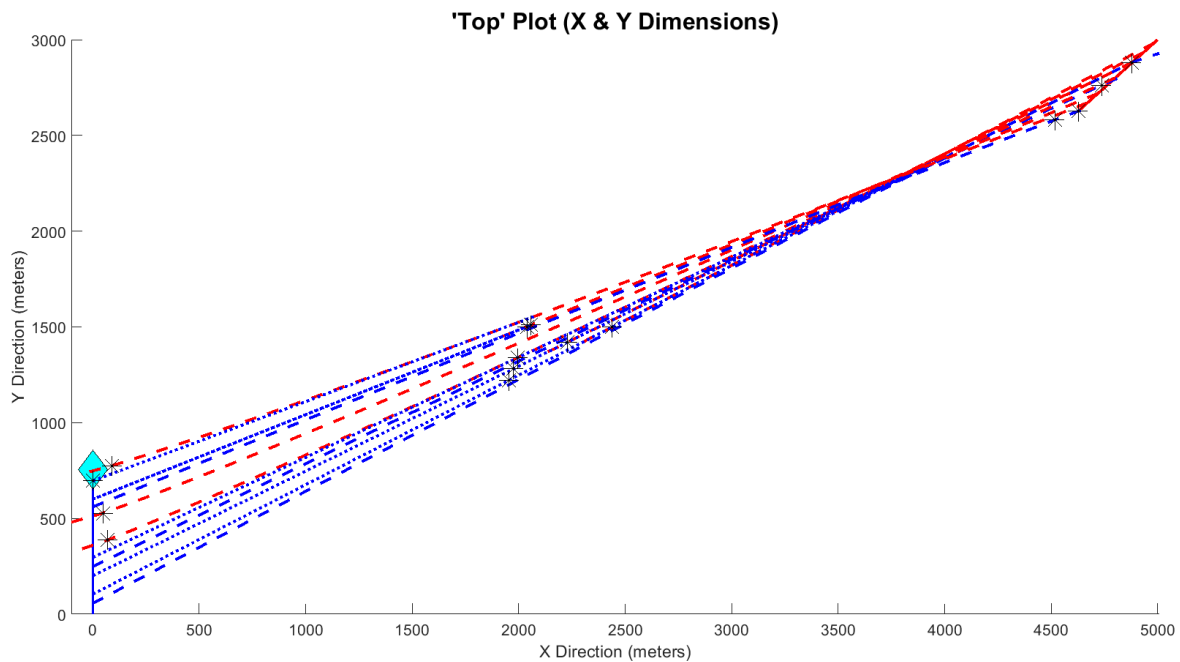


Figure 93. OPSIT 3 Aerial View Time = 100 seconds (end of scenario)

The dashed lines represent the paths taken by the ASM's and the dotted lines represent the path taken by the intercepts. The asterisks on the path lines show where they are hit. The solid lines represent the movement of the blue and red ships during the scenario. The asterisks around those lines are the hits it sustains, as tabulated below in Table 12 for the blue ship.

OPSIT 3 (Blue Ship's Hit Table)				
hitCount	time @ hit	damage	agent ID	agent Name
1	34	165	6	Red_1_Exocet [Maneuvering] (6)
2	65	165	11	Red_1_Exocet [Maneuvering] (11)
3	94.5	165	15	Red_1_Exocet [Maneuvering] (15)

Table 12. OPSIT 3 Hit table for Blue Ship

Additional Test Cases During Development

The following additional test cases were run during development to exercise specific results:

- Force Track lost, general: Ensure that the kill chain reset to detect when track was lost
- Force track lost, energy intercept: Ensure the energy engagement failed and that the target was re-engaged
- Decoy only engagement: Ensure decoy modeling and impacts was being done correctly

Conclusion

This paper proposes and demonstrates a framework and surface ship Operational Architecture (OA) for assessing ship system designs using a Design Reference Mission in surface ship Concept and Requirements Exploration. This OA uses a Mission-Means Framework approach to decompose the problem and prioritize threats, capabilities, and its components support a Mission, Power, and Energy System Dynamic Architecture Flow Optimization (DAFO). The DAFO will optimize system alignment and recoverability at each time-step in response to the operational model and damage. Mission effectiveness is assessed and optimized in the time domain to support ship and ship system assessment and development in a Model Based Systems Engineering (MBSE) and Digital Engineering approach.

This methodology also supports less computationally intensive integration testing during development at each level in the design V because it allows the testing to be done using a representative model rather than full fidelity models. When appropriate, higher fidelity models can be utilized rather than less detailed representative behavior models. Developing in this manner also allows the use of these behavior models at a lesser fidelity for blue ship assessment, but can easily support the full detail model during later stages of design.

Developing the warfighting environment, each agent, and the way they interact in an MBSE context, as a system of interconnected models at each level and as systems of interconnected models between levels, will provide a Digital Thread from the highest level down to the lowest.

This Digital Thread will be useful because it shows:

- How an agent responds to capability requests, and what systems/components are used to provide each capability.
- Which systems drive the ability to perform tasks.
- How an agent performs tasks in independent or group operations.
- What systems/components are most important to an agent's measure of effectiveness.

This research lays the groundwork for enabling more detailed assessment of ship concept designs by expanding the Ship Behaviors and Interaction Model (SBIM) to include more detailed capability models, system models, and probabilistic interactions between agents. Below is a list of additional areas that were considered, and in most cases given implementation considerations, that while not used for this work, should help in the expansion into these and other areas.

- Mission doctrine
- Threat prioritization across warfare areas (e.g. making Anti-Air Warfare more important than Anti-Surface Warfare)
- Modeling other warfare areas (Anti-Submarine Warfare)
- Incorporating more representative models (like the SBIM) for other agents
- More advanced damage tracking, scenario ending
- Cost/benefit matrix for when to engage
- More advanced maneuvering, moving through waypoints, etc. rather than just straight line
- Additional operational modes (e.g. offensive, area/group defense)
- Sharing mission data between allied agents
- Sharing missions and warfare areas across multiple agents (an integrated fighting force)
- Off board sensors

This OA also provides the foundation to assess the total ship system design in independent and group operations. Independent operations will not be the norm in the future. Design and analysis methods and tool must support networked forces

fighting as a unit. The Digital Thread, when fully integrated into upper levels of the design V, also will allow for analysis of:

- An individual agent's (or force's) Operational Architecture.
- Specific task allocations to, between, and within models.
- Agent designs compared against each other in an integrated force context.

- How design decisions for an agent impact an integrated force's mission effectiveness.

Acknowledgments

The authors would like to thank Ms. Kelly Cooper, ONR Code 331, for supporting this work under contract N00014-15-1-2476. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the Office of Naval Research. DCN# 43-7812-21.

Author Biographies

Alan Shane is currently an Ocean Engineering Master's Degree Candidate at the Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech. He is interested in developing ship concept development and assessment tools that supports a path towards MBSE and DE in those processes. He received a B.S. in Ocean Engineering from Virginia Tech in 2010. He is a student member of ASNE and SNAME.

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. He researches network-based methods to assess surface ship distributed system vulnerability, survivability, and deactivation recoverability in concept stage design. He received his B.S. in Naval Architecture and Marine Engineering from the University of New Orleans in 2016. He is a student member of ASNE and SNAME.

David J. Berrow is currently a M.S. Ocean Engineering Student of the Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech. He is employed with the Department of National Defence (Canada). He received his B.S. in Ocean Engineering and Naval Architecture from Memorial University of Newfoundland in 2011.

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 surface ship distributed system vulnerability, survivability, and deactivation recoverability in concept stage design. He received his B.S. in Naval Architecture and Marine Engineering from the Turkish Naval Academy in 2006. He received his S.M. in Naval Architecture and Marine Engineering from MIT in 2010. He is a student member of ASME and SNAME and alumni of MIT (Educational Counselor).

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 2015 recipient of the SNAME Webb Medal for Outstanding Contributions to NA&ME Education. 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.

References

- Appleget, J., Burks, R., & Cameron, F. (2020). *The Craft of Wargaming*. Naval Institute Press.
- Brefort, Dorian, Shields, Colin, Habben Jansen, Agnieta, Duchateau, Etienne, Pawling, Rachel, Droste, Koen, Jasper, Ted, Sypniewski, Michael, Goodrum, Conner, Parsons, Mark A., Kara, Mustafa, Roth, Mark, Singer, David J., Andrews, David, Hopman, Hans, Brown Alan J., Kana, Austin (2018). An architectural framework for distributed naval ship systems. *Ocean Engineering*, 147, 375–385
- Berrow, D. J., Parsons, M. A., Shane, A., Kara, M. Y., & Brown, A. J. (2021). Capability Modeling for Assessing Mission Effectiveness in Surface Ship Concept and Requirements

- Exploration. To be submitted to Combat Systems Symposium 2021.
- Brown, A. J. (2020). Design of Marine Engineering Systems in Ship Concept Design. In M. G. Parsons (Ed.), *Marine Engineering* (4 Ed., pp. 1–39). SNAME.
- Brown, Alan, Salcedo, Juan. (2003). Multiple-Objective Genetic Optimization in Naval Ship Design, *Naval Engineers Journal*, 115(4), 49-61
- Brown, Alan J., Thomas, M. (1998). Reengineering the Naval Ship Concept Design Process" in *From Research to Reality in Ship Systems Engineering Symposium*, ASNE
- Brown, Alan J., Sajdak, John. (2015). Still Re-Engineering the Naval Ship Concept Process. *Naval Engineers Journal*, 127(1), 49-61
- Department of Defense. (2020). DOD Dictionary of Military and Associated Terms. Washington, D.C., USA.
- Friedman, N. (2006). Naval Institute Guide to World Naval Weapon Systems (Fifth. Ed.). Naval Institute Press.
- Goodfriend, David, Brown, Alan J. (2018). Exploration of System Vulnerability in Naval Ship Concept Design, *Journal of Ship Production and Design*, 34(1), 42-58.
- Habben Jansen, A.C., Kana, A.A., Hopman, J.J. (2019). A Markov-based vulnerability assessment for the design of on-board distributed systems in the concept phase. *Ocean Engineering*, 190
- Hughes, W., & Girrier, R. P. (2018). Fleet Tactics and Naval Operations (Third Ed.). Naval Institute Press.
- Kerns, C., Brown, A. J., & Woodward, D. (2011). Application of a DoDAF Total-Ship System Architecture in Building Naval Ship Operational Effectiveness Models. MAST Americas, 2011.
- Kerns, L. C., Brown, A. J., & Woodward, D. (2011). Application of a DoDAF Total-Ship System Architecture in Building a Design Reference Mission for Assessing Naval Ship Operational Effectiveness. *Naval Engineers Journal*.
- Office of the Chief of Naval Operations. (2007). Universal Naval Task List (UNTL), OPNAVINST 3500.38B. tinyurl.com/y5owuroa
- Office of the Chief of Naval Operations. (2014). Projected Operational Environment (POE) for CG 47 (Ticonderoga) Class Guided Missile Cruisers, OPNAVINST 3501.160C CH-2. <https://tinyurl.com/y6ch4jak>
- Parsons, M. A., Kara, M. Y., Shane, A., Berrow, D. J., & Brown, A. J. (2021a). System Dynamic Architecture Flow Optimization to Assess Mission Effectiveness in Surface Ship Concept and Requirements Exploration. To be submitted to Combat Systems Symposium 2021.
- Parsons, M. A., Kara, M. Y., Robinson, K. M., Stinson, N. T., & Brown, A. J. (2021b). Early-Stage Naval Ship Distributed System Design Using Architecture Flow Optimization. *Journal of Ship Production and Design*, 37(02) 78-96. <https://doi.org/10.5957/JSPD.10190058>
- Parsons, Mark A., Robinson, Kevin, Kara, M. Y. Stinson, Nick, Snyder, Dan, Woodward, David, Brown, Alan J., (2019). Application of a Distributed System Architecture Framework to Naval Ship Concept and Requirements Exploration (C&RE), in *Intelligent Ships Symposium 2019*, Philadelphia, PA: ASNE
- Payne, C. M. (2010). Principles of Naval Weapon Systems (Second Ed.). Naval Institute Press. <https://books.google.com/books?id=MUUmQwAACAAJ>
- Purdy, E. M. (2004). "Test and Evaluation WIPT." Proceedings of the 20th Annual Test & Evaluation Conference & Exhibition. Reno, NV, USA.
- Stevens, John D., Opila, Daniel F., Oh, Eun S., Zivi, Edwin L. (2017). All-Electric Warship Load Demand Model for Power and Energy System Analysis Using Exogenously Initiated Threats, in *Electric Ship Technologies Symposium 2017*, Arlington, VA: IEEE
- Stepanchick, Justin, Brown, Alan. (2007). Revisiting DDGX/DDG-51 Concept Exploration. *Naval Engineers Journal*, 119(3), 67-88
- Strock, Justin, Brown, Alan. (2008). Methods for Naval Ship Concept and Propulsion System Technology Exploration in a CGX Case Study. *Naval Engineers Journal*, 120(4), 95-122
- Snyder, Daniel J. (2019). *Deactivation Diagram Development for Naval Ship System*

Vulnerability Analysis (thesis), Virginia
Polytechnic Institute and State University,
Blacksburg, VA
Snyder, Daniel J., Parsons, Mark A., Brown, Alan
J., Chalfant, Julie. (2019). Network

Architecture Framework Applications with
FOCUS-compliant Ship Designs, in Electric
Ship Technologies Symposium 2019,
Alexandria, VA: IEEE

Paper #5 - Capability Modeling for Assessing Mission Effectiveness in Surface Ship Concept and Requirements Exploration

David J. Berrow¹, Mark A. Parsons¹, Alan Shane¹, Mustafa Y. Kara¹, and Alan J. Brown¹

Abstract

This paper describes the development and implementation of mission capability models necessary in the development of a system design framework for Mission, Power and Energy Systems (MPES) in Surface Ship Concept and Requirements Exploration. This system framework includes architectures for ship operations, physical arrangements and for the logical relationship of MPES vital components including simple energy and data models of their function. The mission capability models provide a critical interface between logical and operational architectures, quantifying warfighting capabilities through system measures of performance at specific capability nodes. The operational architecture queries the capability models representing the behavior at these nodes for necessary operational capabilities and implements them in the warfighting environment. The capability model also provides essential mission and vital component priorities used to guide the alignment of system vital components over time using a dynamic architecture flow optimization (DAFO).

Introduction

Mission, Power and Energy Systems (MPES) are fundamental to the design, mission, and operation of surface ships. MPES design and architecture are critical in 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 Vital Components (VCs) distributed throughout a ship that are connected to work together. This includes mission systems. 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. (2020b) describe 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, Kerns, et al., 2011a, Kerns, et al., 2011b, Brown & Sajdak, 2015, and Parsons, et al., 2020a). Goodfriend & Brown (2018) describe 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. Survivability must be considered in C&RE.

Goodfriend & Brown (2018); Snyder (2019); Snyder et al. (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. Recoverability is also not considered. Stevens et al (2017) consider power, but only electrical power. The total ship system is not modeled.

¹ Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech

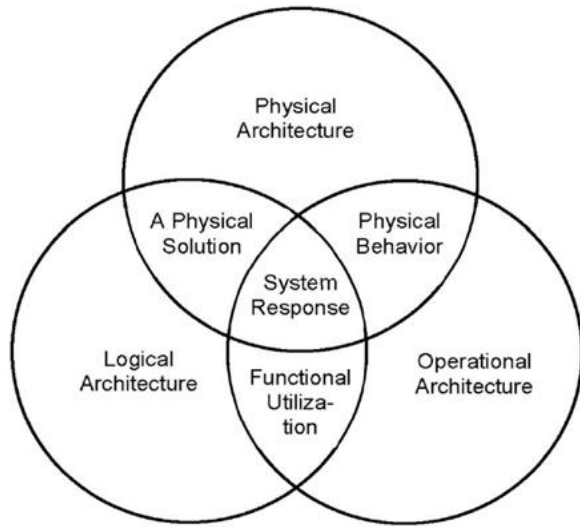


Figure 94. Architectural Framework for Distributed Ship Systems (Brefort et al., 2018)

The authors began exploring the use of 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 94 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).

The interface between the logical architecture and the operational architecture occurs at capability nodes in the logical architecture and is quantified using Ship Behavior and Interaction Models (SBIMs). The capability nodes also reside in the “Functional Utilization” intersection shown in Figure 94. The operational architecture is illustrated in the lower right corner of Figure 95 and its development, application and associated SBIMs are summarized in the next section of this paper before discussing the capability nodes.

The simplified operational architecture, warfighting model, and mission system vital component models presented in this paper are for academic purposes only, adapted from content provided by Friedman (2006), Payne (2010), Hughes & Girrier (2018), and Appleget, et al. (2020) to a very basic level of detail sufficient for fundamental research and the development of new methods, processes, and system framework

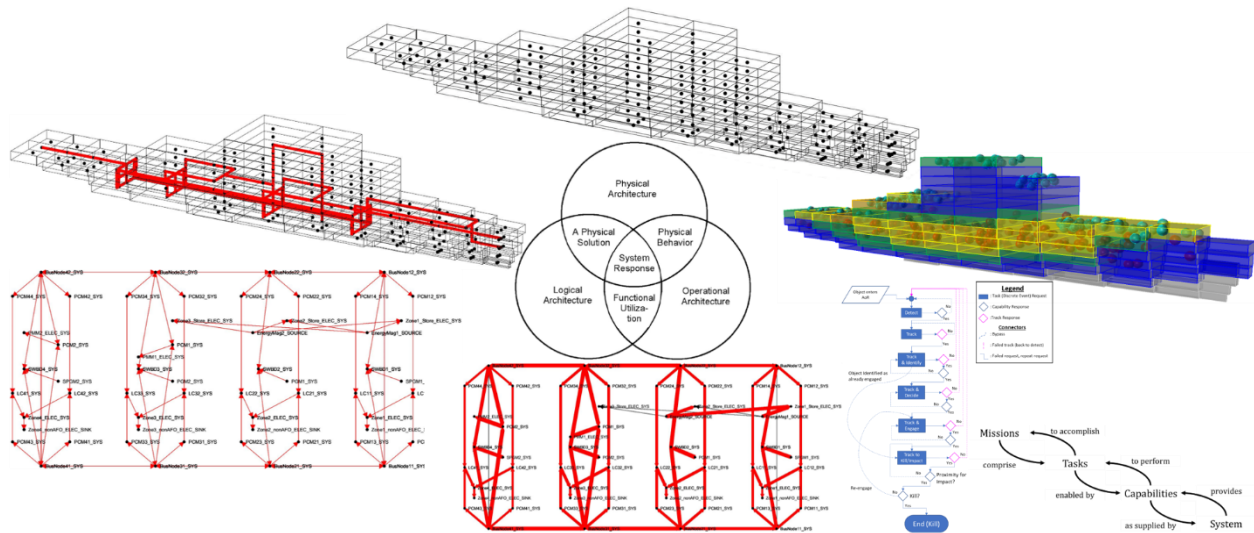


Figure 95. Ship System Architectural Framework (Shane et al., 2021)

Ship Operational Architecture, Behavior and Interaction Models

Traditionally, early C&RE evaluation is performed based on relative effectiveness by comparing ship designs to each other, rather than modeling the ship design in an operational scenario to determine its effectiveness. Shane, et al. (2021) describe an improved assessment process that explicitly considers the ship's effectiveness during execution of a Design Reference Mission (DRM). This process allows for a ship's Overall Measure of Effectiveness (OMOE) for a specific DRM to be used to compare designs.

Lexicon and Identification

The following sub-sections detail the language and conventions used to describe the ship operational architecture, operational model, warfighting model, and warfighting environment used in this paper.

Identification/Naming

- Library: Generic source information. Agents and their associated characteristics are described in the Library.
- Agent: An intelligent operating vehicle, aircraft, missile, ship, boat, land base, etc. in the warfighting model.
- Blue Ship: "own" ship system of systems represented in the logical and physical architectures. The blue ship is also an agent, in the context of the warfighting environment.
- Object: an individual green, red, or gray agent viewed from the perspective of the blue ship.
- Threat: an individual red object (or green/gray object prior to identification) that is being analyzed or acted upon.
- Team Colors:
 - Green: applied to allied objects
 - Red: applied to enemy objects
 - Gray: applied to neutral objects

Mission Means Framework (MMF)

The definitions for terms in the mission means framework are taken primarily from the DOD Dictionary of Military and Associated Terms (2020).

- Mission – a task and an operational objective assigned to a system or system of systems.
- Task – a clearly defined action or activity performed by a system which requires system capabilities, resources and/or information. Tasks may be decomposed into subtasks.
- Capability – a state of system function having sufficient system resources and/or information to perform a task.
- System – a functional (logical architecture), physical (physical architecture), and/or behavioral (operational architecture) group of related interacting/interdependent components. Systems may be decomposed into subsystems.

Models

The models used in implementing the Operational Architecture are as follows:

- Warfighting Model (WM): an agent-based behavior model for determining how agents move and interact with each other (events) in the warfighting environment.
- Ship Operational Model (OM): the behavior model of a single ship agent implemented in a discrete event simulation and able to apply requested ship capabilities to operational tasks.
- Ship Capability Model (CM): the behavior model of the capability nodes in the logical architecture able to assess the application of available ship systems to provide requested operational capabilities.
- Ship Dynamic Architecture Flow Optimization (DAFO) Model: the behavior model of the ship's distributed systems able to align and apply available system energy and data components to provide requested capabilities and maximize effectiveness.

Warfighting Environment Areas

- Wargame Area (Total Warfighting Environment): Covers all areas, including all local warfighting environments.
- Operational Area (Local Warfighting Environment): Area in which operations take place.
- Area of Responsibility (AoR) Radius: The observable radius around and relative to the blue ship.

Mission Means Framework (MMF)

Figure 96 shows the Purdy (2004) MMF, which is a modified systems-engineering V-model, that illustrates the relationships between necessary elements in a system's operational architecture.

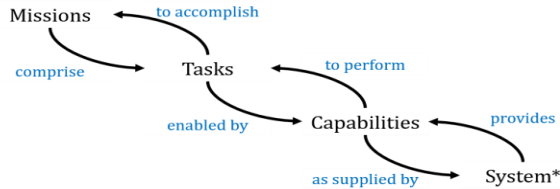


Figure 96. Modified Mission-Means Framework (Purdy, 2004)

A mission is comprised of and accomplished by tasks, the clearly defined actions or activities of a system which require system capabilities, resources and/or information to be performed. Each mission is assigned a measure of effectiveness (MOE), a quantitative or qualitative metric for how well a mission is accomplished by its completed tasks. Each system capability is assigned measures of performance (MOPs), quantitative or qualitative metrics describing how well a task is performed by the capability that enables it. Both MOPs and MOEs can change with respect to time, system configuration, and availability of resources/information. The necessary and accomplished time-dependent relationships between one system state and the next comprise the operational architecture. This state-based approach to modeling an operational architecture is similar to Stevens et al (2017).

Ship Behavior and Interaction Models

The Ship Behavior and Interaction Models (SBIMs) implement the MMF to accomplish the mission(s) and perform tasks specified by the DRM as system responses in a discrete event simulation. The SBIMs and their relationship are represented in Figure 97.

The SBIMs model ship behavior throughout an operational situation (OPSIT) over a series of time-steps. A uniform time-step of one second is currently used in the SBIMs. This is consistent with the time scale required for the measurement of system energy usage, heat dissipation, and energy storage charging/discharging. It is not intended to consider transient stability and other shorter time scale phenomena.

A typical detect to engage sequence occurs in less than a minute, so a 1 second time interval allows for operational modelling but is limited for operations that occur in less than a second. Operations that occur in less than a second are modelled for the entire time-step (one second) even if they occur more quickly.

Figure 97 is an application and refinement of Figure 96 where the (blue) ship agent operational model requests capabilities from the CM. Following this query, the CM assesses the ability of the ship to provide the capabilities if supported by the MPES.

The OM is the blue ship mission/task behavior model implementing the blue ship's Operational Architecture. It serves as the interface between the WM and the blue ship CM. It interacts with the CM through capability requests and responses, as shown in Figure 97. As an example, when the WM requires the blue ship to perform an Anti-Air Warfare (AAW) task, the OM determines necessary capabilities and sends capability request(s) from the OM to AAW system's (or plex's) capability node(s), where the capabilities are modeled and managed. Capability nodes are indicated by the blue circle in the logical architecture in Figure 98. The outcome of the execution of a task defined in the OM is determined by whether or not the ship possesses the capability to perform the task. If the necessary capability is available, the task can be successfully performed. This is discussed in more detail later in the paper.

The CM interfaces with the OM and DAFO model to answer queries at each time step. The specific query requested is specified by the OM based on the operational mode of the blue ship which determines decision capability logic and mission doctrine. The operational mode of an agent is selected during setup based on the OPSIT. The available operational modes of an agent are: loitering, self-defense, offense, and attack. The offense and attack operational modes allow an agent to engage other agents. The attack mode is reserved for agents that require an intercept course to engage another agent such as an Anti-Ship Missile (ASM). The objective function in the DAFO model is updated at each time step based on priorities specified by the OM and consistent with the operational architecture. This enables blue ship system alignment by the DAFO.

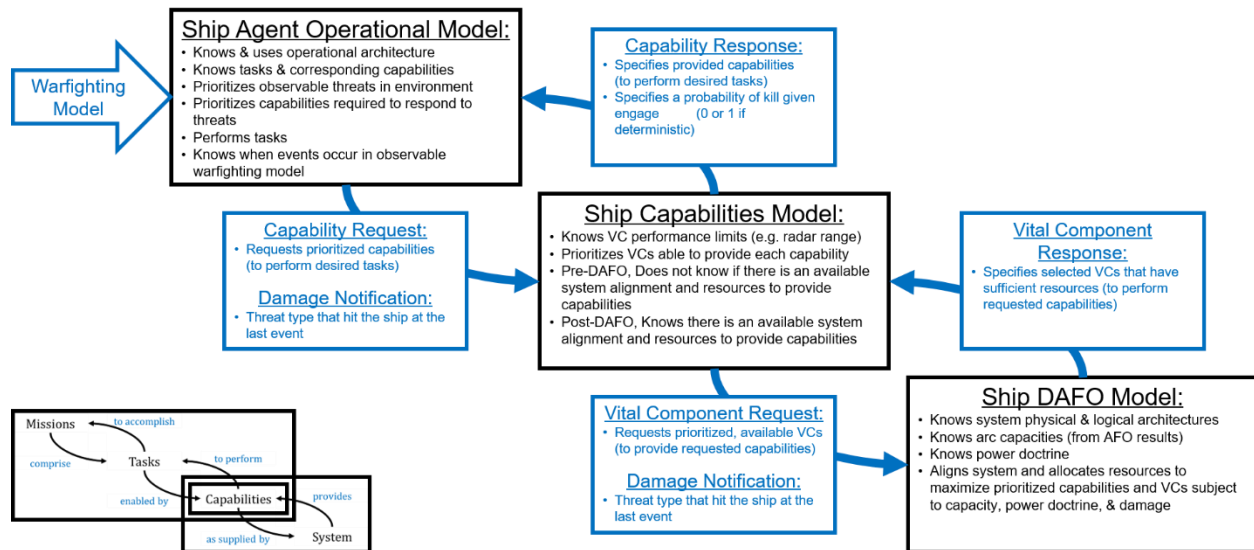


Figure 97. Ship Behavior and Interaction Models (SBIMs)

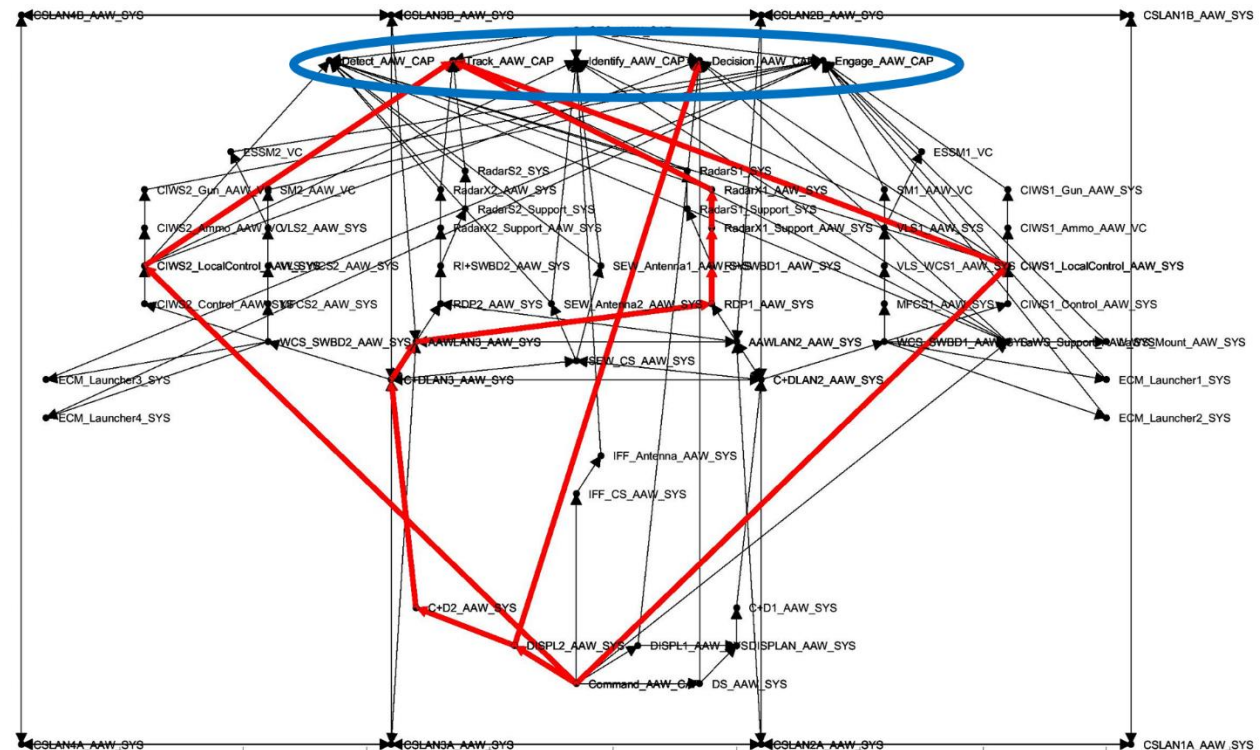


Figure 98. AAW Mission Plex Vital Components and Circled Capability Nodes with Data Commodity Flows (adapted from Friedman, 2006, p 105 and Chalfant et. al, 2017)

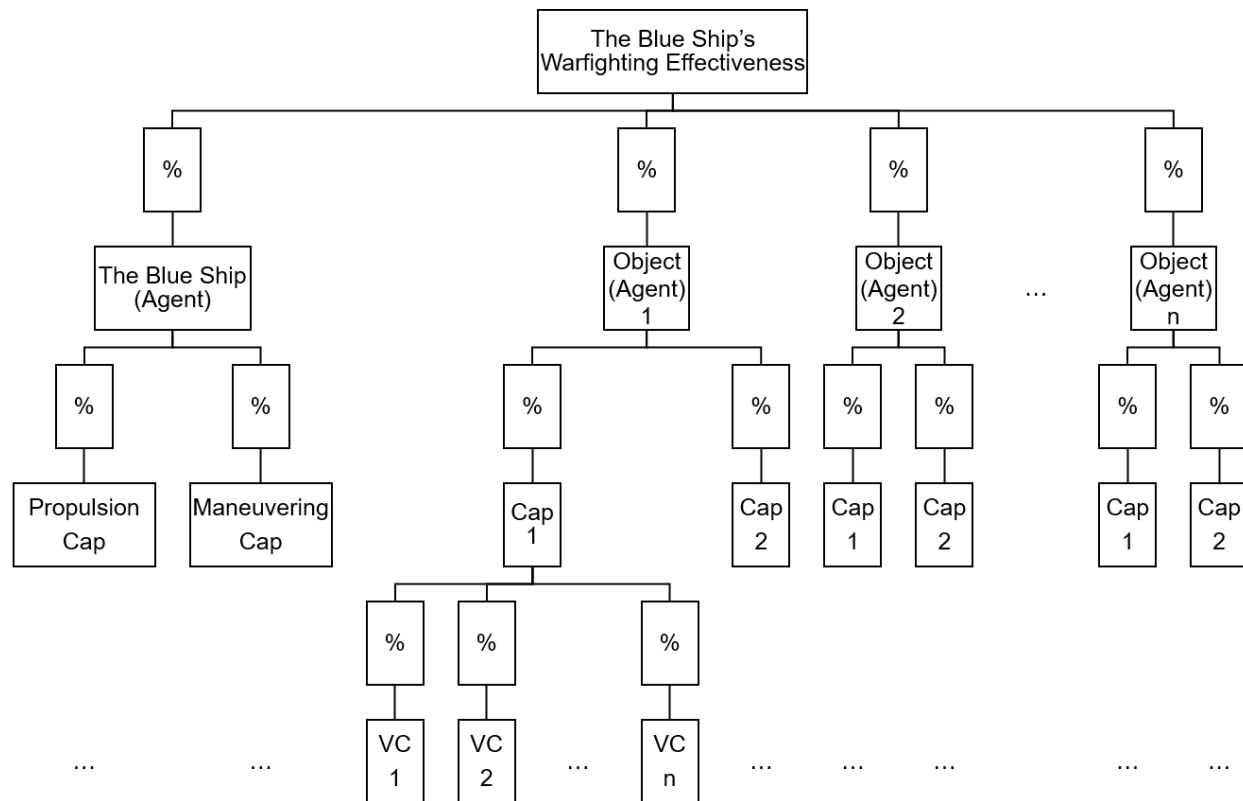


Figure 99. Effectiveness Hierarchy

The DAFO model uses both an energy formulation and a mission system data formulation to support and interface with the CM and OM as shown in Figure 97. The DAFO model determines the optimum energy flow and mission system data flow (0, 1) through the logical architecture to support the capability pull, translated by the CM, from the operational architecture at each time step. The data flow is a DAFO commodity in addition to the energy flow used in earlier AFO formulations to model a functional mission system, as shown in Figure 98. Each of the AAW VCs in Figure 98 requires electric power and cooling which must be provided in the energy solution. The power and energy formulation and the basic AFO is described by Parsons et al. (2020a), Brown (2020) and Parsons et al. (2020b). The DAFO model determines the mission system usage, data and energy flow using the prioritized capability pulls on the system to determine which Vital Components (VCs) are available and active during the discrete event.

At each time step, the mission effectiveness for the blue ship system is maximized in the DAFO model using the hierarchy shown in Figure

99, with priorities provided by the OM and CM. Objects approaching the blue ship area of responsibility are assigned a priority between 0 and 1 by the OM based on:

- Time to impact the blue ship (or not)
- Potential damage to the ship (i.e. warhead kg TNT)

Objects reaching an engage task capability request are prioritized above all other objects. Object priorities are normalized to sum to 1 for all detectable objects in the warfighting environment.

Warfighting tasks in the OA and their corresponding capability requests are structured according to the steps in the kill chain (adapted from Payne, 2010; Office of the Chief of Naval Operations, 2007; and Office of the Chief of Naval Operations, 2014):

1. **Detect:** Detect
2. **Track:** Track
3. **Identify:** Track and Identify
4. **Decide:** Track and Decide
5. **Engage:** Track and Engage

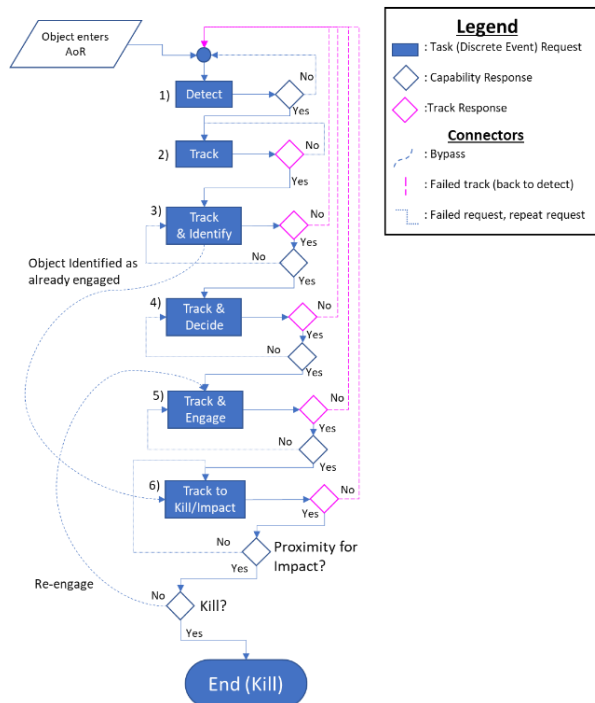


Figure 100. Kill Chain Operational Architecture

Capabilities are prioritized and sum to 1 for each object. This basic series of tasks is also used as a simple and generic warfighting operational architecture as discussed and illustrated in Figure 100. The temporal implementation of these generic tasks is more completely specified and described by the WM and OM consistent with the OA.

System VCs provide capabilities, but more than one VC may be able to provide a single capability. To determine which VCs are best suited to provide each capability, capability MOPs are calculated for each applicable VC. Based on these MOPs, VCs are prioritized between 0 and 1, and normalized to sum to 1 for each capability. For example, the engage capability may be requested for an object, and may be provided by VC 1 or VC 2. For engage, the MOP used is the Probability of Kill (PKill), so the PKill against the threat is calculated for VC 1 and VC 2. In this example, if PKill for VC 1 is assessed as being two times greater than for VC 2, then VC 1 would receive a priority of 0.67 and VC 2 would receive a priority of 0.33.

The priorities associated with each VC, each capability, and each object (see Figure 99) are used in the DAFO objective function. The DAFO model maximizes effectiveness by selecting VCs

to provide the optimum combination of successful capabilities as responses against the objects, as described in Parsons, et. al (2021).

Capability Modelling

Capability modelling is the process of quantifying warfighting capabilities through system measures of performance. Capability nodes provide the interface between the blue ship OM and blue ship DAFO. The determination of whether a capability can be provided, along with how it is provided, requires a query of the blue ship DAFO, which maintains and modifies the status of the ship's systems and VCs. At each time step, the OM determines if a task or tasks must be performed following the operational architecture sequence. If capabilities are required to perform the tasks, the OM queries the CM to determine if the capabilities can be provided, which triggers the DAFO to determine which capabilities can be supported by the MPES.

The DAFO manages the power and energy status of all ship systems and components at each time step. It also assesses combat system component connectivity between the Command_SYS node and capability nodes within each warfighting plex. Intact connectivity with intact nodes supported by necessary power and cooling are assumed to provide a complete functional system necessary to support a specific capability. It is also assumed that all components capable of providing the detection capability are initially operating at their standby power level. Once a capability has been requested and a specific VC has been selected to provide that capability, the selected VC operates at full power (i.e. mission power).

The a DAFO time-based AFO method is used to determine feasible and optimal energy and data flows in the total ship system at each time step necessary to optimize the ship response to capabilities requested by the operational architecture through the capability nodes. The DAFO depends on the operational architecture to provide a "pull" on capabilities from the logical and physical architectures through the capability nodes as illustrated in Figure 98. The DAFO integrates the AFO energy formulation with a mission system data formulation and scenario to determine the optimum mission system data flow (0, 1) and simultaneous energy flow through the

logical architecture to support the capability pull from the OM at multiple time steps. The DAFO models mission system usage using prioritized capability pulls (Shane et al, 2021) on the system to determine which prioritized VCs are active

during the discrete time step. This data flow is a new commodity in addition to the energy flow, necessary to establish a functional mission system. The SBIM execution process is illustrated in Figure 101.

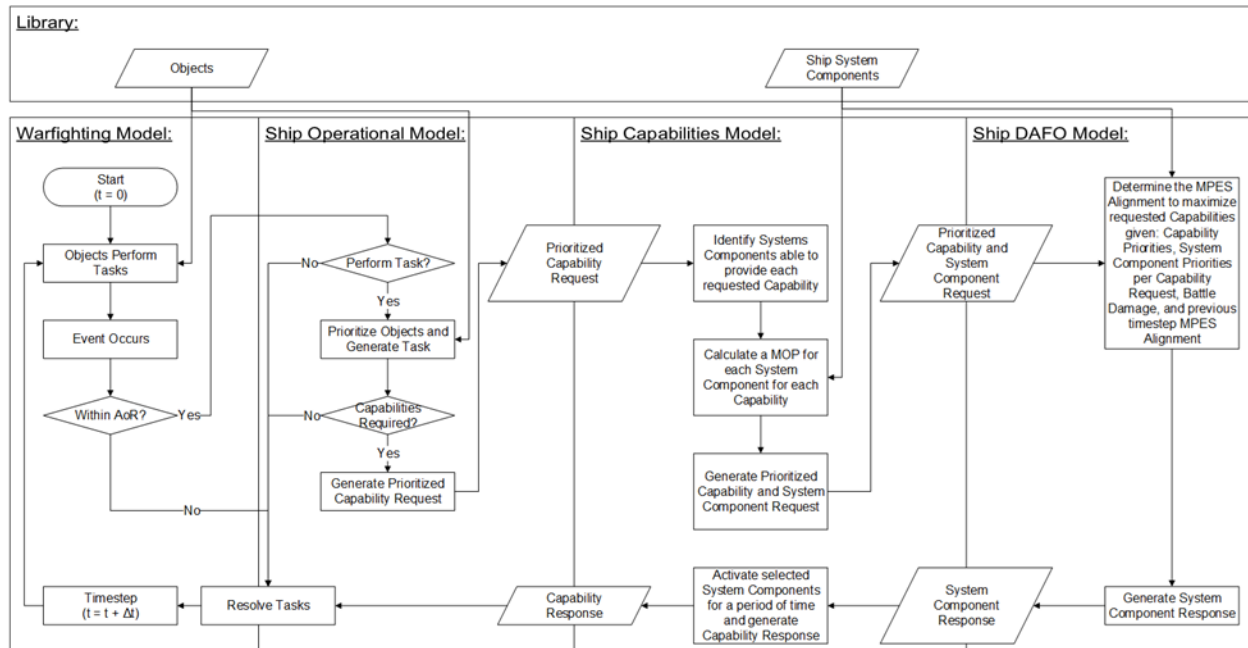


Figure 101. SBIM Execution Process

SBIM Execution Example

The following process steps describe the execution of a single time-step (at $t = 1$ second) during an OPSIT that involves three initial objects: 1 x Blue Surface Ship and 2 x Red Anti-Ship Missiles (ASMs):

1. The WM determines that an event occurs: the red ASMs move to the following locations:
 - Red ASM 1 = 10 meters above sea level at 20 kilometers away from Blue Ship.
 - Red ASM 2 = 10 meters above sea level at 20 kilometers away from Blue Ship.
2. The WM determines the red ASMs are located within the blue ship's AoR.
3. The OM determines which tasks the blue ship should perform to respond to each object.
 - Red ASM 1: Detect
 - Red ASM 2: Detect
4. The OM prioritizes each object based on a combination of time to impact the blue ship and potential damage to the blue ship:
 - Red ASM 1: Detect (50%)
5. The OM prioritizes each task to respond to each object:
 - Red ASM 1: Detect (100%)
 - Red ASM 2: Detect (100%)
6. The OM queries the CM to determine if the blue ship has the capability to perform the requested tasks.
7. The CM determines which blue ship VCs can perform the requested tasks given sufficient resources/information and prioritizes these VCs based on MOPs:
 - Red ASM 1:
 - S-Band Radar 1 = 11.11%
 - X-Band Radar 1 = 33.33%
 - S-Band Radar 2 = 11.11%
 - X-Band Radar 2 = 33.33%
 - ESM Antenna 1 = 5.56%
 - ESM Antenna 2 = 5.56%
 - Red ASM 2:
 - S-Band Radar 1 = 11.11%
 - X-Band Radar 1 = 33.33%
 - S-Band Radar 2 = 11.11%
 - X-Band Radar 2 = 33.33%

- ESM Antenna 1 = 5.56%
 - ESM Antenna 2 = 5.56%
8. The CM queries the DAFO to determine if the Blue Ship can provide sufficient resources/information to the prioritized VCs providing prioritized capabilities.
 9. The DAFO maximizes the provided capabilities by aligning the total ship system to allocate energy and information to the highest prioritized VCs, per requested capability, per object, subject to: capacity constraints, power doctrine, and damage constraints.
 10. The DAFO responds to the CM's request by providing a list of VCs that are providing each requested capability. All other combat system VCs are assumed to be in standby mode:
 - S-Band Radar 1 = Standby
 - X-Band Radar 1 = Standby
 - S-Band Radar 2 = Standby
 - X-Band Radar 2 = Active
 - ESM Antenna 1 = Standby
 - ESM Antenna 2 = Standby
 - All other combat system VCs = Standby
 11. The CM records any multi-time step characteristics about the selected VCs and responds to the OM's request by providing a list of capabilities that are being provided.
 - Blue Ship can detect Red ASM 1 with X-Band Radar 2.

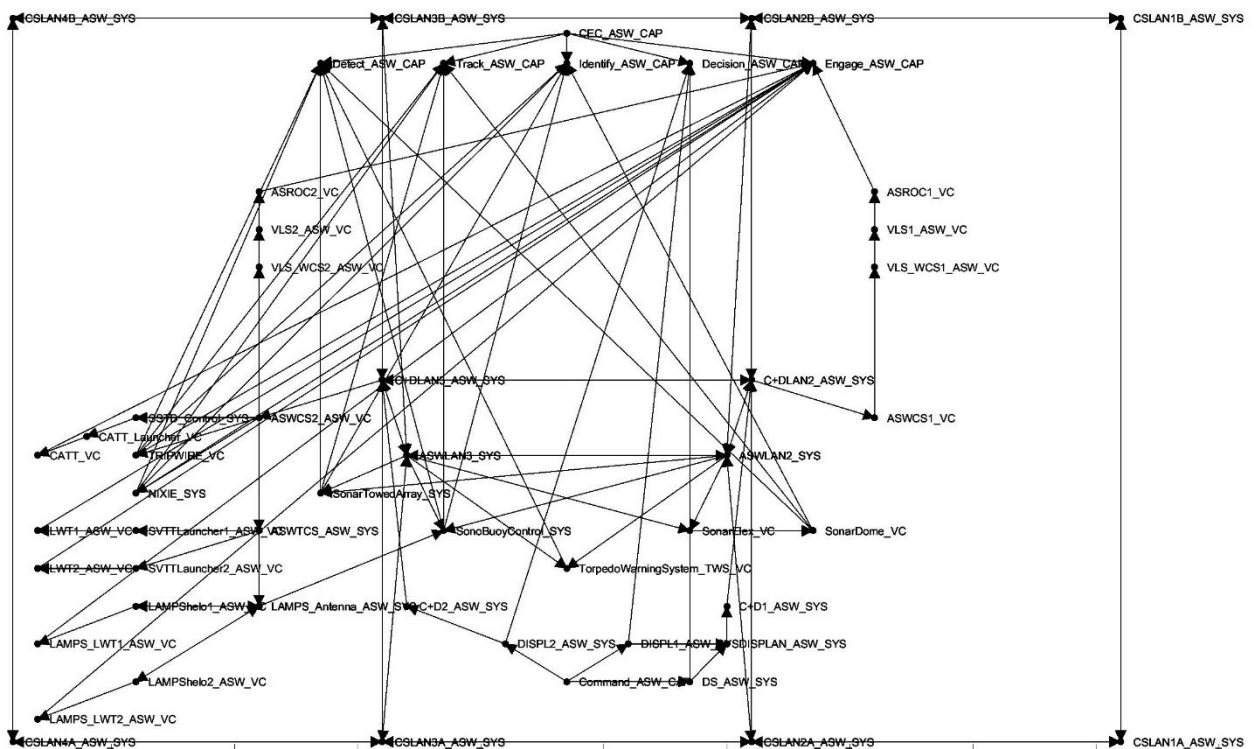
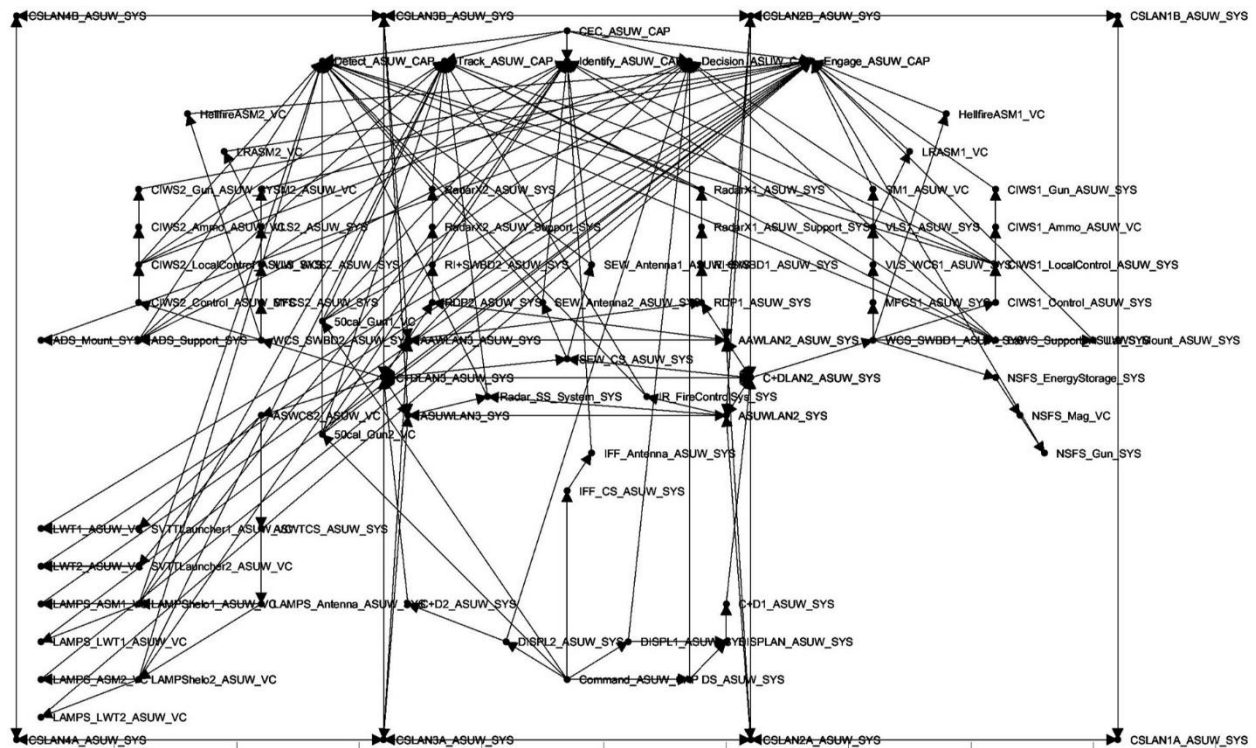
- Blue Ship can detect Red ASM 2 with X-Band Radar 2.
12. The OM resolves the tasks:
 - Red ASM 1 detected by blue ship.
 - Red ASM 2 detected by blue ship.
 13. The WM advances to the next time step.
 - $t = t + \Delta t$

Warfighting Areas

The MPES mission systems are grouped into three warfighting area plexes:

- Anti-Air Warfare (AAW)
- Anti-Surface Warfare (ASUW)
- Anti-Submarine Warfare (ASW)

The remaining systems are the power and energy systems or plexes. Each warfighting area uses specialized systems to provide capabilities and perform tasks unique and inherent to that area. Figure 98, Figure 102, and Figure 103 show the logical architectures for each warfighting plex. In addition to the warfighting systems, systems providing ship propulsion and maneuvering capabilities must also be included. An example mechanical propulsion system logical architecture is shown in Figure 104. These logical architectures identify which VCs connect to each capability, and therefore, which VCs provide each capability.



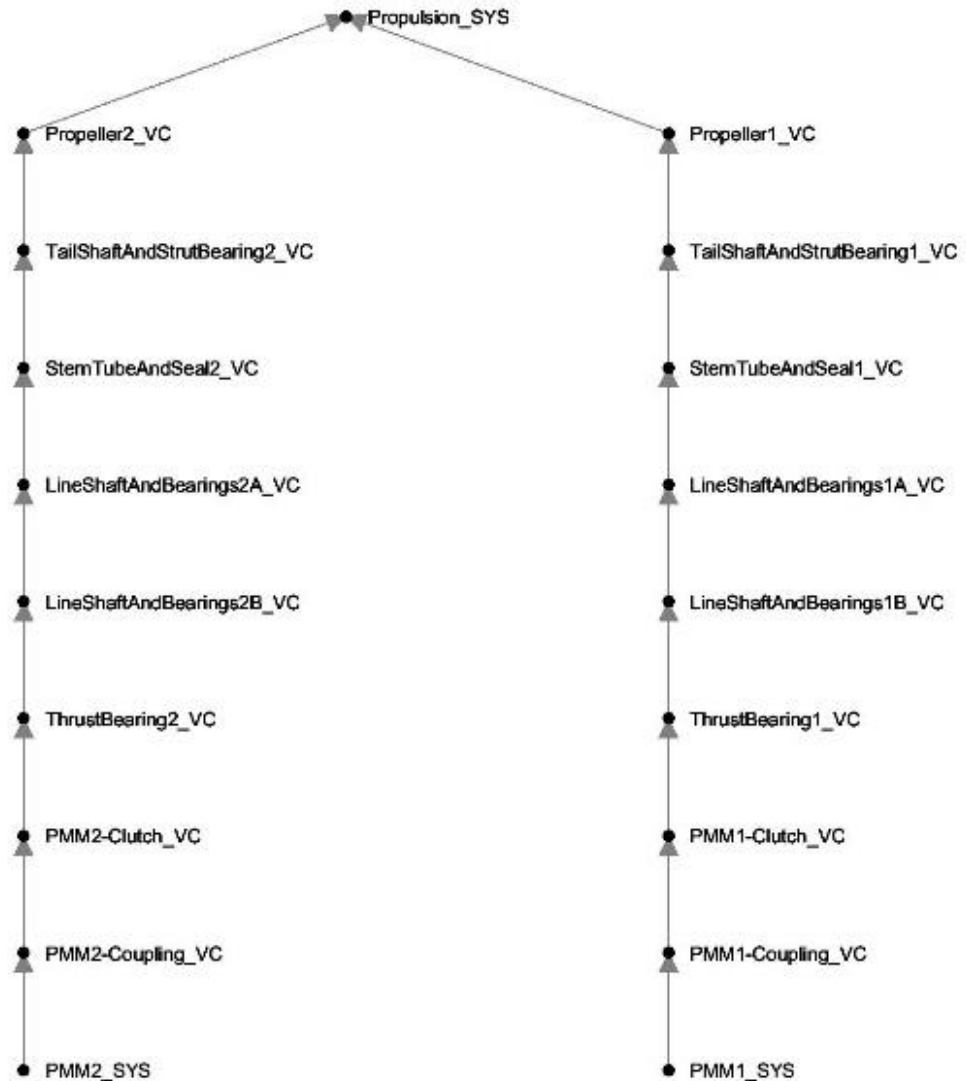


Figure 104. Mechanical System Plex Logical Architecture (Parsons, et al., 2020a)

Detect Capability

A surface ship must have the capability to detect objects such as aircraft, ships, unmanned vehicles, and missiles. Within the CM, both AAW and ASUW detect capabilities are provided by the same VCs, which are grouped into one or more of the following:

- Active Radar
- Electronic Support Measures (ESM)
- IR (Infra-Red)
- Visual

The AAW detect-capability nodes and the ASUW detect-capability nodes interface with

these VCs and their supporting systems. The OM provides a named object and its current operating parameters (speed, altitude, Radar Cross Section) and queries the AAW and ASUW detect-capability nodes through the CM as to whether the ship can detect the object. Fixed data associated with specific objects are available in the library, including “generic” data to be used before an object is identified. The detect-capability nodes determine, from the logical and physical architectures, which VCs are physically available to provide the requested capability. VCs that can provide the detect capability when intact and supported by the MPES are shown in the logical architecture definition of the AAW plex in Figure 98 and ASUW plex in Figure 102. The physical

architecture advises whether VCs are intact. Each intact VC that can provide the capability is assessed to determine its maximum detection range, minimum detection range, and detection standard period for the specific object using the object and VC characteristics. A VC's detection standard period is the time required for it to detect the object. The methodologies used to determine the detection standard period for a VC are dependent on the detection method employed by the VC (i.e. active radar, ESM, infrared, visual, rotating, fixed array) and are explained in the next four sections. Those VCs with sufficient detection range are prioritized through a weighting function. The weighting function is used to represent warfighting doctrine and is very simplistic, but sufficient to serve the purposes of this research. More sophisticated models could be substituted in a real application.

Detect Capability – Active Radar

Active radar detection performance is complex and involves many factors such as pulse shape, pulse width, pulse repetition frequency, carrier frequency, scan rate, beam width, receiver sensitivity, transmitter power, antenna gain and target radar cross-section. When assessing active radar VCs, the CM calculates maximum range using the minimum of the two-way radar equation and an Over the Horizon (OTH) test. The two-way radar equation (Weapons Division, Naval Air Warfare Center, 2013, p. 4-4.6 and Payne, 2010) is:

$$R_{max} = \sqrt[4]{\frac{P_t G_t G_r L_t L_r \lambda^2 \sigma}{(4\pi)^3 k T_0 B_r N_f SNR_{min}}} \quad (36)$$

where:

R_{max}	Maximum Detection Range (km)
P_t	Transmit Power
G_t	Transmitter Gain
G_r	Receiver Gain
L_t	Transmit Loss
L_r	Receive Loss
λ	Wavelength
NF	Noise Factor
k	Boltzman's Constant
T_0	Temperature
B_r	Receiver Noise Bandwidth
SNR_{min}	Minimum Signal to Noise Ratio
σ	Target Radar Cross Section

Radar Cross Section (RCS) is a specific characteristic of a reflective object that depends on many factors. The analytical calculation of the radar cross-section is complex and depends on:

- Physical geometry and exterior features
- Direction of the illuminating radar
- Radar transmitter frequency
- Material

For simplicity, in the CM, targets are pre-defined with a notional RCS. An OTH test, in addition to the two-way radar equation, is also completed (Payne, 2010, p. 24):

$$R_{los} = \sqrt{17 \cdot h_{sensor}} + \sqrt{17 \cdot h_{object}} \quad (37)$$

where:

h_{sensor}	Height of sensor above waterline (m)
h_{object}	Height of object above waterline (m)
R_{los}	Range (line-of-sight) (m)

The maximum detection range (R_{max}) for an active radar is determined as the lower of the OTH test (R_{los}) and the two-way Radar Equation (R_e):

$$R_{max} = \min(R_{los}, R_e) \quad (38)$$

In addition to the maximum detection range, a check is completed for minimum detection range using the following equation (Payne, 2010, p. 31):

$$R_{min} = \frac{c(PW)}{2} \quad (39)$$

where:

R_{min}	Minimum detection range (m)
c	Speed of Light (m/s)
PW	Pulse width (m)

For an active radar to reliably detect an object, it must transmit and receive in the direction of an object. The transmission and reception of these pulses requires a period of time (i.e. the detect standard period). For each active radar, the detect standard period is calculated based on the distance between the object and the radar. The equation used is:

$$D_{sp} = N_p \left(\frac{2 \cdot R_{object}}{c} \right) \quad (40)$$

where:

R_{object}	Range of Object (m)
c	Speed of Light (m/s)
D_{sp}	Detect Standard Period (s)
$N_p = 10$	Number of pulses required to detect

All active radars are assumed to require 10 pulse returns from a point object to detect it (Payne, 2010, p. 34). The following systems detect using active radar within the CM:

- Active Denial System (ADS)
- Electronic Warfare System
- Air and Missile Defense Radar - S Band
- Air and Missile Defense Radar - X and C Band
- Close-in Weapon System (CIWS)
- Helicopter
- Surface Search Radar System

Detect Capability – ESM

An Electronic Support Measures (ESM) system gathers information through passive surveillance of electromagnetic radiation to detect and identify an object. An ESM system requires a wide-spectrum surveillance because the parameters of enemy transmissions are unknown beforehand (Payne, 2010). For VCs that operate using ESM, the CM uses the one-way radar equation, rewritten to solve for maximum detection range as shown below (Weapons Division, Naval Air Warfare Center, 2013, p. 4-3.8 and Payne, 2010):

$$R_e = \sqrt{\frac{P_t G_t A_{esm}}{4\pi k T_0 B_r N_f SNR_{min}}} \quad (41)$$

Where:

R_e	Maximum Detection Range (km)
NF	Noise Factor
A_{esm}	Receiver's Effective Antenna Aperture
k	Boltzmann's Constant
T_0	Standard Temperature
B_r	Receiver Noise Bandwidth
N_f	Noise figure of receiver
SNR_{min}	Minimum Detection Signal to Noise Ratio
G_t	Object Gain
P_t	Object Power

In addition to the one-way radar equation, an OTH test is also completed for ESM VCs (Payne, 2010, p. 24):

$$R_{los} = \sqrt{17 \cdot h_{sensor}} + \sqrt{17 \cdot h_{object}} \quad (42)$$

Where:

h_{sensor}	Height of sensor above waterline (m)
h_{object}	Height of object above waterline (m)
R_{los}	Range (Line of Sight) (m)

The maximum detection range (R_{max}) for an ESM system is determined as the lower of the OTH test (R_{los}) and the one-way Radar Equation (R_e):

$$R_{max} = \min(R_{los}, R_e) \quad (43)$$

For ESM systems, the detect standard period (i.e. time required for a radar to detect an object) is calculated based on the distance between the object and the radar. The equation used is:

$$D_{sp} = N_p \left(\frac{R_{object}}{c} \right) \quad (44)$$

Where:

R_{object}	Range of Object (m)
c	Speed of Light (m/s)
D_{sp}	Detect Standard Period (s)
$N_p = 10$	Number of pulses required to detect

All ESM systems are assumed to require 10 pulse returns from a point object to detect it (Payne, 2010, p. 34). The following VCs detect using ESM within the CM:

- ESM 1 & 2

Detect Capability – Infrared

Infrared systems allow a surface ship to detect a target by the collection and processing of its thermal radiation. Thermal radiators emit their energy over a wide band of wavelengths. It is not practical to detect equally over all the wavelengths so infrared detectors have upper and lower bounds on the wavelengths that they are designed to detect (i.e. λ_{upper} and λ_{lower}). For simplicity in this paper, it is assumed that IR detectors can pick up any energy that is within this range. To account for

the fact that thermal emissions are not all within an IR sensor's detection band, a Bandwidth Factor (F) is used to quantify the fraction of the IR radiation that is within a IR system's wavelength band. Within the CM, the universal black-body curve (Federation of American Scientists, 1998) is used to determine the fraction of the total flux which is outside of the band from zero to the variable λT , in units of $\mu\text{m-K}$.

The following equation can be used to quantify the maximum detection range of an IR system in a vacuum (Federation of American Scientists, Introduction to Naval Weapons Infrared Propagation and Detection, 1998):

$$R_{IR} = \sqrt{\frac{A_T \epsilon \sigma T^4 F A_e}{4\pi S_{min}}} \quad (45)$$

Where:

R_{IR}	Maximum Detection Range (m)
F	Bandwidth Factor
ρ	Collection Efficiency
A	Physical size of the detector opening
A_e	Detection Aperture = ρA
σ	Stefan-Boltzmann Constant
T	Temperature
ϵ	Emissivity
A_T	Target surface area
S_{min}	Minimum flux that receiver can detect

The maximum range predicted by this formula does not include atmospheric attenuation. The correction factor for atmospheric attenuation is excluded for simplification.

In addition to the maximum detection range of an IR system in a vacuum equation, a geometric line of sight test is also completed for each IR system as follows (Payne, 2010, p. 24):

$$R_{glos} = \sqrt{13 \cdot h_{sensor}} + \sqrt{13 \cdot h_{object}} \quad (46)$$

Where:

h_{sensor}	Height of sensor above waterline (m)
h_{object}	Height of object above waterline (m)
R_{glos}	Range (Geometric Line of Sight) (m)

The maximum detection range (R_{max}) is determined as the lower of the geometric line of sight test (R_{glos}) and the maximum detection range of an IR system in a vacuum (R_{IR}):

$$R_{max} = \min(R_{glos}, R_{IR}) \quad (47)$$

For IR systems, the detect standard period (i.e. time required for the sensor to detect an object) is calculated based on the distance between the object and the sensor. The equation used is:

$$D_{sp} = \left(\frac{R_{object}}{c} \right) \quad (48)$$

where:

R_{object}	Range of Object (m)
c	Speed of Light (m/s)
D_{sp}	Detect Standard Period (s)

The following systems detect using infrared within the CM:

- 1200 kW Laser
- CIWS
- ADS
- IR Search and Track System (IRST)

Detect Capability – Visual

For surface ships, detection capability is usually provided by sensors, but in close-in situations in support of some weapons, the CM also considers visual detection for the following systems:

- 0.50 cal Heavy Machine Gun (HMG)

The HMGs are assumed to have a static detection range of 1000 meters and can provide the detect capability for ASUW objects that are within this range. A detect standard period of 1 second is assumed for the HMGs.

Detect Capability – Prioritization

VCs that have sufficient detection range for an object are prioritized against that object through a simplistic methodology that is intended to represent warfighting doctrine. For the detect capability, the following prioritization of VCs is implemented:

- Active Radars

- If more than one Active Radar is available, priority is given to those with higher carrier frequency.
- ESM sensors
- IR Sensors
- Visual (i.e., HMG for ASUW objects only)

Track Capability

Tracking capability is the ability to continuously monitor object motion after initial detection, to predict future positions of the object, and to help in the identification of objects based on this motion. In the CM, track-capability is provided by the following VC types:

- Active Radar
- IR
- Visual

Track-capability nodes calculate track-capability for each VC that is capable of tracking an object. Track capability is modeled using the same methodology as the detect capability, but once a VC is selected to provide the track-capability, the same VC must be used for the entire track standard period. The track-capability VC does not need to be the same as the detect-capability VC, but the Track Standard Period must start after the end of a successful Detect Standard Period. The Track Standard period is the amount of time required for the sensor to track an object. The track standard period is calculated based on a VC's detect standard period, as follows:

$$T_{sp} = 2 \cdot D_{sp} \quad (49)$$

Where:

T_{sp}	Track Standard Period (s)
D_{sp}	Detect Standard Period (s)

In the CM, all systems that are able to track are assumed to be able to track an unlimited number of objects simultaneously, which is not possible on an actual ship.

Track Capability – Prioritization

VCs that have sufficient track range for an object are prioritized against that object through a simplistic methodology that is intended to represent warfighting doctrine. For the Track capability, the prioritization of VCs is as follows:

- Active Radars
 - If more than one Active Radar available, priority is given to those with higher carrier frequency.
- IR sensors
- Visual (i.e., HMG for ASUW objects only)

VC's that were used for a specific object in the previous time step are given a preference over any other equally capable VCs. An example of this would be if X-Band Radar 1 and X-Band Radar 2 were both equally able to track an object, but X-Band Radar 1 was used to provide a detect capability for the object in the previous time step, then X-Band Radar 1 would be slightly prioritized over X-Band Radar 2.

Identify Capability

Identify capability is provided through the collation and processing of sensor information. This can be accomplished by a ship's Combat Management System (CMS), but can also be provided through stand-alone Electronic Support Measure (ESM) systems. ESM systems have the capability to rapidly acquire signals, characterize the signal parameters and identify the signal by comparison with an emitter library.

In the CM, the identify-capability is treated as a mandatory step in the detect to engage sequence. Following a successful track-capability request, the OM can submit an identify-capability request. A successful response to an identify-capability request must be provided to the OM before the decision capability can be requested.

The following VCs provide the identify capability within the CM:

- Electronic Warfare System
- Laser Support Equipment
- CIWS
- Interrogation Friend or Foe (IFF) System
- ADS
- HMGs

Identify Capability – Prioritization

Following an identify-capability request from the OM, the identify-capability is assessed for each system that is capable of identifying an object. The measure of performance used to prioritize VCs for the identify-capability is the identification standard period, which is the amount

of time required for the system to complete the identification process for a single object. VC priorities are assigned in the following order:

- VCs with lower identify standard periods.

VC's that were used for a specific object in a previous time step are given a preference over any other equally weighted VCs. The selected VC then becomes active for the identify standard period, meaning it is operating at its mission power. Refer to the Track Prioritization section for an example of this.

Decision Capability

On a surface ship, the decision-capability is provided through sets of formal guidance such as mission doctrine and Rules of Engagement (ROE) and human intelligence. Mission doctrine is a guide to action rather than an explicit set of rules and ROEs are the military rules or directives that define the circumstances, conditions, degree, and manner in which the use of force, or actions which might be construed as provocative, may be applied.

In the CM, the decision-capability is a mandatory step in the detect to engage sequence. It is modeled as the ability to decide whether to engage an object or to continue tracking an object. Following a successful identify-capability request from the previous time step, the OM uses simplified ROEs to assess whether to proceed to submission of a query to the ship's decision-capability node. These ROEs are based on the operational mode of the ship and the object. They are presented in Table 13. If a decision-capability request is answered with a "yes", an engage-capability request can be made to the engage-capability nodes in the following time step. The operational modes listed in Table 13 are defined as follows:

- Loiter: Does not engage any objects;
- Self Defense: Engage all opposing team objects if they are in attack mode;
- Offense: Engage all red team objects with no restrictions; and
- Attack: Engage opposing teams objects except for those in loiter mode. Note: a ship cannot be in attack mode. Attack mode represents a missile or round that is travelling towards and will impact its target.

In the CM, the decide-capability is assessed for each VC that is capable of decisions or at final VCs before a Command (human) node. In the Figure 98 and Figure 102 plexes this includes:

- Combat Information Center (CIC) Equipment and Displays
- Laser Support Equipment (always assumed in automatic mode in CM)
- CIWS (always assumed in automatic mode in CM)

Decide Capability – Prioritization

Following a decide-capability request from the OM, the decide-capability is assessed for each system that is capable of deciding to engage an object. The measure of performance used to prioritize VCs for the decision-capability is the decision standard period, which is the amount of time required for the system to complete the decision process for a single object. VC priorities are assigned with a higher priority for VCs with lower decide standard periods.

VC's that were used for a specific object in a previous time step are given a preference over any other equally weighted VCs. Refer to the Track Prioritization section for an example of this.

		Agent/Threat Mode			
		Loiter	Self-Defense	Offense	Attack
Blue Ship Mode	Loiter	Decide to Track	Decide to Track	Decide to Track	Decide to Track
	Self-Defense	Decide to Track	Decide to Track	Decide to Track	Decide to Engage
	Offense	Decide to Track	Decide to Engage	Decide to Engage	Decide to Engage

Table 13. Ship CM Decide Rules of Engagement

Engage Capability

Engage capability is the ability of the ship to engage a threat. It is achieved through the application of a weapon. To form the basis for deciding which of the available weapons to use to engage a target, a P_{kill} MOP is used to determine which weapon is most likely to neutralize the target. P_{kill} is the probability that a hit by a weapon will destroy a specific threat. P_{kill} is calculated based on the probability of hitting a target (P_{hit}) and the probability that a hit will destroy the target (P_d). The P_{kill} equation is:

$$P_{kill} = P_{hit} \times P_d \quad (50)$$

To determine P_d , pre-determined tables are used based on the threat type and the weapon type. To determine P_{hit} , pre-populated tables are generated for each of the ship's weapons based on each threat type and threat range. The data in the P_d and P_{hit} tables are estimated based on publicly available data for each weapon where available using an approach similar to Appleget et al. (2020, p. 111). Where publicly available data is not available or sensitive, the authors have generated estimates which are reasonable, but not actual values. A speed factor is used to adjust P_{hit} based on a threat's speed using the following formula:

$$P_{hit_factored} = \left(1 - \frac{V_{threat}}{10000}\right) \cdot P_{hit} \quad (51)$$

Where:

$P_{hit_factored}$	Probability of Hit (factored for speed)
V_{threat}	Threat Speed (m/s)

This formula is an estimate that the authors have generated for simplification purposes and is not reflective of actual values. It is intended to reduce the value of P_{hit} for high-speed threats and serve as a placeholder for future work regarding the generation of P_{hit} values. In the CM, the ship systems that provide the Engage capability include both hard-kill and soft-kill systems. As part of this analysis, the following assumptions/limitations exist for weapons:

- All weapons are considered to have unobstructed, 360-degree firing arcs. In the CM, any engagement VC can engage any

threat approaching from any direction which is not true for an actual surface ship; and

- Soft-kill weapons always engage the threat just before the threat reaches the ship.

To assess whether the engage capability can be provided (as described in the steps below) and to implement an engagement in the OM, the following parameters exist for all weapons:

- Fire and Forget Indicator (each weapon is classified as either:
 - Fire and Forget – Weapon has its own tracking system and does not require input from the ship once launched. A Fire and Forget weapon does not require the ship to provide tracking for the engagement to be successful.
 - Ship Illumination – Weapon does not have an independent tracking capability and requires the ship to provide tracking for the engagement standard period of the weapon. If the track capability is unable to be provided by the ship during the engagement, the engagement fails.
- Engagement Standard Period – This is a parameter that is specific to directed-energy weapons (e.g. ADS and LaWS). It is a time period during which a weapon must be engaging a threat (i.e. directing energy), before an engagement can be considered successful.
- Engagement Magazine Capacity – This is the current number of rounds remaining for a VC. This value is maintained during the execution of an OPSIT. The Vertical Launch System (VLS) magazine capacity considers the number and type of missiles and rockets loaded into the VLS.
- VC Salvo/Rounds Per Engagement – This is the number of rounds that a VC would fire for a single engagement. This parameter is required for weapons, such as the CIWS, which fire more than one round during an engagement.
- Engagement Delay Period – This parameter is intended to account for the time required for a weapon to reach its engagement speed (e.g. launching a missile from a VLS requires a period of time for the missile to reach its engagement speed).

- Engagement Speed –The engagement speed is the speed (m/s) at which the munition will travel after completion of the Engagement Delay period. For example: a rail gun must be powered up for a given time period prior to firing (i.e. Engagement Delay period), after which the round is fired and will travel at the engagement speed towards the target.
 - Note: Decoys and soft-kill weapons do not work this way, as they do not fire munitions at a target. In CM, these weapons are assigned an Engagement Speed of -1. This indicates to the OM that, once the weapon is “fired”, the threat is not defeated until it reaches the ship. This effectively indicates that the threat has been lured away from the ship.
- Engagement Cooldown Period – This parameter is intended to account for the time required for a weapon to cooldown after completing a previous engagement. E.g. A rail gun must cool down for a given time period prior to subsequent firings.

Engage capability is assessed through the following steps:

1. P_{Hit} , P_D and P_{Kill} values are calculated for a VCs salvo fired against each threat.
2. Weapons that are unable to achieve the goal P_{Hit} are not included in the following steps. Note: In the CM, the goal P_{Hit} is defined as 0.5 or higher.
3. The magazine capacity of each weapon is assessed to confirm that there are adequate rounds available. Weapons that do not have adequate magazine capacity are not included in Step 4 through 7.
4. Weapons are queried to determine if they are currently in-use (i.e. whether they are currently executing any engagements requested in a previous time step). Unavailable weapons are not included in Step 5.
5. Weapons are queried to determine if they are able to complete an engagement before the threat would hit the blue ship. Weapons that require more time to complete an engagement than is available are not included in Step 6.
6. At the completion of Step 5, a list of weapons that: have enough ammunition, can provide a

P_{Hit} value > 0.5 , are not currently executing an engagement, and are able to engage within the required timeframe exists. The VCs are prioritized based on their P_{Kill} and are passed to the DAFO as options for providing the engage capability.

7. A DAFO is completed and a weapon is selected to provide the Engage capability. The result is provided to the capability nodes as the firing solution. If the DAFO is unable to provide any VCs, the engage capability is not provided.
8. The capability nodes flag the weapon as active for its engagement standard period. This indicates that it cannot be used for additional engagements until this time period has elapsed. If no weapons are able to provide the engage capability, no weapons are activated.
9. The capability nodes provide a yes/no response to the OM, along with information on the weapon used. This additional information includes:
 - a. Fire and Forget indicator
 - b. Engagement Standard Period
 - c. Engagement Delay Period
 - d. Engagement Speed

Single Object Vital Components (SOVCs)

In the CM, the following VCs have additional considerations not described in the previous sections:

- CIWS 1
- CIWS 2
- Laser

For each of these SOVCs, prioritization is based on the capability range (R_c), which is the range at which a SOVC can be used to provide a capability. The capability range was developed as part of this study to ensure that these SOVCs are only used to engage objects once they reach the SOVC’s maximum effective engagement range. The capability range is calculated using the following formula:

$$R_c = R_{eff} + (V_{ref} * t_{min}) \quad (52)$$

Where:

R_c Capability Range (m)

R_{eff}	Maximum Effective Engagement Range (m)
V_{ref}	Reference Object Speed (m/s)
t_{min}	Minimum time required to advance from the first kill chain step to the Engage step(s)

To ensure that SOVCs are prioritized to engage threats once they reach SOVC's maximum engagement range, the SOVCs must be prioritized to provide the detect, track, identify, or decide capabilities based on the time it takes for an object to reach the blue ship. The reference object speed is selected to account for the fastest AAW object type of the AAW class used by the WM.

This CM prioritization limits each SOVC to only providing capabilities in response to a single object at each time step. If an object is determined to be within the capability range for the automated VCs, the automated VCs are prioritized against each other as follows:

- Zero objects
 - CIWS 1 is not assigned to any object.
 - CIWS 2 is not assigned to any object.
 - Laser is not assigned to any object.
- One object
 - CIWS 1 is assigned to the object.
 - CIWS 2 is assigned to the object.
 - Laser is assigned to the object.
- Two objects
 - CIWS 1 is assigned to the highest priority object.
 - CIWS 2 is assigned to the second highest priority object.
 - Laser is assigned to the highest priority object.
- Three (or more objects)
 - CIWS 1 is assigned to the highest priority object.
 - CIWS 2 is assigned to the second highest priority object.
 - Laser is assigned to the third highest priority object.

Capability Model Demonstration

This section describes the execution of a simple OPSIT (from the perspective of the blue ship). Table 14 shows the event log generated by this OPSIT when events are resolved at each time

step as part of the SBIM Execution Process (Figure 101). Shane, et al. (2021) describe the Warfighting Model (WM) and Ship Operational Model (OM) and Parsons, et al. (2021) describe the Ship DAFO Model.

This OPSIT initially has three objects: 1 x Blue Ship and 2 x Red ASMs. The OPSIT begins at $t = 1$ s when the two Red ASMs enter the Blue Ship's area of responsibility which is set to a radius of 20 km from the blue ship.

The first time step of this OPSIT is described in detail in the SBIM Execution Example section earlier in this paper. In summary: The OM requests two detect capabilities (one for each Red ASM). The CM provides prioritized list of VCs that could provide the requested capabilities (six VCs in total) using the methodology described in the Detect Capability sections of this paper. The DAFO uses these requests to select the VCs (ESM Antenna 2 in this case) that will provide each capability. These selected VCs are provided to the CM which in turn determines which capabilities are provided to the OM. The OM then resolves the events and generates the first line in the event log shown in Table 14.

The resolved events (from each time step) are shown in Table 14. During the first five seconds of the OPSIT the blue ship completes the first five steps of the kill chain:

- At $t = 1$ s the Blue Ship detects the Red ASMs with ESM Antenna 2.
- At $t = 2$ s, the Blue Ship tracks the Red ASMs with X-Band Radar 2.
- At $t = 3$ s, the Blue Ship tracks and the Red ASMs with X-Band Radar 2 and identifies the Red ASMs with the IFF Antenna.
- At $t = 4$ s, the Blue Ship tracks and the Red ASMs with X-Band Radar 2 and decides to engage with Display 2.
- At $t = 5$ s, the Blue Ship tracks and the Red ASMs with X-Band Radar 1 and engages the Red ASMs with two ESSMs (one per Red ASM).

Then, from $t = 6$ s to $t = 14$ s, the Blue Ship tracks and the Red ASMs with X-Band Radar 2 while the Green ESSMs move toward the Red ASMs. Finally, at $t = 15$, the Green ESSMs kill the Red ASMs. This event ends the OPSIT.

t (s)	Object	Event	Capability	VC
1	Red ASM 1	Enters AoR	Blue Ship	Detects with X-Band Radar 2
1	Red ASM 2	Enters AoR	Blue Ship	Detects with X-Band Radar 2
2	Red ASM 1	Moves	Blue Ship	Tracks with X-Band Radar 2
2	Red ASM 2	Moves	Blue Ship	Tracks with X-Band Radar 2
3	Red ASM 1	Moves	Blue Ship	Tracks with X-Band Radar 2
3	Red ASM 1	Moves	Blue Ship	Identifies with IFF Antenna
3	Red ASM 2	Moves	Blue Ship	Tracks with X-Band Radar 2
3	Red ASM 2	Moves	Blue Ship	Identifies with IFF Antenna
4	Red ASM 1	Moves	Blue Ship	Tracks with X-Band Radar 2
4	Red ASM 1	Moves	Blue Ship	Decides with Display 2
4	Red ASM 2	Moves	Blue Ship	Tracks with X-Band Radar 2
4	Red ASM 2	Moves	Blue Ship	Decides with Display 2
5	Red ASM 1	Moves	Blue Ship	Tracks with X-Band Radar 2
5	Red ASM 1	Moves	Blue Ship	Engages with ESSM 1
5	Red ASM 2	Moves	Blue Ship	Tracks with X-Band Radar 2
5	Red ASM 2	Moves	Blue Ship	Engages with ESSM 2
6-14	Red ASM 1	Moves	Blue Ship	Tracks with X-Band Radar 2
6-14	Red ASM 2	Moves	Blue Ship	Tracks with X-Band Radar 2
15	Red ASM 1	Killed by	Green ESSM 1	
15	Red ASM 2	Killed by	Green ESSM 2	

Table 14. OPSIT Event Log

Conclusions and Future Work

The Capability Model (CM) described in this paper serves as the critical link between the ship's distributed systems and the warfighting environment. This link is represented by the capability sink nodes and their incoming arcs in the mission system's logical architecture (Figure 98). These capability nodes enable the Ship Behavior and Iteration Models (SBIMs) to simulate an OPSIT and determine a ship mission effectiveness during Concept & Requirements Exploration (C&RE).

The capability and operational models that support these nodes provide essential mission and vital component priorities used to guide the alignment of system vital components over time, ultimately using a Dynamic Architecture Flow Optimization (DAFO). The ultimate objective of

coupling ship system architecture and function to the operational architecture is that it enables time-stepping operational scenarios to be implemented that are fully coupled to ship system design, function, damage and even alignment for optimum mission performance. The most important take-away from this paper is the concept of using capability nodes to pull function from the ship energy and data systems thus enabling the whole framework. This is not a paper about combat systems, but about enabling a total ship system approach and framework.

These methods are fully scalable to force-level operational situations with separate system models for all operational units using parallel computing. Pseudo-intelligence is provided by an agent-based approach in the warfighting model and by a doctrine-based network energy and data flow optimization in the ship systems. These

algorithms are efficient and effective. This approach is also adaptable for machine learning.

The most critical future work includes completion of the fully-functional DAFO including energy flow and data flow responding to capability requests from the operational architecture through the capability nodes. These two commodities (energy and data) provide a sufficient level of detail to assess mission effectiveness in C&RE.

Another area for future work is to modify this methodology allowing the DAFO to select more than one VC to respond to each capability request. For example, tracking an object with a single VC is sufficient but, tracking that same object with two or more VCs may provide a higher level of confidence in the track.

Author Biographies

David J. Berrow is currently a M.S. Ocean Engineering Student of the Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech. He is employed with the Department of National Defence (Canada). He received his B.S. in Ocean Engineering and Naval Architecture from Memorial University of Newfoundland in 2011.

Mark A. Parsons is currently a Ph.D. Candidate and Graduate Research Assistant of the Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech. He researches network-based methods to assess surface ship distributed system vulnerability, survivability, and deactivation recoverability in concept stage design. He received his M.S. in Ocean Engineering from Virginia Tech in 2019 and his B.S. in Naval Architecture and Marine Engineering from the University of New Orleans in 2016. He is a student member of ASNE and SNAME.

Alan Shane was an Ocean Engineering Master's Degree Candidate at the Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech. He is interested in developing ship concept development and assessment tools that supports a path towards MBSE and DE in those processes. He received his M.S. and B.S. in Ocean Engineering from Virginia

Tech in 2020 and 2010 respectively. He is a student member of ASNE and SNAME.

The final area for future work is to add additional time-marching functions to the DAFO algorithm for properly modeling energy storage and the ramping up and down of mechanical and thermal-fluid systems, particularly for damage control with system realignment.

Acknowledgments

The authors would like to thank Ms. Kelly Cooper, ONR Code 331, for supporting this work under contract N00014-15-1-2476. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the Office of Naval Research.

Tech in 2020 and 2010 respectively. He is a student member of ASNE and SNAME.

Mustafa Y. Kara is currently a Ph.D. Candidate and Graduate Research Assistant of the Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech. He researches network-based methods to assess surface ship distributed system vulnerability, survivability, and deactivation recoverability in concept stage design. He received his B.S. in Naval Architecture and Marine Engineering from the Turkish Naval Academy in 2006. He received his S.M. in Naval Architecture and Marine Engineering from MIT in 2010. He is a student member of ASME and SNAME and alumni of MIT (Educational Counselor).

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 2015 recipient of the SNAME Webb Medal for Outstanding Contributions to NA&ME Education. 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 Systems Engineering from MIT in 1986.

References

- Appleget, J., Burks, R., & Cameron, F. (2020). *The Craft of Wargaming*. Naval Institute Press.
- Brefort, Dorian, Shields, Colin, Habben Jansen, Agnieta, Duchateau, Etienne, Pawling, Rachel, Droste, Koen, Jasper, Ted, Sypniewski, Michael, Goodrum, Conner, Parsons, Mark A., Kara, Mustafa, Roth, Mark, Singer, David J., Andrews, David, Hopman, Hans, Brown Alan J., Kana, Austin (2018). An architectural framework for distributed naval ship systems. *Ocean Engineering*, 147, 375–385
- Brown, Alan J. (2020). Ship and Marine Engineering System Concept Design. In Michael G. Parsons (Ed.), *Marine Engineering* (4th ed.). Alexandria, VA: SNAME
- Brown, Alan, Salcedo, Juan. (2003). Multiple-Objective Genetic Optimization in Naval Ship Design, *Naval Engineers Journal*, 115(4), 49-61
- Brown, Alan J., Thomas, M. (1998). Reengineering the Naval Ship Concept Design Process" in *From Research to Reality in Ship Systems Engineering Symposium*, ASNE
- Brown, Alan J., Sajdak, John. (2015). Still Re-Engineering the Naval Ship Concept Process. *Naval Engineers Journal*, 127(1), 49-61
- Chalfant, Julie, Chrysostomidis, Chrys, Snyder, Daniel, Parsons, Mark A., Brown, Alan (2017). Graph Theory Applications in FOCUS-Compliant Ship Designs, in *Electric Ship Technologies Symposium 2017*, Alexandria, VA: IEEE
- Department of Defense. (2020). DOD Dictionary of Military and Associated Terms. Washington, D.C., USA.
- Goodfriend, David, Brown, Alan J. (2018). Exploration of System Vulnerability in Naval Ship Concept Design, *Journal of Ship Production and Design*, 34(1), 42-58.
- Federation of American Scientists, "Introduction to Naval Weapons Infrared Propagation and Detection", accessed 16 November 2019, https://fas.org/man/dod-101/navy/docs/es310/IR_prop/IR_prop.htm.
- Friedman, N. (2006). *Naval Institute Guide to World Naval Weapon Systems* (Fifth Ed.). Naval Institute Press.
- Hughes, W., & Girrier, R. P. (2018). *Fleet Tactics and Naval Operations* (Third Ed.). Naval Institute Press.
- Kerns, C., Brown, A. J., & Woodward, D. (2011). Application of a DoDAF Total-Ship System Architecture in Building Naval Ship Operational Effectiveness Models. MAST Americas, 2011.
- Kerns, L. C., Brown, A. J., & Woodward, D. (2011). Application of a DoDAF Total-Ship System Architecture in Building a Design Reference Mission for Assessing Naval Ship Operational Effectiveness. *Naval Engineers Journal*.
- Parsons, M. A., Kara, M. Y., & Brown, A. J. (2020a). Refinement of a Mission, Power, and Energy System Architecture Flow Optimization Method and Tool for Surface Ship Concept Design. *Advance Machinery Technology Symposium 2020*.
- Parsons, M. A., Kara, M. Y., Shane, A., Berrow, D. J., & Brown, A. J. (2021). Dynamic Architecture Flow Optimization for Assessing Mission Effectiveness in Surface Ship Concept and Requirements Exploration. To be submitted to *Combat Systems Symposium 2021*.
- Parsons, M. A., Robinson, K. M., Kara, M. Y., Stinson, N. T., Snyder, D., Woodward, D., & Brown, A. J. (2020b). Application of a Distributed System Architectural Framework to Naval Ship Concept and Requirements Exploration (C&RE). *Naval Engineers Journal*, 132(4), 105–124. <https://www.ingentaconnect.com/contentone/asn/nej/2020/00000132/00000004/art00031%0A>
- Payne, C. M. (2010). *Principles of Naval Weapon Systems* (Second Ed.). Naval Institute Press. <https://books.google.com/books?id=MUUMQwAACAAJ>
- Purdy, E. M. (2004). "Test and Evaluation WIPT." *Proceedings of the 20th Annual Test & Evaluation Conference & Exhibition*. Reno, NV, USA.
- Shane, A., Parsons, M. A., Berrow, D. J., Kara, M. Y., & Brown, A. J. (2021). Operational Architecture and Framework for Assessing Mission Effectiveness in Surface Ship Concept and Requirements Exploration. *Intelligent Ships Symposium 2021*.
- Stevens, John D., Opila, Daniel F., Oh, Eun S., Zivi, Edwin L. (2017). All-Electric Warship Load Demand Model for Power and Energy

- System Analysis Using Exogenously Initiated Threats, in *Electric Ship Technologies Symposium 2017*, Arlington, VA: IEEE
- Stepanchick, Justin, Brown, Alan. (2007). Revisiting DDGX/DDG-51 Concept Exploration. *Naval Engineers Journal*, 119(3), 67-88
- Strock, Justin, Brown, Alan. (2008). Methods for Naval Ship Concept and Propulsion System Technology Exploration in a CGX Case Study. *Naval Engineers Journal*, 120(4), 95-122
- Snyder, Daniel J., Parsons, Mark A., Brown, Alan J., Chalfant, Julie. (2019). Network Architecture Framework Applications with FOCUS-compliant Ship Designs, in *Electric Ship Technologies Symposium 2019*, Alexandria, VA: IEEE
- Weapons Division, Naval Air Warfare Center (2013). *Electronic Warfare & Radar Systems Engineering Handbook*. Point Mugu, California.

I am an Engineer. In my profession I take deep pride. To it I owe solemn obligations.
–Order of the Engineer

Integrity and Excellence in Engineering
–Tau Beta Pi,
The Engineering Honor Society

Paper #6 – System Dynamic Architecture Flow Optimization to Assess Mission Effectiveness in Surface Ship Concept and Requirements Exploration

Mark A. Parsons¹, Mustafa Y. Kara¹, Alan Shane¹, David J Berrow¹, and Alan J. Brown¹

Abstract

This paper describes the development and implementation of a Dynamic Architecture Flow Optimization (DAFO) for Mission, Power and Energy System (MPES) design in Surface Ship Concept and Requirements Exploration (C&RE). The DAFO interfaces with a warfighting model, ship operational model, and mission capability models to determine optimum MPES alignment and provide capabilities over multiple time steps as required for operational effectiveness in ship operational situations (OPSITs). These Ship Behavior and Interaction Models (SBIMs) are part of a system design framework that includes architectures for ship operations, physical arrangements and the logical relationship of MPES vital energy and data components (VCs). The mission capability models provide a critical interface between logical and operational architectures, quantifying warfighting capabilities through system measures of performance at specific capability nodes. The operational architecture queries the capability models for necessary operational capabilities and implements them in the warfighting environment. The capability models also provide essential mission and vital component priorities used to guide the alignment of system vital components by the DAFO.

Introduction

Mission, Power and Energy Systems (MPES) are fundamental to the design, mission, and operation of surface ships. MPES design and architecture are critical in determining all aspects of a surface ship's effectiveness, survivability, and cost. MPES are distributed systems, most simply defined as mechanical, electrical and electronic Vital Components (VCs) 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. (2020b) describe 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, Kerns, et al., 2011a, Kerns, et al., 2011b, Brown & Sajdak, 2015, Parsons, et al., 2020a, Parsons, et al., 2021). Goodfriend & Brown (2018) describe the application of this process to C&RE considering vulnerability. The Dynamic Architecture Flow Optimization (DAFO) presented in this paper enables the assessment of both vulnerability and recoverability, two of three critical survivability elements.

Goodfriend & Brown (2018); Snyder et al. (2019); and Habben Jansen, et al. (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. Recoverability is also not considered. Stevens, et al. (2017a and 2017b) and Sinsely, et al. (2019) consider power, but only electrical power. The total ship system is not modeled.

¹ Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech

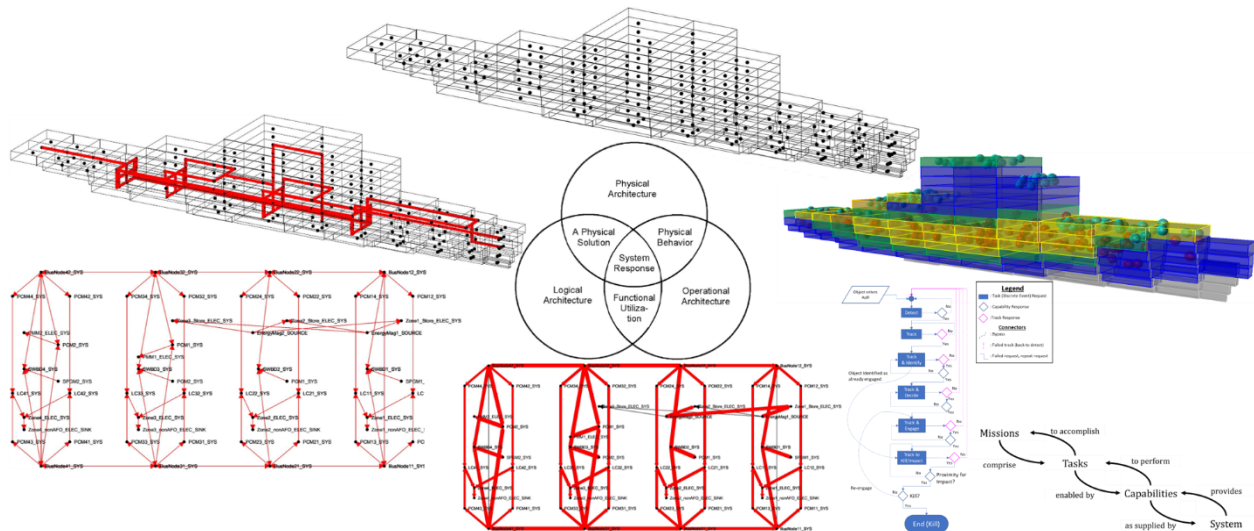


Figure 105. Ship System Architectural Framework (Shane et al., 2021)

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 architectural 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. The center Venn diagram in Figure 105 shows how this Architectural 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 105 shows examples of these architectures and their relationships. These architectures and their application in C&RE using an architecture flow optimization (AFO), particularly working with the logical architecture, are described in Brown (2020), Parsons et al. (2020a, 2020b).

The interface between the logical architecture and operational architecture occurs at capability nodes in the logical architecture and is quantified using Ship Behavior and Interaction Models (SBIMs). The capability nodes also reside in the “Functional Utilization” intersection shown in Figure 105. The operational architecture is illustrated in the lower right corner of Figure 105 and its development, application and associated SBIMs are described by Shane, et al., (2021), Berrow, et al., (2021) and this paper.

The simplified operational architecture, warfighting model, and mission system vital component models presented in this paper are for academic purposes only, adapted from content provided by Friedman (2006), Payne (2010), Hughes & Girrier (2018), and Appleget, et al. (2020) to a very basic level of detail sufficient for fundamental research and the development of new methods, processes, and a system framework.

Mission-Means Framework and Ship System Behavior Models

Figure 106 shows the Purdy (2004) Mission-Means Framework (MMF), a modified systems-engineering V-model, which illustrates the relationships between necessary elements in a system’s operational architecture. The definitions for terms in the MMF are taken primarily from the DOD Dictionary of Military and Associated Terms (2020).

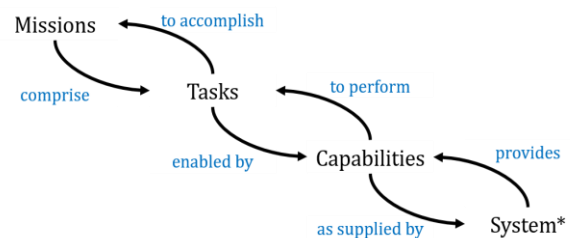


Figure 106. Modified Mission-Means Framework (Purdy, 2004)

The SBIMs implement the MMF to accomplish mission(s) and perform tasks specified by the Design Reference Mission (DRM) as system responses in a discrete event simulation. The SBIMs and their relationship are represented in Figure 107. The SBIMs model ship behavior throughout an operational situation (OPSIT) which is completed over a series of time-steps. Traditionally, early C&RE evaluation is performed based on relative effectiveness by comparing ship designs to each other, rather than modeling the ship design in an operational scenario to determine its effectiveness. Shane, et al. (2021) describe an improved assessment process that explicitly considers the ship's effectiveness during execution of an OPSIT. This process allows for a ship's mission effectiveness for a specific OPSIT to be used to compare designs.

A uniform time-step of one second is currently used in the SBIMs. This is consistent with the time scale required for the measurement of system energy usage, heat dissipation, and energy storage charging/discharging. It is not intended to consider transient stability and other shorter time scale phenomena as in the electrical subsystem. A typical detect to engage sequence can occur in less than a minute, so a 1 second time interval allows for operational modelling but is limited for operations that occur in less than a second. Operations that occur in less than a second are

modelled for the entire time-step (one second) even if they occur more quickly.

Figure 107 is an application and refinement of Figure 106 where the (blue) ship agent operational model requests capabilities from the Capability Model (CM). Following this query, the CM assesses the ability of the ship to provide the capabilities if supported by the Ship DAFO Model.

The Operational Model (OM) is the blue ship mission/task behavior model implementing the blue ship's Operational Architecture. It serves as the interface between the Warfighting Model (WM) and the blue ship CM. It interacts with the CM through capability requests and responses, as shown in Figure 107. As an example, when the WM requires the blue ship to perform an Anti-Air Warfare (AAW) task, the OM determines necessary capabilities and sends capability request(s) from the OM to AAW system (or plex) capability node(s), blue circle in the logical architecture shown in Figure 4, where the capabilities are modeled and managed (Shane, et al. 2021). The outcome of the execution of a task defined in the OM is determined by whether or not the ship possesses the capability to perform the task. If the necessary capability is available, the task can be successfully performed. Shane, et al. (2021) define several terms relating to the WM and OM that are used throughout this paper.

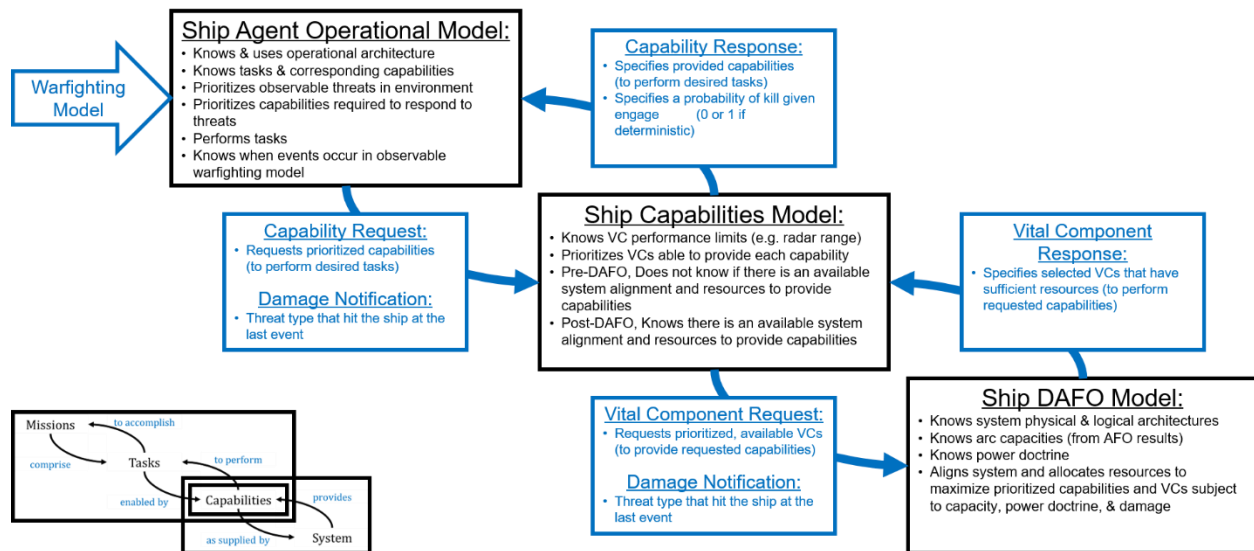


Figure 107. Ship Behavior and Interaction Models (SBIMs)

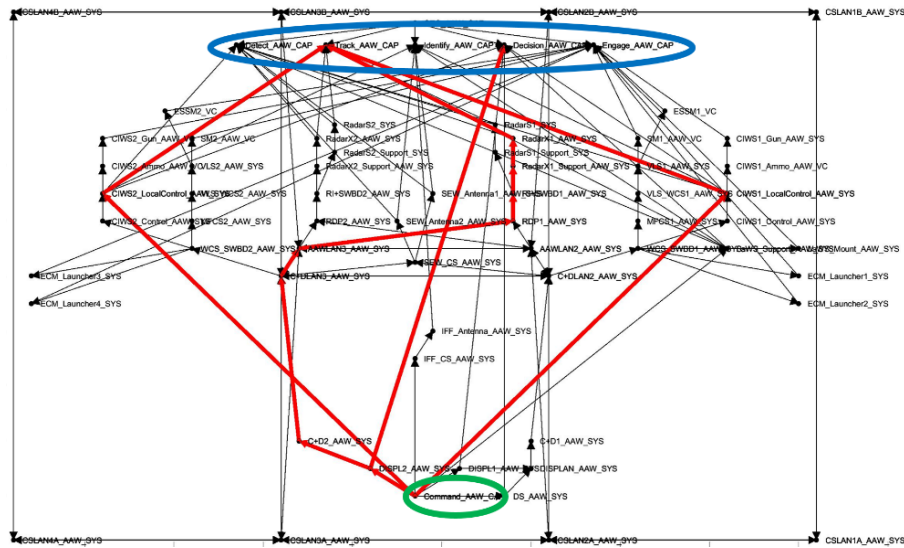


Figure 108. AAW Mission Plex Vital Components and Circled Capability Nodes with Data Commodity Flows (adapted from Friedman, 2006, p 105 and Chalfant et. al, 2017)

The CM interfaces with the OM and the DAFO model to answer queries at each time-step (Berrow, et al., 2021). A system response objective function in the DAFO model is updated at each time-step based on priorities specified by the OM and consistent with the operational architecture. This enables blue ship system alignment by the DAFO.

The DAFO model uses both an energy formulation and a mission system data formulation to support and interface with the CM and OM as shown in Figure 107. The DAFO model determines the optimum energy flow and mission system data flow (0, 1) through the logical architecture to support the capability pull, translated by the CM, from the operational

architecture at each time-step. The data flow is a DAFO commodity in addition to the energy flow used in earlier AFO formulations to model a functional mission system, as shown in Figure 108. Each of the AAW VCs in Figure 108 requires electric power and cooling which must be provided in the energy solution. The power and energy formulation and the basic AFO is described by Parsons et al. (2020a), Brown (2020) and Parsons et al. (2021). The DAFO model determines the mission system usage, data and energy flow using the prioritized capability pulls on the system to determine which VCs are available and active during the discrete event. Describing the DAFO is the primary focus of this paper.

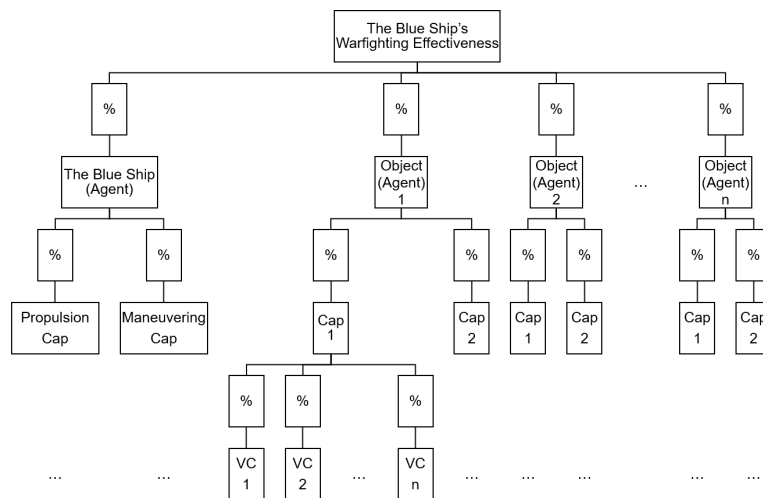


Figure 109. Effectiveness Hierarchy

At each time-step, the mission effectiveness for the blue ship system is maximized in the DAFO model using the hierarchy shown in Figure 109, with priorities provided by the OM and CM, passed through the CM. Objects approaching the blue ship area of responsibility are assigned a priority between 0 and 1 by the OM based on:

- Time to impact the blue ship (or not)
- Potential damage to the ship (i.e. warhead kg TNT)

Objects reaching an engage task capability request are prioritized above all other objects. Object priorities are normalized to sum to 1 for all detectable objects in the warfighting environment. Shane, et al (2021) describe how these warfighting tasks in the Operational Architecture (OA) and their corresponding capability requests are structured according to the steps in the kill chain:

1. **Detect:** Detect
2. **Track:** Track
3. **Identify:** Track and Identify
4. **Decide:** Track and Decide
5. **Engage:** Track and Engage

Capabilities are prioritized and sum to 1 for each object. This basic series of tasks is also used as a simple and generic warfighting operational architecture as discussed by Shane, et al. (2021). The temporal implementation of these generic tasks is more completely specified and described by the WM and OM consistent with the OA.

System VCs provide capabilities, but more than one VC may be able to provide the same capability. To determine which VCs are best suited to provide each capability, capability Measures of Performance (MOPs) are calculated for each applicable VC. Based on these MOPs, VCs are prioritized between 0 and 1, and normalized to sum to 1 for each capability. For example, the engage capability may be requested for an object, and may be provided by VC 1 or VC 2. For engage, the MOP used is the Probability of Kill (PKill), so the PKill against the threat is calculated for VC 1 and VC 2. In this example, if PKill for VC 1 is assessed as being two times greater than for VC 2, then VC 1 would receive a priority of 0.67 and VC 2 would receive a priority of 0.33.

The priorities associated with each VC, each capability, and each object (see Figure 109) are used in the DAFO objective function. The DAFO model maximizes effectiveness by selecting VCs to provide the optimum combination of successful capabilities.

Dynamic Architecture Flow Optimization (DAFO)

MPES 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. 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 2008a and 2008b, Chinneck 2020, Konak and Smith 2018). The 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. 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 Smart Ship System Design (S3D) (Chalfant 2015).

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 result, plexes are similar to traditional marine engineering distributed systems (i.e. fuel oil service system, electrical distribution system, chilled water system, mission system 1/MS1) (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.

Directed edges connecting nodes in a single plex are called explicit arcs and arcs connecting nodes in different plexes are called implicit arcs. Figure 110 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. Anti-Air Warfare (AAW) / Mission System 1 (MS1)
14. Anti-Submarine Warfare (ASW) / Mission System 2 (MS2)
15. Anti-Surface Warfare (ASUW) / Mission System 3 (MS3)

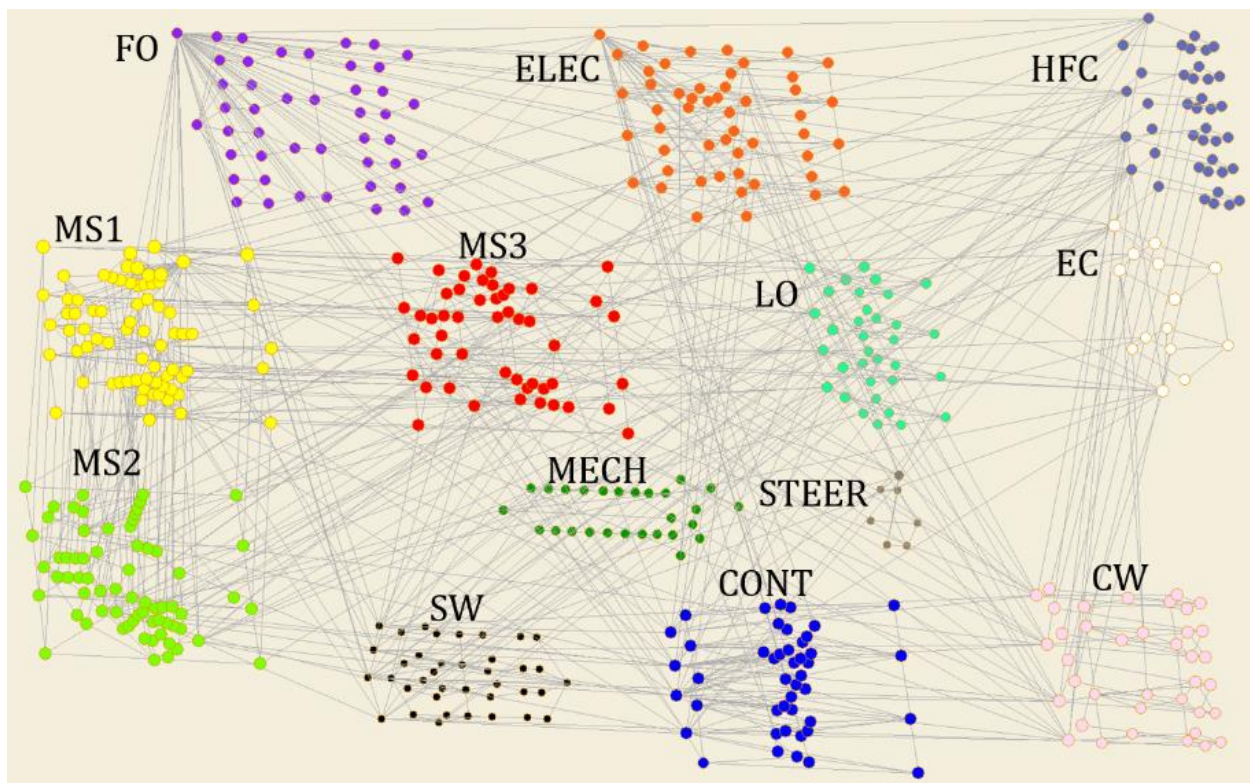


Figure 110. Notional Surface Ship Total-Ship Multiplex Logical Architecture

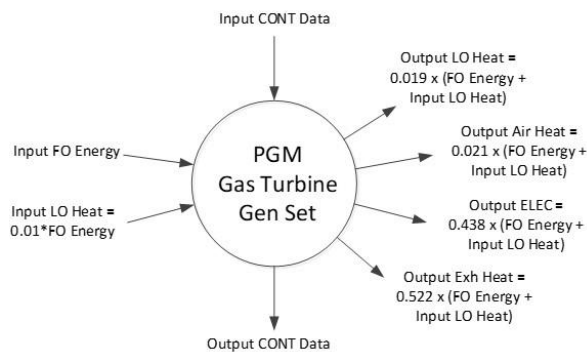


Figure 111. Nominal PGM (Gas Turbine and Generator Set Combination) Nodal Input and Output Coefficients

Figure 111 shows a Power Generation Module (PGM) gas turbine generator set as an example Power System (PSYS) VC 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 ($0.01 \times \text{FO Energy}$) 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 = 0.438). 52.2% is lost in the engine exhaust and module air-cooling. This energy goes up the stack to the external 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. The commodity flowing in these arcs is data/information and is used primarily by the CONT plex. CONT data is used for similar functions to data in the in MS1, MS2, and MS3 plexes, that is Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) functions.

Energy coefficients are assigned to the input and output arcs of PSYS vital components based on these simple component models. Figure 112 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 with an equipment type does not connect to are assigned values of zero. Nonzero coefficients are highlighted in green in Figure 112. Note the PGM coefficients are consistent with Figure 111.

This network approach has proven to be exceptionally capable and flexible for the C&RE application. As a result, the entire C&RE process was reworked to apply this approach and its associated framework as described in Parsons et al. (2020b) and Chapter 1 of Marine Engineering (Brown, 2020).

Robinson (2018) and Parsons, et al. (2020a) describe the incorporation of this Architecture Framework into an energy-based variation of Trapp's (2015) non-simultaneous multi-commodity which is called Architecture Flow Optimization (AFO). 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). AFO has become the primary method used in the C&RE to explore the MPES design, preliminary arrangements, and survivability (Parsons et al., 2020b). 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 VC sizing algorithm (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 completes the initial sizing of the total ship system.

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

Figure 112. Excerpt from MEL Equipment Input and Output Energy Coefficient Matrix

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. A variation of this time domain system modeling approach is combined with the energy-based total ship system model developed by Parsons, et al. (2020a) and a new data-based commodity flow method to create the DAFO.

The DAFO's mission capabilities are provided using a new commodity, data. The source of this data commodity is the command node included in each mission system plex (green circle in Figure 108) and the data sinks are the capability nodes (blue circle in Figure 108). For each capability request in a time-step, the command source node sources a data flow equal to 1 and the capability sink node attempts to receive it. The incoming arcs to the capability sink node from supporting VCs can provide effectiveness corresponding to the product of their threat priority, capability priority, VC priority and data flow (0,1) for that request as shown in Figure 109. When effectiveness is maximized, a single continuous data flow is required starting at the command source node and ending at the capability sink node for that request through the optimum supporting

VC. This data flow will pass through the VC (flow = 1) that has the highest measure of performance for the requested capability. A minor penalty is assigned to each active arc and node in the flow path to insure that the data flow takes the most direct path from the source to the sink.

All of the data flows for the capability requests of a single time-step are aggregated together to produce the final data flow for each time-step. This aggregation process looks at each arc across all capability requests for a single time-step and saves the largest value of that individual arc. This process is repeated for each arc. When complete, the arcs and nodes required to be active to provide the requested capabilities are identified.

Figure 113 shows how these active data arcs and nodes are used to control the power and heat generated by a given missions system VC. This VC has two incoming data arcs. It also has an active node variable, d_v , that is equal to the max of the incoming data flows. If one or more of the incoming data flows are active (equal to 1), then d_v is active and equals 1. If d_v equals 0, then the input ELEC power is equal to the VC's cruise power level. If d_v equals 1, then the input ELEC power is equal to that VC's battle power level (i.e., Battle Power = Cruise Power + the difference in Battle and Cruise Power). These two power levels for mission VCs are adapted from Smart, et al.

(2017). The heat generated by the VC flows to the cooling system (EC, glycol or CW), to the compartment air and in some cases to the external air heat sink when the VC radiates outside of the ship, following the same methodology as the PSYS VCs. In case of Figure 113, the VC's cooling system is the GLYCOL plex and the external heat sink is the Ext Air heat sink.

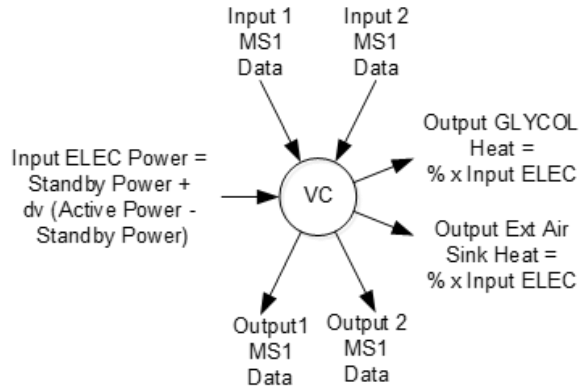


Figure 113. MS1 VC Energy Model

The formulation of the DAFO shares many similarities with the formulation of the AFO (Parsons, et al., 2020a). Many variables are used in both formulations and retain their AFO definitions, notation, and meaning. Some AFO variables' definitions or notation have changed slightly and are redefined below. The DAFO formulation also includes new variables and definitions following the notation conventions established by the AFO formulation where possible. Although the AFO and DAFO formulations use many of the same variables written in the same convention, it should be noted that the DAFO formulation is separate and distinct from the AFO formulation. This two-commodity flow methodology effectively models both the mission VC functionally (data) and energy usage. This methodology is ultimately expressed in the DAFO mathematical formulation:

Maximize:

Objective Function

Penalty Sum

Data Flow Penalties

Energy Flow Penalties

Energy Storage Penalty

Subject to:

Data Directed Arc Constraint

Data Capability Source Node Constraint

Data Capability Sink Node Constraint

Conservation of Data Constraint

Aggregate Data Arc Constraint

Active Data Node Constraint

Binary Data Arc Constraint

Energy Directed Arc Constraint

Energy Source Node Constraint

Energy Sink Node Constraint

Conservation of Energy Node Constraint

Known ELEC Arc Constraint

Mission System ELEC Arc Constraint

Energy In-Arc Constraint

Energy Out-Arc Constraint

Energy Redundant Arc Constraint

$$\text{maximize} \left(\sum_{(r) \in R} (W_o^r W_c^r W_{VC}^r y_{k,l}^r) - \Pi \right) \quad (53)$$

$$\Pi = \Pi_{Data Flow} + \Pi_{Energy Flow} + \Pi_{Energy Storage} \quad (54)$$

$$\Pi_{Data Flow} = \sum_{(k,l) \in V} (\Pi_{k,l} B_{k,l}) + \sum_{(v) \in V} (\Pi_v d_v) \quad (55)$$

$$\Pi_{Energy Flow} = \sum_{(i,j) \in A} (\Pi_{i,j} B_{i,j}) + \sum_{(n) \in N} (\Pi_n d_n) \quad (56)$$

$$\Pi_{Energy Storage} = d_{es} * 0.01 \quad (57)$$

$$y_{k,l} \geq 0 \quad (58)$$

$$1 \geq \sum_{(v,l) \in V} (y_{k,l}^r) \quad (\text{e.g., Command_AAW_CAP}) \quad (59)$$

$$1 \geq \sum_{(k,v) \in V} (y_{k,l}^r) \quad (\text{e.g., Detect_AAW_CAP}) \quad (60)$$

$$\sum_{(k,v) \in Z} (y_{k,l}^r) - \sum_{(v,l) \in Z} (y_{k,l}^r) = 0 \quad (61)$$

$$y_{k,l} = \max_{r \in R} (y_{k,l}^r) \quad (62)$$

$$d_v = \max(y_{k,v}) \quad (63)$$

$$B_{k,l} = \begin{cases} 0, & \text{if } y_{k,l} = 0 \\ 1, & \text{if } y_{k,l} = 1 \end{cases} \quad (64)$$

$$x_{i,j} \geq 0 \quad (65)$$

$$0 \leq \sum_{(n,j) \in A} (x_{i,j}) \quad (\text{e.g., FO_Source}) \quad (66)$$

$$0 \leq \sum_{(i,n) \in A} (x_{i,j}) \quad (\text{e.g., Propulsion_SYS}) \quad (67)$$

$$\sum_{(i,n) \in A} (x_{i,j}) - \sum_{(n,j) \in A} (x_{i,j}) - d_n = 0 \quad (68)$$

$$x_{m,n} = e_n \quad (\text{e.g., CONT VC electric load}) \quad (69)$$

$$x_{m,v} = e_v^S + d_v(e_v^A - e_v^S) \quad (\text{e.g., MS1 VC electric load}) \quad (70)$$

$$x_{i,n} = C_n^{p(i)}(x_{m,n}) \quad (\text{uses VC In-flow coefficients}) \quad (71)$$

$$x_{n,j} = C_n^{p(j)} \sum_{(i,n) \in A} (x_{i,j}) \quad (\text{uses VC Out-flow coefficients}) \quad (72)$$

$$x_{m,n_a} = x_{m,n_a} \quad (73)$$

Energy Primary In-Arc Limit Constraint	$x_{m,n} \leq e_n$	(e.g., CW Cooler capacity)	(74)
Energy Primary Out-Arc Limit Constraint	$x_{n,o} \leq e_n$	(e.g., PGM power capacity)	(75)
AFO Capacity Arc Constraint	$x_{i,j}^{DAFO} \leq x_{i,j}^{AFO}$		(76)
Binary Arc Constraint	$B_{i,j} = \begin{cases} 0, & \text{if } x_{i,j} = 0 \\ 1, & \text{if } x_{i,j} > 0 \end{cases}$		(77)
Active Energy Storage Constraint	$d_{es} = \max(B_{n,o})$		(78)

Where:

- R is the set of capabilities requested.
- r is an indexed scenario within R .
- V is the set of Mission System (MS) nodes.
- v is a specified node within V .
- k and l are indexed nodes within V .
- Z is the set of all explicit MS arcs.
- (k, l) is an indexed arc within Z from node k to node l .
- $y_{k,l}$ is the aggregate data flow through arc (k, l) .
- $y_{k,l}^r$ is the data flow through arc (k, l) in capability request r .
- d_v is the binary value associated with MS node v . It is set to 1 if there is a data flow at node v and it is set to 0 if there is not.
- $\Pi_{l,k}$ is the objective penalty associated with using arc (l, k) . This penalty minimizes the MS explicit arcs used. This value is set to 0.001 and will have a minor effect on the objective function.
- Π_v is the objective penalty associated with using MS node v . This penalty minimizes the MS nodes used. This value is set to 0.001 and will have a minor effect on the objective function.
- $B_{l,k}$ is the value associated with whether the arc (l, k) is used or not.
- B_v is the value associated with whether the MS node v is used or not.
- N is the set of all nodes.
- n is a specified node within N .
- m is the node at the tail of a given 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 .
- A is the set of all other arcs excluding CONT and STEER explicit arcs.
- (i, j) is an indexed arc within A from node i to node j .
- $x_{i,j}$ is the energy flow through arc (i, j) .
- e_v^S is the power demanded by node v in when in cruise mode.
- e_v^A is the power demanded by node v in when in active or mission mode.
- P is the set of PSYS plexes (multiplex).
- $p(n)$ is the plex of node n .
- $C_n^{p(i)}$ is the coefficient of arcs to node n from the nodes in the p plex.
- $C_n^{p(j)}$ is the coefficient of arcs from node n to the nodes in the p plex.
- d_n is the energy flow slack variable for node n .
- $\Pi_{i,j}$ is the objective penalty associated with using arc (i, j) . This penalty minimizes the non-MS explicit arcs used. This value is set to 0.001 and will have a minor effect on the objective function.
- Π_n is the objective penalty associated with violating conservation of energy at node n . This value is set to 1,000,000 and will have a major effect on the objective function.
- $B_{i,j}$ is the value associated with whether the arc (i, j) is used or not.
- d_{es} is the binary variable associated with whether an outgoing arc from the Energy Magazines is active (i.e., one or more of the outgoing arcs from the Energy Storage nodes has a $B_{i,j} = 1$).

DAFO Examples and Results

SBIM Execution Process at t = 3 seconds

This section describes the t = 3 seconds capability request of the OPSIT provided by Berrow, et al. (2021). This capability request is also used in the following subsections to describe how the aggregate data flow is formed for the mission systems at a given time step.

Prior to the t = 3 seconds capability request in this OPSIT, the blue ship has successfully detected and tracked two red anti-ship missiles (ASM)s approaching the blue ship. The following process

steps describe the execution of at the $t = 3$ seconds time-step.

1. The WM determines that an event occurs: the red ASMs move to the following locations:
 - Red ASM 1's range is 18.1 kilometers away from the Blue Ship.
 - Red ASM 2's range is 18.1 kilometers away from the Blue Ship.
2. The WM determines the red ASMs are located within the blue ship's Area of responsibility (AoR).
3. The OM determines which tasks the blue ship should perform to respond to each object. Since both ASMs have been detected and tracking has begun, the next step is (continue to) track and (now) identify:
 - Red ASM 1: Track & Identify
 - Red ASM 2: Track & Identify
4. The OM prioritizes each object based on a combination of time to impact with the blue ship and potential damage to the blue ship. The prioritization of all objects sums to 100%:
 - Red ASM 1 = 50%
 - Red ASM 2 = 50%
5. The OM prioritizes each task to respond to each object. The prioritization of requested capabilities sums to 100% for each object:
 - Red ASM 1 Track = 60%
 - Red ASM 1 Identify = 40%
 - Red ASM 2 Track = 60%
 - Red ASM 2 Identify = 40%
6. The OM queries the CM to determine if the blue ship has the capability to perform the requested tasks.
7. The CM determines which blue ship VCs can perform the requested tasks given sufficient resources/information and prioritizes these VCs based on their MOPs. X-Band Radar 2 receives a minor prioritization over X-Band Radar 1 since it was used to track the objects in the previous time-step. The prioritization of the requested VCs sums to 100% for each capability and for each object:
 - Red ASM 1 Track:
 - S-Band Radar 1 = 12.45%
 - X-Band Radar 1 = 37.73%
 - S-Band Radar 2 = 12.45%
 - X-Band Radar 2 = 37.36%
 - Red ASM 1 Identify:
 - SEW Antenna 1 = 33.33%
 - SEW Antenna 2 = 33.33%
 - IFF Antenna = 33.33%
8. The CM queries the DAFO to determine if the Blue Ship can provide sufficient resources/information to the prioritized VCs to provide the prioritized capabilities.
9. The DAFO maximizes the effectiveness of the provided capabilities by aligning the total ship system to allocate energy and information to the prioritized VCs, per requested capability, per object, subject to: capacity constraints, power doctrine and damage constraints.
10. The DAFO responds to the CM's request by providing a list of VCs that are selected to provide each requested capability. In this example:
 - Red ASM 1 Track w/X-Band Radar 1
 - Red ASM 1 Identify w/IFF Antenna
 - Red ASM 2 Track w/X-Band Radar 1
 - Red ASM 2 Identify w/IFF Antenna
11. These VCs are assumed to be in battle mode. Intact combat system VCs not in the path to through these VCs are assumed to be in cruise mode.
12. The CM records any multi-time-step characteristics about the selected VCs and responds to the OM's request by providing a list of capabilities that are being provided.
 - Blue Ship can track Red ASM 1 with X-Band Radar 2.
 - Blue Ship can identify Red ASM 1 with SEW Antenna 2.
 - Blue Ship can track Red ASM 2 with X-Band Radar 2.
 - Blue Ship can identify Red ASM 2 with SEW Antenna 2.
13. The OM resolves the tasks:
 - Red ASM 1 is tracked and identified by the blue ship.

- Red ASM 2 is tracked and identified by the blue ship.

14. The WM advances to the next time-step.

- $t = t + \Delta t$

Table 15 summarizes these four requests and their corresponding responses. Table 15 also provides the blue ship's mission effectiveness in this OPSIT at $t = 3$ seconds. This mission

effectiveness is not the overall measure of effectiveness (OMOE). It applies only to the single time step and changes based on the requests and response for each time-step. This value typically varies between 0.20 and 0.50 (before penalties are applied) at each time-step for an undamaged blue ship responding to all requested capabilities.

TIME		OBJECT			CAPABILITY			VITAL COMPONENT			REQUEST				RESPONSE	
t	[s]	ID	Type	Weight	Node Name	Node	Weight	Node Name	Node	Weight	From Node	To Node	Arc	Weight	Provided	Weight
		[#]		[-]		[#]	[-]		[#]	[-]	[#]	[#]	[#]	[-]	[0 or 1]	[-]
3		1	Red ASM	0.50	Track_AAW_CAP	2066	0.60	RadarS1_SYS	2026	0.1245	2026	2066	658	0.0374	0	0.0000
3		1	Red ASM	0.50	Track_AAW_CAP	2066	0.60	RadarX1_AAW_SYS	2027	0.3736	2027	2066	665	0.1121	1	0.1121
3		1	Red ASM	0.50	Track_AAW_CAP	2066	0.60	RadarS2_SYS	2028	0.1245	2028	2066	666	0.0374	0	0.0000
3		1	Red ASM	0.50	Track_AAW_CAP	2066	0.60	RadarX2_AAW_SYS	2029	0.3773	2029	2066	667	0.1132	0	0.0000
3		1	Red ASM	0.50	Identify_AAW_CAP	2067	0.40	SEW_Antenna1_AAW_SYS	2044	0.3333	2044	2067	676	0.0667	0	0.0000
3		1	Red ASM	0.50	Identify_AAW_CAP	2067	0.40	SEW_Antenna2_AAW_SYS	2045	0.3333	2045	2067	671	0.0667	1	0.0667
3		1	Red ASM	0.50	Identify_AAW_CAP	2067	0.40	IFF_Antenna_AAW_SYS	2057	0.3333	2057	2067	672	0.0667	0	0.0000
3		2	Red ASM	0.50	Track_AAW_CAP	2066	0.60	RadarS1_SYS	2026	0.1245	2026	2066	658	0.0374	0	0.0000
3		2	Red ASM	0.50	Track_AAW_CAP	2066	0.60	RadarX1_AAW_SYS	2027	0.3736	2027	2066	665	0.1121	1	0.1121
3		2	Red ASM	0.50	Track_AAW_CAP	2066	0.60	RadarS2_SYS	2028	0.1245	2028	2066	666	0.0374	0	0.0000
3		2	Red ASM	0.50	Track_AAW_CAP	2066	0.60	RadarX2_AAW_SYS	2029	0.3773	2029	2066	667	0.1132	0	0.0000
3		2	Red ASM	0.50	Identify_AAW_CAP	2067	0.40	SEW_Antenna1_AAW_SYS	2044	0.3333	2044	2067	676	0.0667	0	0.0000
3		2	Red ASM	0.50	Identify_AAW_CAP	2067	0.40	SEW_Antenna2_AAW_SYS	2045	0.3333	2045	2067	671	0.0667	1	0.0667
3		2	Red ASM	0.50	Identify_AAW_CAP	2067	0.40	IFF_Antenna_AAW_SYS	2057	0.3333	2057	2067	672	0.0667	0	0.0000
3		Mission Effectiveness (before penalties are applied)														0.3575

Table 15. OPSIT SBIM Request and Response at $t = 3$ seconds

DAFO Result Comparison to System with Power Generation Offline

The following four subsections describe the blue ship responding to the same OPSIT while operating in two different conditions, Conditions A and B. The blue ship is the same ship described by Parsons et al. (2021) presented in the previous section. In Condition A, the blue ship is operating normally and responds to the OPSIT while transiting at a sustained speed of 29.2 knots as in the previous section. In Condition B, the blue ship has PGM 1 in ELEC Zone 2 and Secondary Power Generation Module 1 (SPGM 1) in ELEC Zone 1 offline. The next two subsections describe the blue ship in Condition A at $t = 3$ and 4 seconds. The last two subsections describe the blue ship in Condition B at $t = 3$ and 4 seconds.

Condition A at $t = 3$ Seconds

During the $t = 3$ seconds time step, the CM sends the VC request to the DAFO. While the blue ship operates in Condition A, the DAFO selects the X-Band Radar 2 VC to provide the tracking capability for both ASMs as described in the previous section. The DAFO also selects the IFF Antenna to provide the identify capability for both ASMs. Figure 114 and Figure 115 show the data flow paths through the mission system components to provide these capabilities. The magnitudes of these data flows (the red arcs) in these figures are 1. The black arcs have a data flow value of 0.

These capability path selections are combined into a single aggregate AAW system response shown in Figure 116. The arcs and paths in the aggregate time-step system response include all of the arcs and paths in the individual time-step capability responses. If an arc's data flow value is 0 in all time-step capability requests, then it will have a value of 0 in the aggregate system response. If an arc's data flow value is 1 in one or more capability responses, then it will have a value of 1 in the aggregate.

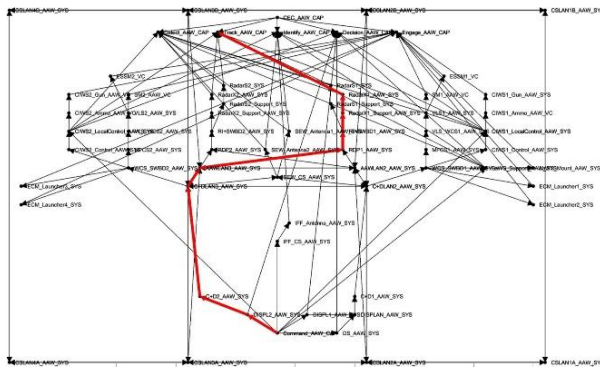


Figure 114. Condition A, AAW Plex, $t = 3$ seconds – ASM1 and 2 Track-Capability Response (adapted from Friedman, 2006, p 105 and Chalfant et. al, 2017)

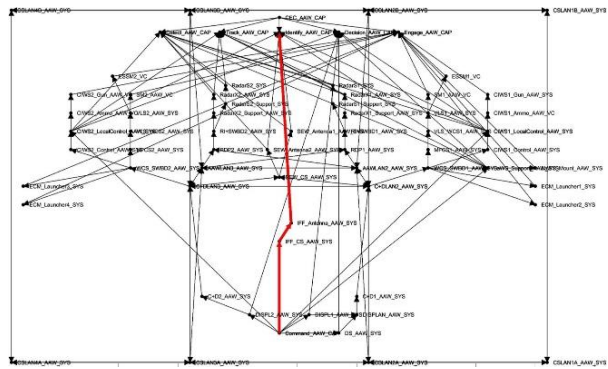


Figure 115. Condition A, AAW Plex, $t = 3$ seconds – ASM 1 and 2 Identify-Capability Response (adapted from Friedman, 2006, p 105 and Chalfant et. al, 2017)

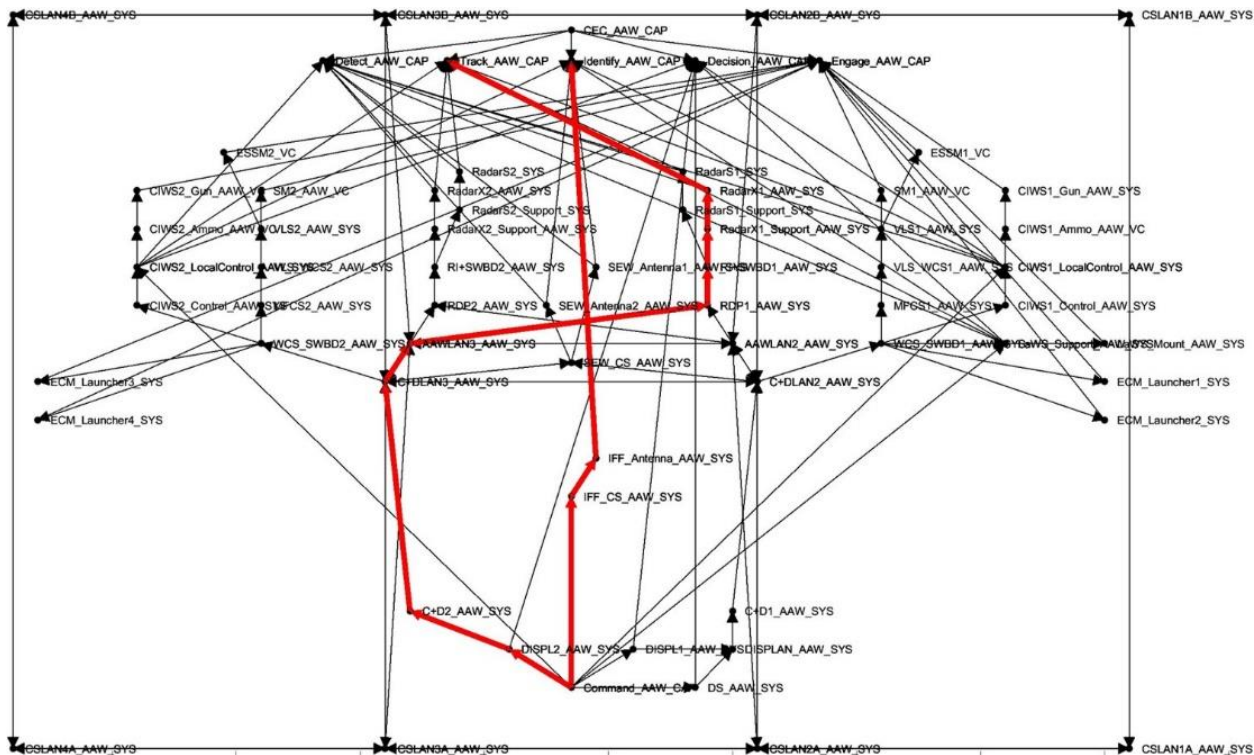


Figure 116. Condition A, AAW Plex, $t = 3$ seconds, Aggregate System Response (adapted from Friedman, 2006, p 105 and Chalfant et. al, 2017)

Any nodes in the AAW plex's aggregate system response with an active data flow are active and draw their battle electrical power level. Any nodes without an active data flow are on standby and draw their cruise electrical power level. All of these VCs also generate heat proportional to their electrical power level. These power and heat loads are supplied and removed by the energy-based plexes connected to the mission

system plexes (e.g., ELEC, GLYCOL, EC, CW, and HVAC).

The individual capability responses, the aggregate, and energy-based plexes' system responses are all determined in a single linear optimization. If, for any reason, sufficient power or cooling cannot be provided to a VC, then conservation of energy cannot be maintained at that VC. The objective function includes a significant penalty if conservation of energy is

broken at a VC. This prevents the optimization from selecting VCs to provide a capability that cannot also be provided sufficient power and cooling.

The logical architecture of the ELEC plexes in this paper is based on the MVDC reference power system architecture developed by Doerry and Amy (2016). Figure 117 shows power generated by PGM 1, PGM 2, SPGM 1, and SPGM 2. This power is distributed to the four Zone#_ELEC_SYS nodes and the four Zone#_nonAFO_ELEC_SYS nodes. The four Zone#_ELEC_SYS nodes supply power to the VCs in the PSYS and mission system plexes. The magnitude of the power delivered to these nodes is partially determined by the electrical power loads demanded by the aggregate mission system response (e.g., Figure 116). The electrical loads demanded by the four Zone#_nonAFO_ELEC_SYS nodes are the blue ship's non-vital electrical loads.

Figure 117 also shows power is sent to Propulsion Motor Modules (PMMs) 1 and 2 in

ELEC zones 3 and 4 respectively. Electrical power is converted to mechanical power at these nodes and sent to the PMM 1 and PMM 2 nodes in the MECH plex (Figure 117). Figure 118 shows this power evenly split between the port and starboard propulsion shafts. The final VC on these shafts are Propeller 1 VC and Propeller 2 VC. These VCs send propulsion power to the Propulsion_SYS sink node of the MECH plex. This node represents the energy absorbed by the ocean as the blue ship propels itself. In the current multiplex logical architecture, the Propulsion_SYS node is the only capability node that exists outside of a mission system plex. The blue ship is able to provide these required mission system power loads, propulsion load, and supporting VC loads without using power provided by the energy magazines (see the inactive energy storage sub-plex in upper left of Figure 117). If these arcs are active the objective function receives a small penalty insuring the energy magazines are only used when the power system is otherwise unable to meet the demanded power load.

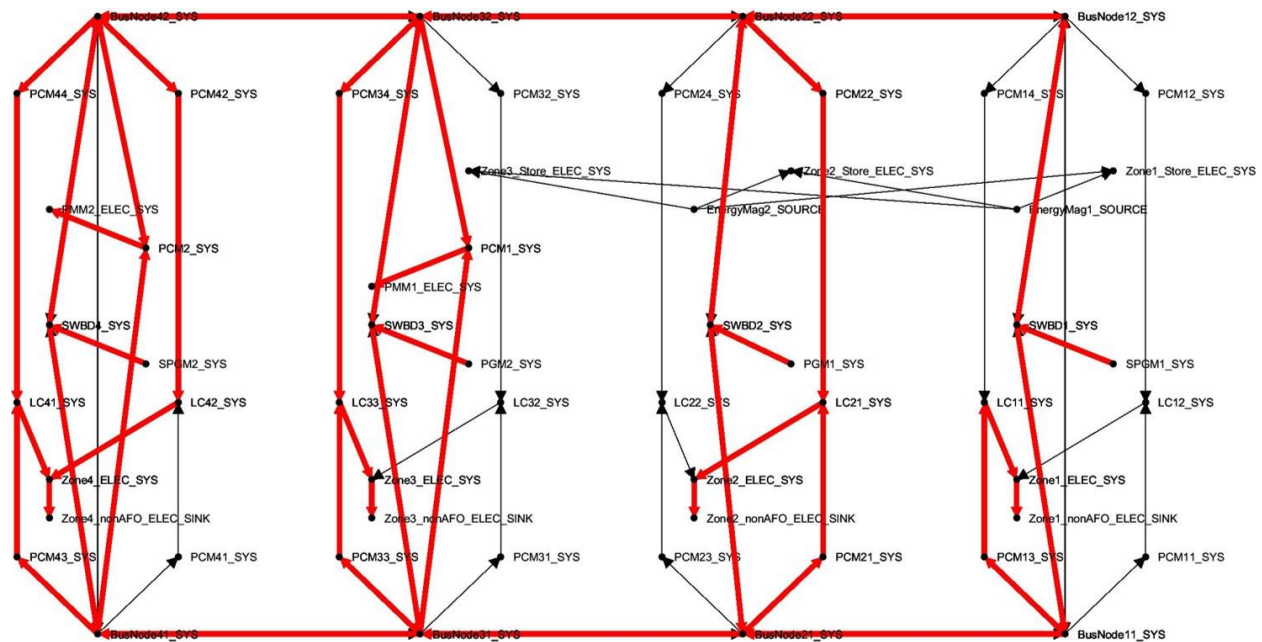


Figure 117. Condition A, ELEC Plex, t = 3 seconds, System Response

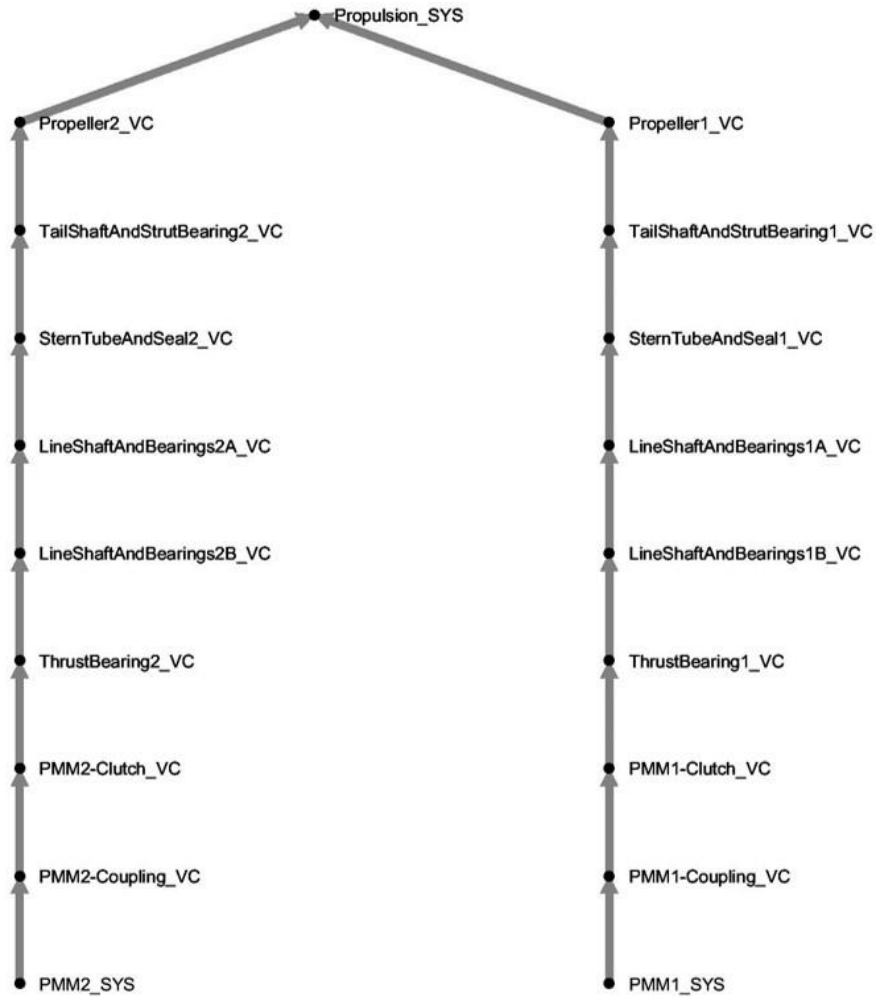


Figure 118. Condition A, MECH, t = 3 seconds, System Response

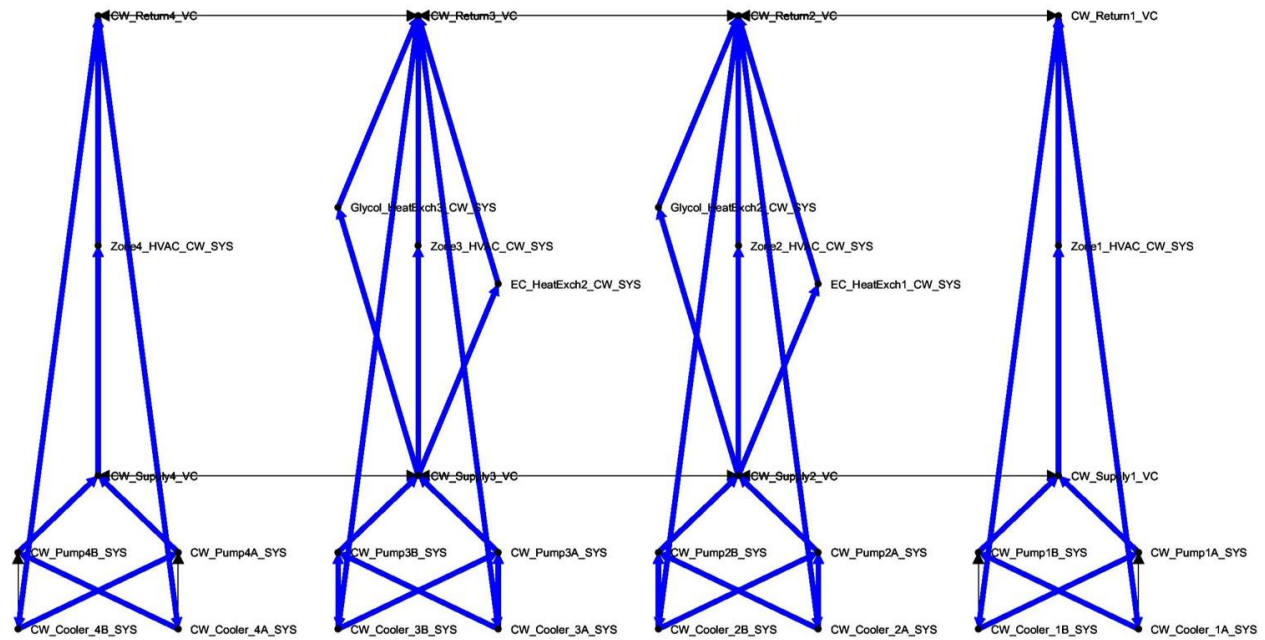


Figure 119. Condition A, CW Plex, t = 3 seconds, System Response

At the conclusion of the $t = 3$ seconds time step, the OM resolves the events that occur. During the time step, the OM requested track and identify capabilities in response to movement of

Condition A at t = 4 Seconds

In Condition A, the DAFO selects the X-Band Radar 1 VC to satisfy both tracking capability requests and selects the Display 2 VC to satisfy both decision capability requests. Figure 120 shows the aggregate system response of the AAW plex at t = 4 seconds.



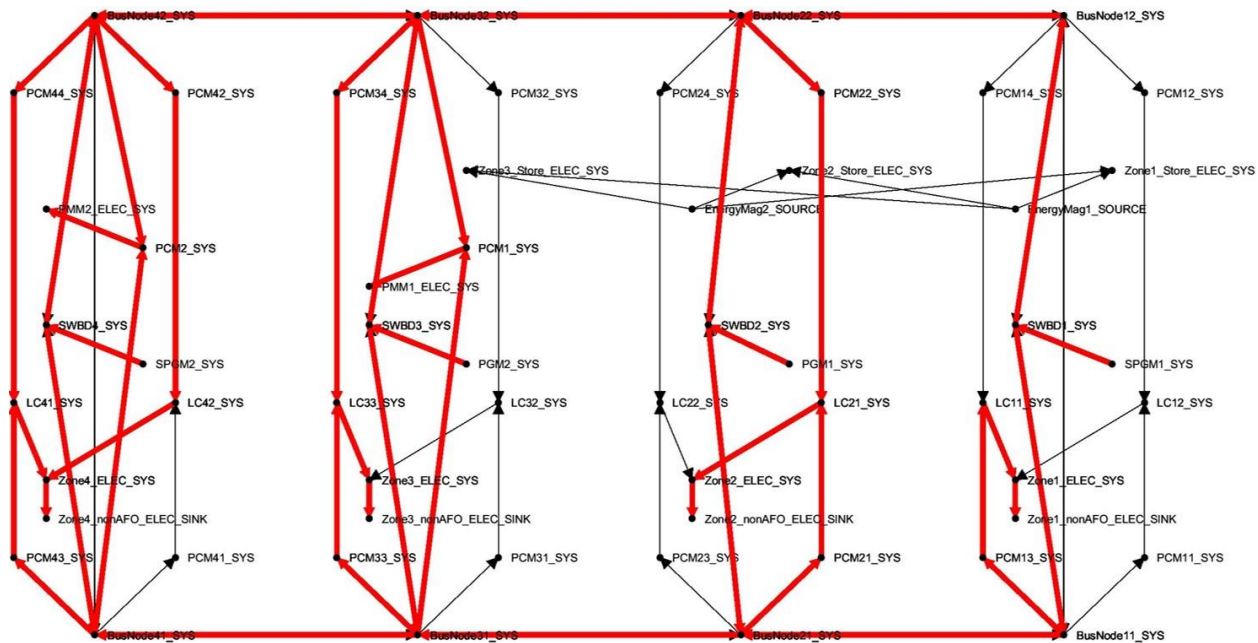


Figure 121. Condition A, ELEC Plex, $t = 4$ seconds, System Response

Again, any nodes in the AAW plex's aggregate system response with an active data flow draw battle level electric loads and nodes without an active data flow draw cruise electric power loads. Heat is generated by the mission systems VC proportional to these power loads. Figure 120 shows the data flow supporting the IFF Antenna as inactive in the $t = 4$ seconds time step. This is because the identify capability is not requested in the $t = 4$ seconds time step and this data flow path is deactivated. However, the decide capability is requested in the $t = 4$ seconds time step and Figure 120 shows outgoing arc from the Display 2 VC to the decision capability node as active.

As with the $t = 3$ seconds time step, the electrical and heat loads are applied to the energy-based plexes as constraints. A portion of the electrical power demanded at the Zone#ELEC_SYS nodes in the ELEC plex supports these mission systems.

Figure 121 shows an ELEC plex response nearly identical to Figure 117. A few energy flow magnitudes change in response to the new mission system loads, but the overall system alignment remains unchanged. The PGMs and SPGMs are still active. The energy magazines are still inactive. The sustained speed propulsion load is satisfied. The paths of the energy flows through

the switchboards, bus nodes, power conversion modules, and load centers is unchanged.

The DAFO determines the system responses of the energy-based plexes at each time step independent of system responses at other time steps. A comparison of the CW plex's system responses between the two time steps demonstrates this. For $t = 3$ seconds, shows all eight CW Coolers active and no cross zonal chilled water flow. For $t = 4$ seconds, Figure 122 shows only six CW Coolers active and shows chilled water crossing between CW zones 3 and 4. The GLYCOL and EC heat exchangers in CW zone 2 are no longer active. The GLYCOL and EC plexes are diverting all of their energy flows to the CW zone 3 GLYCOL and EC heat exchangers. Similarly, the HVAC diverts heat flow away from CW zone 1. These two different system responses are only 1 second apart. The CW plex and supporting plexes cannot be realigned this quickly. Even if heat is suddenly diverted away from CW Zone 1 at $t = 4$ seconds, residual heat from the $t = 3$ seconds system response would still be present in CW zone 1 at $t = 4$ seconds. This heat would have to be removed from the system before the commodity flow could stop in CW zone 1. A solution for this problem will be discussed in the Conclusions and Future Work section.

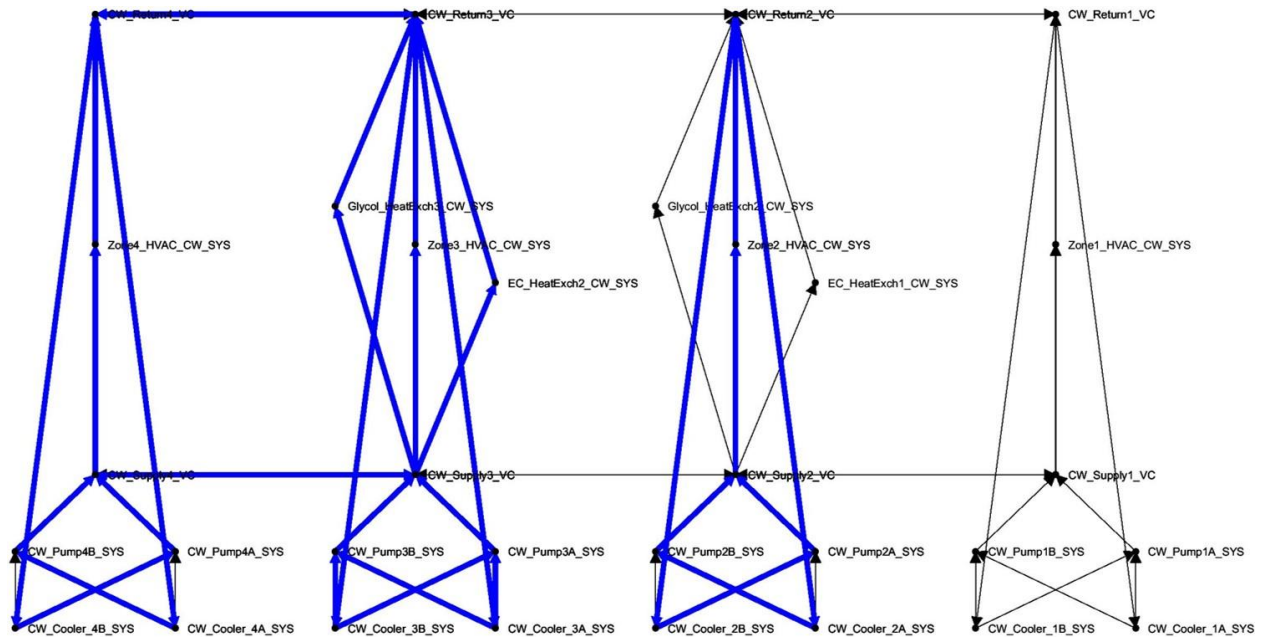


Figure 122. Condition A, CW Plex, t = 4 seconds, System Response

At the conclusion of the $t = 4$ seconds time step the OM resolves the events that occur. During the time step, the OM requested track and decide capabilities in response to movement of two red ASMs within its AoR. The DAFO determined a system alignment to maximize the mission effectiveness by providing the requested capabilities with the prioritized VCs. The OM then records the two red ASMs as tracked and identified at $t = 4$ seconds in the event log. The WM then advances the OPSIT to the next time step, $t = 5$ seconds.

Condition B at $t = 3$ Seconds

This and the following subsection describe the blue ship responding to the same OPSIT in Condition B with PGM 1 and SPGM 1 offline. This section compares the system responses of Condition B with those of Condition A at the $t = 3$ seconds time step.

The Condition B, AAW plex, $t = 3$ seconds aggregate system response is identical to the Condition A response, Figure 117. At the $t = 4$ seconds time step, the blue ship tracks both red ASMs with X-Band Radar 1 and identifies both ASMs with the IFF Antenna.

In Condition B, SPGM 1 and PGM 1 in ELEC zones 1 and 2 are offline and do not generate

power. Figure 123 shows PGM 2 and SPGM 2 in ELEC zones 3 and 4 respectively generating power with supplemental power provided by Energy Magazine 2. The mission system power, propulsion power, and supporting VC power required by the blue ship at the $t = 3$ seconds is more than PGM 2 and SPGM 2 can provide. Therefore, the DAFO uses power from the energy magazine and reduces the ship's speed to 24.5 knots. The mission system event resolution in Condition B is identical to Condition A at the $t = 3$ second time step; both red ASMs are tracked and identified.

Condition B at $t = 4$ Seconds

As in Condition A at $t = 4$ seconds, the OM submits track and decide capability requests for each red ASM, totaling four capabilities requested. The CM again identifies a list of VCs that could provide these capabilities given sufficient energy and data. The CM sends the expanded request to the DAFO.

The Condition B AAW system response at $t = 4$ seconds is identical to the Condition A response, Figure 120. The DAFO selects the X-Band Radar 1 VC to respond to both tracking capability requests and selects the Display 2 VC to respond to both decision capability requests.

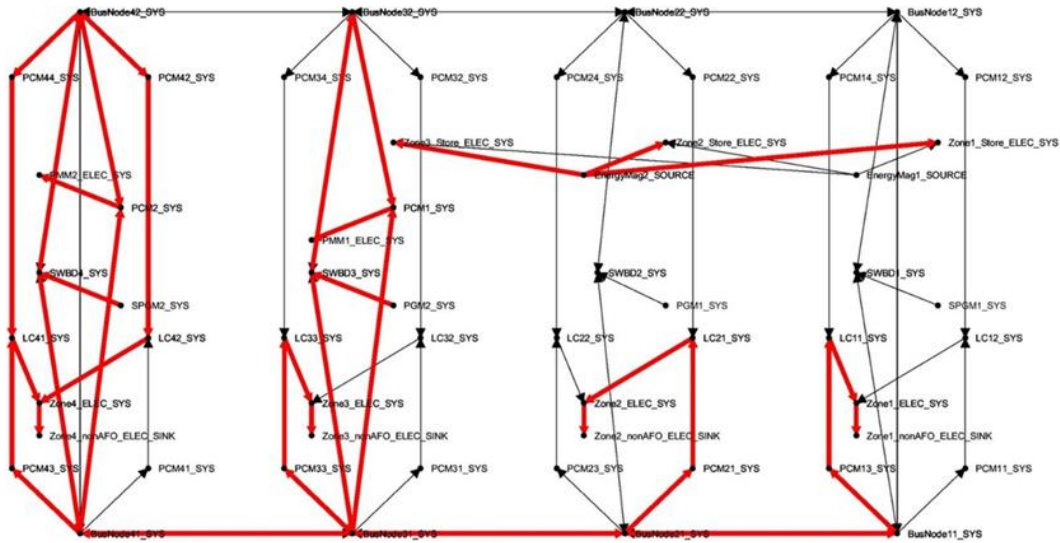


Figure 123. Condition B, ELEC Plex, $t = 3$ seconds, System Response

The $t = 4$ ELEC system response, Figure 124, shows some similarity to the ELEC system response at the $t = 3$ seconds time step, Figure 123. The power required by the mission, propulsion and VC loads is still more than PGM 2 and SPGM 2 can provide. Therefore, the optimization pays the objective penalty to use supplemental power from the Energy Magazines and reduces the ship speed.

Comparing the alignments of Figure 124 and Figure 123 again shows the result of DAFO determining system responses independent of system responses at prior time steps. At $t = 3$ seconds, Figure 123 shows power is distributed to ELEC zone 1 via power conversion module 13 (PCM13) and load center 11 (LC11). In addition,

power is moved forward and aft using only the starboard bus. However, Figure 124 shows power is distributed to ELEC zone 1 via PCM 11 and LC 12. Furthermore, power between ELEC zone 3 and 4 is distributed via the port bus and the starboard bus between these zones is now inactive. Figure 124 is a valid solution using the current DAFO model, but it also demonstrates why future work should consider system stability and avoid potentially unnecessary, rapid system realignments or rapid load cycling. The event resolution of Condition B is identical to Condition A at the $t = 4$ second time step; both red ASMs are tracked and a decision is made to engage.

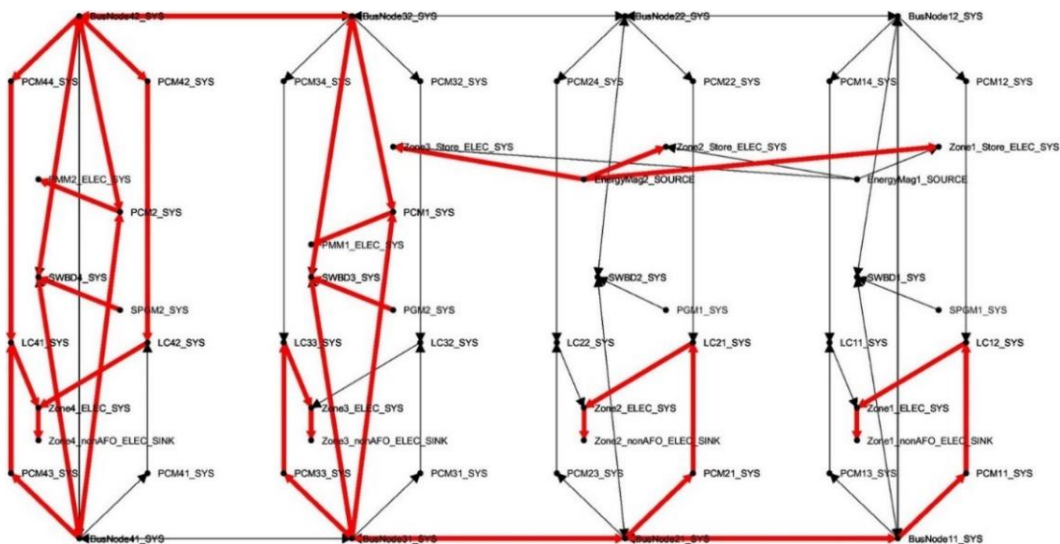


Figure 124. Condition B, ELEC Plex, $t = 4$ seconds, System Response

Conclusions and Future Work

The Dynamic Architecture Flow Optimization (DAFO) described in this paper serves as the final link in the chain connecting the Warfighting Model, Operational Model, and Capabilities Model with the ship's Mission, Power, and Energy Systems (MPES). The capability and operational models that support the capability nodes provide essential mission and vital component priorities to guide the alignment of system vital components over time using the DAFO. This enables the Ship Behavior and Interaction Models (SBIMs) to simulate an operation situation (OPSIT) and determine a ship's mission effectiveness during Concept & Requirements Exploration (C&RE).

The ultimate objective of coupling ship system architecture and function to the operational architecture is that it enables time-stepping operational scenarios to be implemented that are fully coupled to ship system design, function, damage and even alignment for optimum mission performance. The most important take-away from this paper is the concept of using capability nodes to pull functions from the ship energy-based and data-based systems thus enabling the whole framework.

These methods are fully scalable to force-level operational situations with separate system models for all operational units using parallel computing. Pseudo-intelligence is provided by an agent-based approach in the warfighting model and by a

doctrine-based network energy and data flow optimization in the ship systems. These algorithms are efficient and effective. This approach is also adaptable for machine learning and developing control algorithms.

The most critical future work for the DAFO model is the development of time-based system response considerations. These include:

- Generator Ramp Rates
- Energy Storage Charging/Discharging
- Thermal Inertia
- System Stability (not rapidly rerouting power unnecessarily at each time-step)
- Incorporating blue ship damage in the OPSIT

Another area for future work is to modify this methodology allowing the DAFO to select more than one vital component (VC) to respond to each capability request. For example, tracking an object with a single VC is sufficient but, tracking that same object with two or more VCs may provide a higher level of confidence in the track.

Acknowledgments

The authors would like to thank Ms. Kelly Cooper, ONR Code 331, for supporting this work under contract N00014-15-1-2476. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the Office of Naval Research.

Author Biographies

Mark A. Parsons is currently a Ph.D. Candidate and Graduate Research Assistant of the Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech. He researches network-based methods to assess surface ship distributed system vulnerability, survivability, and deactivation recoverability in concept stage design. He received his M.S. in Ocean Engineering from Virginia Tech in 2019 and his B.S. in Naval Architecture and Marine Engineering from the University of New Orleans in 2016. He is a student member of ASNE and SNAME.

Mustafa Y. Kara is currently a Ph.D. Candidate and Graduate Research Assistant of the Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech. He researches

network-based methods to assess surface ship distributed system vulnerability, survivability, and deactivation recoverability in concept stage design. He received his B.S. in Naval Architecture and Marine Engineering from the Turkish Naval Academy in 2006. He received his S.M. in Naval Architecture and Marine Engineering from MIT in 2010. He is a student member of ASME and SNAME and alumni of MIT (Educational Counselor).

Alan Shane was an Ocean Engineering Master's Degree Candidate at the Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech. He is interested in developing ship concept development and assessment tools that supports a path towards MBSE and DE in those processes. He received his

M.S. and B.S. in Ocean Engineering from Virginia Tech in 2020 and 2010 respectively. He is a student member of ASNE and SNAME.

David J. Berrow is currently a M.S. Ocean Engineering Student of the Kevin T. Crofton Department of Aerospace and Ocean Engineering, Virginia Tech. He is employed with the Department of National Defence (Canada). He received his B.S. in Ocean Engineering and Naval Architecture from Memorial University of Newfoundland in 2011.

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 2015 recipient of the SNAME Webb Medal for Outstanding Contributions to NA&ME Education. 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 Systems Engineering from MIT in 1986.

References

- Appleget, J., Burks, R., & Cameron, F. (2020). *The Craft of Wargaming*. Naval Institute Press.
- Ashish, G. (2008a). Chapter 3 Linear Programs. <http://web.stanford.edu/~ashishg/msandde111/notes/chapter>
- Ashish, G. (2008b). Chapter 5 Network Flows. <http://web.stanford.edu/~ashishg/msandde111/notes/chapter>
- Brefort, Dorian, Shields, Colin, Habben Jansen, Agnieta, Duchateau, Etienne, Pawling, Rachel, Droste, Koen, Jasper, Ted, Sypniewski, Michael, Goodrum, Conner, Parsons, Mark A., Kara, Mustafa, Roth, Mark, Singer, David J., Andrews, David, Hopman, Hans, Brown Alan J., Kana, Austin (2018). An architectural framework for distributed naval ship systems. *Ocean Engineering*, 147, 375–385
- Berrow, D. J., Parsons, M. A., Shane, A., Kara, M. Y., & Brown, A. J. (2021). Capability Modeling for Assessing Mission Effectiveness in Surface Ship Concept and Requirements Exploration. To be submitted to Combat Systems Symposium 2021.
- Brown, Alan J. (2020). Ship and Marine Engineering System Concept Design. In Michael G. Parsons (Ed.), *Marine Engineering* (4th ed.). Alexandria, VA: SNAME
- Brown, Alan, Salcedo, Juan. (2003). Multiple-Objective Genetic Optimization in Naval Ship Design, *Naval Engineers Journal*, 115(4), 49-61
- Brown, Alan J., Thomas, M. (1998). Reengineering the Naval Ship Concept Design Process" in *From Research to Reality in Ship Systems Engineering Symposium*, ASNE
- Brown, Alan J., Sajdak, John. (2015). Still Re-Engineering the Naval Ship Concept Process. *Naval Engineers Journal*, 127(1), 49-61
- Chalfant, Julie. (2015). Early-Stage Design for Electric Ship. Proceedings of the IEEE, 103(12), 2252–2266. <https://doi.org/10.1109/JPROC.2015.2459672>
- Chalfant, Julie, Chrysostomidis, Chrys, Snyder, Daniel, Parsons, Mark A., Brown, Alan (2017). Graph Theory Applications in FOCUS-Compliant Ship Designs, in *Electric Ship Technologies Symposium 2017*, Alexandria, VA: IEEE
- Cramer, A. M., Chen, H., & Zivi, E. L. (2013). Shipboard electrical system modeling for early-stage design space exploration. 2013 IEEE Electric Ship Technologies Symposium, ESTS 2013, 128–134. <https://doi.org/10.1109/ESTS.2013.6523723>
- Chinneck, J. (2020). Practical optimization: a gentle introduction. Practical Optimization: A Gentle Introduction. <https://www.optimization101.org/>
- de Vos, P., Stapersma, D., Duchateau, E. A. E., & van Oers, B. (2018). Design Space Exploration for on-board Energy Distribution Systems - A New Case Study. Proc. of 17th Conference on Computer and IT Applications in the Maritime Industries (COMPIT).
- Department of Defense. (2020). DOD Dictionary of Military and Associated Terms. Washington, D.C., USA.
- Doerry, N., & Amy, J. V. (2016). Design considerations for a reference MVDC Power System. Transactions - Society of Naval Architects and Marine Engineers, 124.

- Friedman, N. (2006). *Naval Institute Guide to World Naval Weapon Systems* (Fifth Ed.). Naval Institute Press.
- Goodfriend, David, Brown, Alan J. (2018). Exploration of System Vulnerability in Naval Ship Concept Design, *Journal of Ship Production and Design*, 34(1), 42-58.
- IBM (2014), *IBM ILOG CPLEX Optimization Studio CPLEX User's Manual Version 12 Release 6*. USA: International Business machines Corp.
- Habben Jansen, A.C., Duchateau E.A.E., Kana, A.A., Hopman, J.J. (2019). Assessing complex failure scenarios of on-board distributed systems using a Markov chain. *Journal of Marine Engineering and Technology*, <https://doi.org/10.1080/20464177.2019.1673032>
- Hughes, W., & Girrier, R. P. (2018). *Fleet Tactics and Naval Operations* (Third Ed.). Naval Institute Press.
- Kerns, C., Brown, A. J., & Woodward, D. (2011a). Application of a DoDAF Total-Ship System Architecture in Building Naval Ship Operational Effectiveness Models. MAST Americas, 2011.
- Kerns, C., Brown, A. J., & Woodward, D. (2011b). Application of a DoDAF Total-Ship System Architecture in Building a Design Reference Mission for Assessing Naval Ship Operational Effectiveness. *Naval Engineers Journal*.
- Konak, A., & Smith, A. E. (2018). Network Reliability Optimization. In *Handbook of Optimization in Telecommunications* (pp. 735–760). by M. G. C. Pardalos and P. Resende.
- Parsons, M. A., Kara, M. Y., & Brown, A. J. (2020a). Refinement of a Mission, Power, and Energy System Architecture Flow Optimization Method and Tool for Surface Ship Concept Design. *Advance Machinery Technology Symposium 2020*.
- Parsons, M. A., Kara, M. Y., Robinson, K. M., Stinson, N. T., & Brown, A. J. (2021). Early-Stage Naval Ship Distributed System Design Using Architecture Flow Optimization. *Journal of Ship Production and Design*, 37(02), 78–96. <https://doi.org/10.5957/JSPD.10190058>
- Parsons, M. A., Robinson, K. M., Kara, M. Y., Stinson, N. T., Snyder, D., Woodward, D., & Brown, A. J. (2020b). Application of a Distributed System Architectural Framework to Naval Ship Concept and Requirements Exploration (C&RE). *Naval Engineers Journal*, 132(4), 105–124. <https://www.ingentaconnect.com/contentone/a/sne/nej/2020/00000132/00000004/art00031%0A>
- Payne, C. M. (2010). *Principles of Naval Weapon Systems* (Second Ed.). Naval Institute Press. <https://books.google.com/books?id=MUUmQwAACAAJ>
- Purdy, E. M. (2004). “Test and Evaluation WIPT.” *Proceedings of the 20th Annual Test & Evaluation Conference & Exhibition*. Reno, NV, USA.
- Robinson, Kevin M. (2018). *Modeling Distributed Naval Ship Systems using Architecture Flow Optimization* (thesis), Virginia Polytechnic Institute and State University, Blacksburg, VA
- Shane, A., Parsons, M. A., Berrow, D. J., Kara, M. Y., & Brown, A. J. (2021). Operational Architecture and Framework for Assessing Mission Effectiveness in Surface Ship Concept and Requirements Exploration. *Intelligent Ships Symposium 2021*.
- Smart, R., Chalfant, J., Herbst, J., Langland, B., Card, A., Leonard, R., & Gattozzi, A. (2017). Using S3D to Analyze Ship System Alternatives for a 100 MW 10,000 ton Surface Combatant. *ESRDC Library*. www.esrdc.com/library
- Stevens, John D., Opila, Daniel F., Cramer, Aaron M., Zivi, Edwin L. (2017a). Operational Vignette-based Electric Warship Load Demand, in *Electric Ship Technologies Symposium 2017*, Arlington, VA: IEEE
- Stevens, John D., Opila, Daniel F., Oh, Eun S., Zivi, Edwin L. (2017b). All-Electric Warship Load Demand Model for Power and Energy System Analysis Using Exogenously Initiated Threats, in *Electric Ship Technologies Symposium 2017*, Arlington, VA: IEEE
- Sinsely, Gregory L., Opila, Daniel F., Stevens, John (2019). Dynamically Coupled Process Control and Power Management for Shipboard Power and Energy System Applications, in *Electric Ship Technologies Symposium 2019*, Arlington, VA: IEEE

- Stepanchick, Justin, Brown, Alan. (2007). Revisiting DDGX/DDG-51 Concept Exploration. *Naval Engineers Journal*, 119(3), 67-88
- Stinson, Nicholas T., and Brown, Alan J. (2019). Ship Distributed System Design and Synthesis Using Architecture Framework, in *SNAME Maritime Convention 2019*, Tacoma, WA: SNAME
- Strock, Justin, Brown, Alan. (2008). Methods for Naval Ship Concept and Propulsion System Technology Exploration in a CGX Case Study. *Naval Engineers Journal*, 120(4), 95-122
- Snyder, Daniel J., Parsons, Mark A., Brown, Alan J., Chalfant, Julie. (2019). Network Architecture Framework Applications with FOCUS-compliant Ship Designs, in *Electric Ship Technologies Symposium 2019*, Alexandria, VA: IEEE
- Trapp, Thomas A. (2015). *Shipboard Integrated Engineering Plant Survivable Network Optimization* (dissertation), Massachusetts Institute of Technology, Cambridge, MA

Eureka!
–Archimedes

Dissertation Conclusions and Future Work

Conclusions

Mission, Power, and Energy Systems (MPESs) are an integral part of an overall ship design and must be considered in early 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.

The proposed architectural framework for distributed naval ship systems is a powerful tool for decomposing, analyzing, understanding, decision-making and re-integrating system of system design problems. It enables fast and simple tools for connectivity optimization, component sizing, system vulnerability and recoverability analysis, and energy storage analysis using an architectural flow optimization and dynamic architectural flow optimization.

Achieved Objectives

Architecture Flow Optimization (AFO) is shown to be a useful tool for energy-based linear optimization of a surface ship MPES considering nominal operating and deactivation conditions. AFO has applications in early-stage ship design, Concept & Requirements Exploration (C&RE), MPES design, system validation, commodity-based Vital Component (VC) sizing, and vulnerability/survivability analysis as hypothesized. After multiple case studies and method refinement, the following simplifying approaches based on the Architecture Framework are proven effective and sufficient:

1. The use of subdivision blocks (SDBs) vice curvilinear geometry to define the physical architecture
2. The assignment of 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 ($t = 0$)

The AFO applied consistently using the proposed architecture framework and simplifying approaches achieves the first two objectives of this dissertation.

The Mission-Means Framework (MMF) provides a foundation to develop a set of integrated Ship Behavior and Interaction Models (SBIMs) for determining ship and ship system behavior in a warfighting environment. These models use ship capabilities and an operational architecture to perform tasks necessary to the ship's mission in specified operational situations (OPSITs). Traditionally, C&RE is performed based on relative effectiveness by comparing ship designs to each other. The MMF method models individual ship designs in operational scenarios ($t = 0+$) to determine their effectiveness and then comparing. The Dynamic Architecture Flow Optimization (DAFO) serves as the final link the in SBIM chain. DAFO uses a two-commodity flow (energy and data) to simulate MPES operation with supporting capability and operational models to provide essential mission and vital component priorities guiding the alignment of the total ship system during the specified OPSITs. The SBIMs use the optimization of mission effectiveness at each timestep in specific OPSITs to specify essential mission, task, and capability requirements to capability sinks in the logical architecture. The DAFO applies specified battle doctrine and load priority to simulate a controlled system to provide these capabilities. The DAFO and SBIMs, used with the proposed architecture framework and simplifying design approaches, achieve the final objective of this dissertation.

AFO and DAFO are simplified concept exploration methods based on the architectural framework that optimize the total ship system for operability and survivability. These methods establish the necessary and sufficient information required to size MPES and assess naval ship mission effectiveness in C&RE. With this information, ship designers and program managers can make decisions during C&RE to ensure the final designs are effective, affordable, and meet the required capabilities. With these methods, designers can now:

- Explicitly size all major distributed system power and energy components including piping and cable early in the design process and consider a much broader range of system options and architectures to be considered that might otherwise be outside of the range of historical data-based parametrics.
 - Enable early preliminary general arrangements as a “physical architecture”.
 - Enable a more specific consideration and application of an “operational architecture” including operability and warfighting weapons effects.
 - Enable early flow-based maintenance, reliability and availability analyses.
 - Enable early vulnerability analyses.
 - Enable early recoverability analyses in a DAFO.
 - Enable the application of multiple constraint sets in an automated manner insuring that all results are feasible.
 - Consider multiple combinations of design variable options and better understand their total ship impact on operability and survivability.
- Near-term
 - Investigate and consider mechanical inertias such as generator ramp rates, thermal inertias and flow inertias.
 - Incorporate time delays for system realignment.
 - Incorporate dynamic energy storage into the DAFO to consider the time-stepped storage and use of energy.
 - Mid-term
 - Implement the AFO and DAFO as integral components in C&RE and use parallel processing and HPC to assess multiple system option combinations and apply in multi-objective optimizations to layer design space regions based on feasibility, cost, effectiveness and risk.
 - Assess energy storage and architecture strategies and options.
 - Investigate and manage simulation of OPSIT stochastic loads over time.
 - Consider system stability, particularly for electric loads, power losses and faults.
 - Increase system fidelity by using functional energy distribution components (e.g. wires, pipes, shafts/mechanical linkages) as VCs in the plexes.
 - Far-term
 - Improve tools for preliminary naval ship arrangements with UNDEX and UNDEX Shock Vulnerability Assessment criteria in addition to AIREX.
 - Consider flooding and fire effects.

Future Work

The AFO and DAFO are quasi-static analyses that do not explicitly consider the dynamic behavior of individual vital components including inertias of various types, time delays for changing alignment and coming up to speed, and limited time-based processes such as energy storage and energy use. Future work in this area of research should include: