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14. ABSTRACT

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. This research has developed a simplified approach using a system network architecture framework to add primary subdivision, primary structure, locate mission-critical components, optimize system architecture and component sizing, and perform vulnerability and recoverability (fight-through) analysis sufficient to make these early design decisions considering survivability.

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Major Goals

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 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 may be particularly true for distributed systems and distributed system architectures including combat, power and energy systems. We have devised a simplified approach using a system network architecture framework and working from our current ship synthesis model with hullform and deckhouse definition to add primary subdivision, primary structure, locate mission-critical components, optimize system architecture and component sizing, and perform vulnerability and recoverability (fight-through) analysis sufficient to make these early design decisions considering survivability. Once implemented, we will be able to collect data for our NICOP and answer several critical questions: 1) Is sufficient model detail and fidelity available during concept exploration to make a reasonable survivability assessment? 2) If sufficient detail is available, does early survivability consideration impact the resulting design decisions? 3) Are simplified, but traditional vulnerability models able to discriminate correctly between alternative designs, answer the right questions, provide important insight and enable good decisions for moving forward into concept development and preliminary design? 4) Are tools and resources available to consider survivability and distributed systems early or do we need a completely new approach and new tools? Our project goals are as follows: 1) Answer to above questions in the context of a Large Surface Combatant (LSC) design. 2) Apply a system architecture framework to be developed in this research in new naval ship system design process, methods and tool development that can be implemented in current US Navy ship design tools (LEAPS/ASSET/RSDE and S3D). 3) Work closely with ONR, NSWCCD and NSWCPD to coordinate our design process and tool development with the needs of the Navy. This research is being performed as part of a NICOP multi-university team utilizing network methods for analyzing distributed ship systems. Network methods offer significant potential for understanding the relationships between various aspects of distributed systems for uninterrupted operations and survivability. As a result, earlier and other ongoing research being accomplished at Virginia Tech has been specifically adapted and redirected to utilize and support the NICOP network-based approach and architecture framework. The specific objectives of this research are: 1) Complete and adapt a simplified ship vulnerability model to explicitly consider distributed system design in a network context; 2) Extend this model to concept exploration compartment and vital component arrangements, architecture definition, component sizing and refinement; 3) Develop and utilize a network-based architecture flow optimization (AFO) to improve system architecture considering vulnerability, reliability and recoverability for fight-through, and to perform preliminary sizing of system components for ship synthesis; 4) Link vulnerability analysis with ship synthesis and effectiveness models; 5) Apply this process in notional destroyer/frigate studies to demonstrate the operational and cost value of considering survivability early in the ship design process; 6) Provide vulnerability data to the other NICOP teams for network analysis. 7) Investigate approach and methods for defining operational architecture and interface through capability nodes with the logical architecture. 8) Investigate dynamic architecture flow optimization (DAFO) methods to assess system response and recoverability in operational situations (OpSits) with weapon hits and damage. 9) Analyze results and answer the four critical questions posed above. 10) Transition process and tools as able to USN ship design tools (LEAPS/ASSET/RSDE and S3D).

Accomplishments Under Goals

In the fifth year of this project we began to develop a framework and plan for a Dynamic Architecture Flow Optimization (DAFO) including the addition of capability nodes and discrete event operational architecture. 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. Products of our quasi-static AFO include a linear programming formulation of the ship combat, power and energy system (CPES), an optimum system architecture and optimum sizing solution based on t=0+ scenarios. We will continue with the same AFO formulation and t=0+ solution to perform a time-based recoverability analyses in a realistic 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. In the current AFO, the operational architecture is limited to scenarios for steady-state steaming conditions (endurance, sustained and battle) and scenarios with single subdivision block damage. Capacity sizing is performed in the logical architecture at its functional utilization intersection with the operational architecture. Since the physical size of components (weight, dimensions, and space requirements) is directly related to capacity, it is also determined at the functional utilization intersection. The aggregate sizing is determined in the AFO and will become an additional constraint set for the DAFO and more realistic time-based operational scenarios specified in a Design Reference Mission (DRM). The DAFO will be performed with a time increment able to capture the dynamics of the mechanical and fluid systems, but would not consider the full electrical system dynamics such as power stability and transient effects. These would be considered in subsequent concept development feasibility studies. The plan for a DAFO and operational architecture which was an important product of Year 5 is as follows: • Develop a DAFO time-based method and code to consider damage recoverability. Establish operational doctrine and load priorities for different operational conditions and situations. Consider simple models for generator load sharing, load ramps and switching, and temperature increase/limits with loss of cooling. • Continue to work with MS students to develop and interface with a time-based discrete-event operational situation in the operational architecture, and capability nodes and code in the logical architecture to calculate operational performance as a function of combat system configurations against threats specified by the operational situation. The operational situation will drive the DAFO by specifying a series of time-stepped capability requests to the ship system logical and physical architectures and then applying the answers to the operational situation. • Expand the current AFO to formulate and update an effectiveness objective function at each time step based on the operational situation and load priorities. • Add a combat system data formulation and scenario that will determine the optimum combat system data flow (0,1) through the logical architecture to support the capability pull from the operational architecture. The DAFO will model combat system usage by using prioritized capability pulls on the system to determine which Vital Components (VCs) are active during the discrete event. • Exercise the DAFO in an LSC design study interfacing with a discrete-event operational scenario.

This expanded Dynamic AFO (DAFO) method will provide a foundation for the development of: • Time-based operational architecture approaches and tools • The 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. • Power Transition load analysis using a Dynamic Architecture Flow Optimization (DAFO). • Cascading and secondary deactivation analysis. • Deactivation ship/system recoverability analysis. Specific accomplishments in Year 5, June 2019 to May 2020 included: - Completed plan for DAFO formulation and software including operational architecture and capability nodes. - Began development of discrete event operational architecture with a basic DRM Operational Scenario for interface with capability nodes and DAFO. - Began development of capability node logic and software. - Completed shock model and code Accomplishments by students: • Zhaokuan Lu completed the development of his shock modeling method and software, and successfully defended his PhD dissertation. Nan Si's hull UNDEX damage model work is not yet complete and is proceeding, but very slowly. • Mark Parsons (PhD student) continued work to develop an approach and methods for defining operational architecture and interfaces through capability nodes with the logical architecture, and to develop dynamic architecture flow optimization (DAFO) methods to assess system response and recoverability in operational situations (OpSits) with weapon hits and damage. Mark completed his MS in Ocean Engineering on the way to his PhD. • David Berrow and Alan Shane, distance-learning OE MS students, supported Mark in planning operational architecture and capability models. All of the specific objectives of our research have been completed, but the goal of answering our specific questions relating early stage design and survivability, particularly considering battle damage recovery, has not been fully met. We have demonstrated a significant impact of considering vulnerability in early-stage design, but the consideration of recoverability will require the development and design application of a DAFO tool. A framework for DAFO has been completed, but an additional year is required for its development and simple application.

Plans Next Period

Year 5 is complete. We have submitted a white paper to ONR to provide sufficient one-year funding for Mark Parsons to complete his DAFO formulation and application as conceived in Year 5.

Results Dissemination

Dr. Brown gave a SNAME Webinar on the basic process and methods of this research and has completed Chapter 1 of a new SNAME Marine Engineering text that introduces the entire Marine Engineering and ship design process in the same system network context as developed in this research. Mark Parsons is planning for a follow-on webinar in the Fall 2020.

Honors and Awards

Nothing to Report

Training Opportunities

Summer 2020 - Our PhD student Marks Parsons is again a NSWCCD summer employee. He continues to focus on incorporating operational architecture capabilities within the LEAPS framework. This is totally in line with his graduate research developing an approach and methods for defining operational architecture and interfaces through capability nodes with the logical architecture. Alan Shane, a NAVSEA 05D3 employee and distance learning student is also supporting this effort.

Technology Transfer

Throughout the duration of this project we have worked closely with the ONR S3D/Electric Ship research project and have adapted our goals and objectives to support their development whenever possible. Mark Parsons who is also an NSWCCD employee in the tools group has been applying our process and methods wherever possible in his LEAPS work. David Goodfriend, an early graduate student in this research, was also hired by NSWCCD and used much of our preliminary arrangements and subdivision block approach in his Navy project work.

Participants

Name	Role	Person Months
Berrow, David	Graduate Student (research assistant)	2
Kara, Mustafa	Graduate Student (research assistant)	2
Lu, Zhaokuan	Graduate Student (research assistant)	6
Parsons, Mark	Graduate Student (research assistant)	8
Shane, Alan	Graduate Student (research assistant)	2
Si, Nan	Graduate Student (research assistant)	4
Brown, Alan	PD/PI	4

Research Performance Progress Report (RPPR)

Proposal No. N1605-NV-ONR, Agreement No. N00014-15-1-2476

Naval Ship Distributed System Vulnerability and Battle Damage Recovery in Early-Stage Ship Design

NICOP

Dr. Alan Brown, Virginia Tech, P.I.

June 16, 2020

Distribution Statement

- DISTRIBUTION A. Approved for public release: distribution unlimited.

Accomplishments and Technical Approach

What were the major goals and objectives of the project?

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9) Analyze results and answer the four critical questions posed above.
10) Transition process and tools as able to USN ship design tools (LEAPS/ASSET/RSDE and S3D).

What was accomplished towards achieving these goals and what was your technical approach?

Since our objectives largely address process, methods and tools, our work and accomplishments are closely tied to our technical approach which builds on our previous synthesis model, effectiveness process and tools and provide an excellent foundation for survivability analysis using 3D ship geometry, network architecture system definition, and effectiveness modeling. It also builds on the system architecture framework being developed in our NICOP. In the context of a ship, we define an architectural framework using the conceptual model shown in Fig.1 that includes its physical architecture, logical architecture, and operational architecture, together with the interrelationships between these three architectures. The physical architecture describes the distributed system spatial arrangement and physical attributes, the logical architecture describes the functional relationship of system components, and the operational architecture describes the temporal behavior characteristics of the ship and systems performing their mission(s) (Brefort et al., 2018).

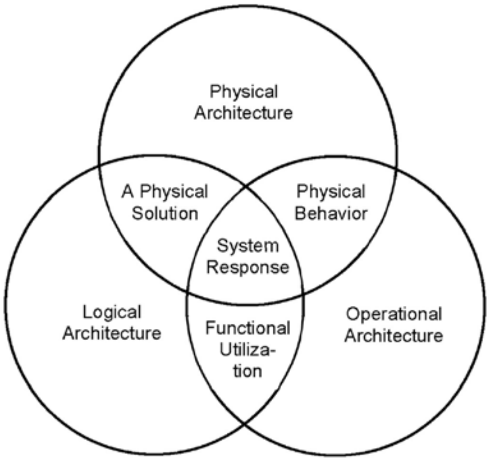


Fig.1 Visual representation of an architectural framework for ship distributed systems

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

The methods and tools being developed are intended to support our Combat and Energy System Process shown in Fig. 2 which has evolved significantly over the first four years of this project. A technology review identifies 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 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 technology risk.

Next, logical system architecture is developed by integrating selected technology components in systems that provide specific capabilities required by the ship. In the naval mission area these might include Anti-Air Warfare (AAW), Anti-Submarine Warfare (ASW) and Anti-Surface Warfare (ASUW) systems. Power and energy systems typically would include propulsion, electric distribution, fuel oil, machinery control, steering, and thermal systems (lube oil, HVAC, seawater, chilled water, electronic cooling, and glycol cooling). Fig.3 shows a simple mechanical subsystem architecture in an integrated power system. The logical architectures for these systems may be developed manually from scratch, by modifying and updating existing system architectures, or by using automated software like the Smart Ship Systems Design (S3D/LEAPS) tool using templates and patterns.

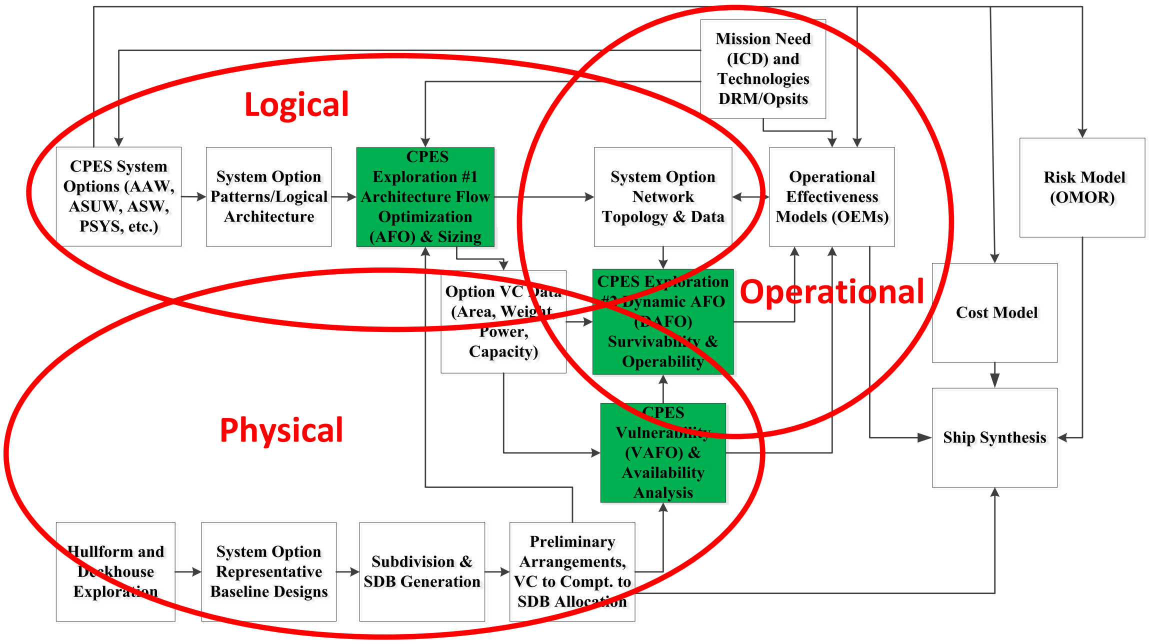


Fig.2 CPES design using architectural framework process

Fig.3 Mechanical (propulsion) subsystem

The constraining ship physical architecture begins with hullform and deckhouse exploration, the creation of representative designs for each combination of system options, and then the creation of subdivision blocks (SDBs) as shown in Fig.4. Transverse bulkheads and decks are added based on stack-up lengths, floodable length parametrics, average deck height, and “style” considerations. 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 later components are allocated to SDBs as shown in Fig.5. 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. These metrics may be operability metrics, probabilities of kill given hit, shock factors or other scalar values. From this point on, a network-approach is used, representing SDBs in a nodal matrix as in Fig.6. 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 Fig.7. When applied to all subsystems, this completes a simple logical and physical model, the "physical solution", sufficient for architecture flow optimization.

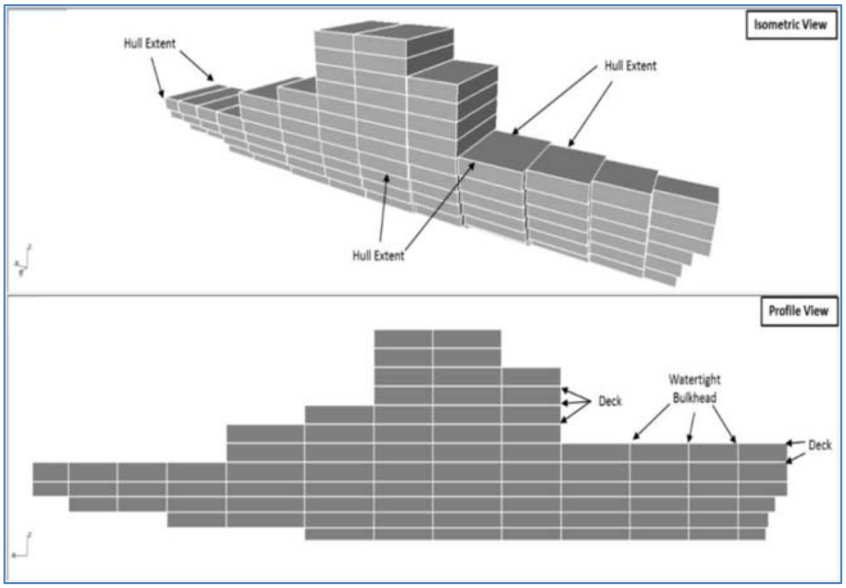
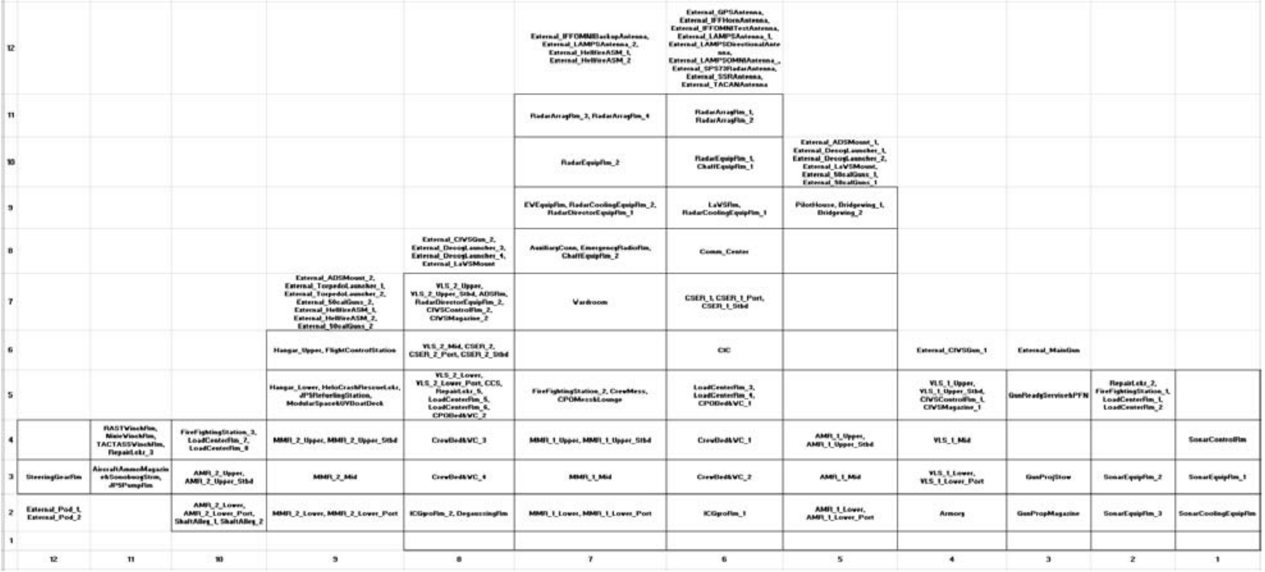


Fig.4 Subdivision Block (SDB) representation of physical architecture



12						External_IFFOMNIBackupAntenna, External_LAMPSAntenna_2, External_HellfireASM_1, External_HellfireASM_2	External_GPSAntenna, External_IFFHornAntenna, External_IFFOMNITestAntenna, External_LAMPSAntenna_1, External_LAMPSDirectionalAntenna, External_LAMPSOMNIAntenna_, External_SPS73RadarAntenna, External_SSRAntenna, External_TACANAntenna					
11						RadarArrayRm_3, RadarArrayRm_4	RadarArrayRm_1, RadarArrayRm_2					
10						RadarEquipRm_2	RadarEquipRm_1, ChaffEquipRm_1	External_ADSMount_1, External_DecoyLauncher_1, External_DecoyLauncher_2, External_LaVSMount, External_50calGuns_1, External_50calGuns_1				
9						EWEquipRm, RadarCoolingEquipRm_2, RadarDirectorEquipRm_1	LaVSRm, RadarCoolingEquipRm_1	PilotHouse, Bridgewing_1, Bridgewing_2				
8					External_CIWSGun_2, External_DecoyLauncher_3, External_DecoyLauncher_4, External_LaVSMount	AuxiliaryConn, EmergencyRadioRm, ChaffEquipRm_2	Comm_Center					
7				External_ADSMount_2, External_TorpedoLauncher_1, External_TorpedoLauncher_2, External_50calGuns_2, External_HellfireASM_1, External_HellfireASM_2, External_50calGuns_2	VLS_2_Upper, VLS_2_Upper_Stbd, ADSRm, RadarDirectorEquipRm_2, CIWSControlRm_2, CIWSMagazine_2	Wardroom	CSER_1, CSER_1_Port, CSER_1_Stbd					
6				Hangar_Upper, FlightControlStation	VLS_2_Mid, CSER_2, CSER_2_Port, CSER_2_Stbd		CIC		External_CIWSGun_1	External_MainGun		
5				Hangar_Lower, HeloCrashRescueLckr, JP5RefuelingStation, ModularSpace&UVBoatDeck	VLS_2_Lower, VLS_2_Lower_Port, CCS, RepairLckr_5, LoadCenterRm_5, LoadCenterRm_6, CPOBed&WC_2	FireFightingStation_2, CrewMess, CPOMess&Lounge	LoadCenterRm_3, LoadCenterRm_4, CPOBed&WC_1		VLS_1_Upper, VLS_1_Upper_Stbd, CIWSControlRm_1, CIWSMagazine_1	GunReadyService&PFN	RepairLckr_2, FireFightingStation_1, LoadCenterRm_1, LoadCenterRm_2	
4		RASTWinchRm, MainWinchRm, TACTASSWinchRm, RepairLckr_3	FireFightingStation_3, LoadCenterRm_7, LoadCenterRm_8	MMR_2_Upper, MMR_2_Upper_Stbd	CrewBed&WC_3	MMR_1_Upper, MMR_1_Upper_Stbd	CrewBed&WC_1	AMR_1_Upper, AMR_1_Upper_Stbd	VLS_1_Mid			SonarControlRm
3	SteeringGearRm	AircraftAmmoMagazine&SonobuoyStrm, JP5PumpRm	AMR_2_Upper, AMR_2_Upper_Stbd	MMR_2_Mid	CrewBed&WC_4	MMR_1_Mid	CrewBed&WC_2	AMR_1_Mid	VLS_1_Lower, VLS_1_Lower_Port	GunProjStow	SonarEquipRm_2	SonarEquipRm_1
2	External_Pod_1, External_Pod_2		AMR_2_Lower, AMR_2_Lower_Port, ShaftAlley_1, ShaftAlley_2	MMR_2_Lower, MMR_2_Lower_Port	ICGproRm_2, DegaussingRm	MMR_1_Lower, MMR_1_Lower_Port	ICGproRm_1	AMR_1_Lower, AMR_1_Lower_Port	Armory	GunPropMagazine	SonarEquipRm_3	SonarCoolingEquipRm
1												
	12	11	10	9	8	7	6	5	4	3	2	1

Fig.5 Allocation of vital compartments to SDBs forms SDB matrix

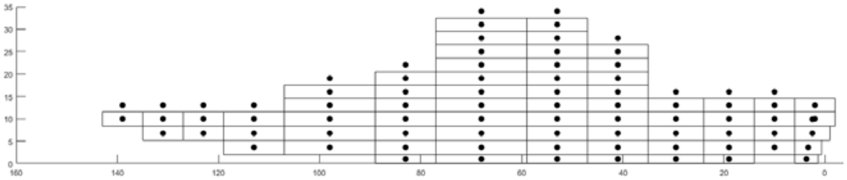


Fig.6 Nodal or network representation of physical architecture

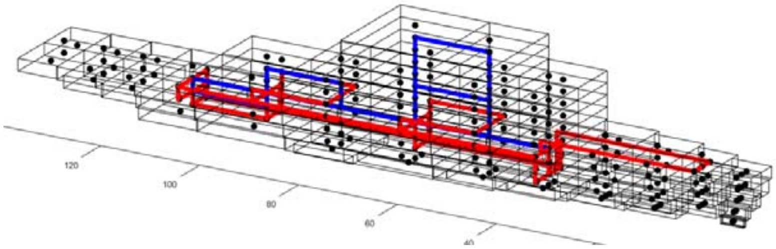


Fig.7 Routing of distributed systems

Operational architecture together with logical and physical architectures are used in an architecture flow optimization (AFO) to optimize system architecture and later size system components. Capacity sizing is performed in the logical architecture at its functional utilization intersection with the operational architecture. Since the physical size of components (weight, dimensions, space requirements) is directly related to capacity, it is also determined at the functional utilization intersection. Operational Effectiveness Models are used to identify probabilistic operational situations (OpSits) including probabilistic weapon hit events and functional capability requirements in the time domain. These may be applied as Architectural Flow Optimization (AFO) constraint sets in addition to normal operating conditions (sustained speed, endurance, battle) and used to assess resulting probabilities of kill given hit and capability loss probabilities. Component deactivation by SDB is specified using a damage ellipsoid method (Fig.9) sensitive to weapon type and charge size to assess the probability of vital component kill given hit (pk/h – Figs. 10 and 11) for a representative number of weapon hit scenarios (250-500).

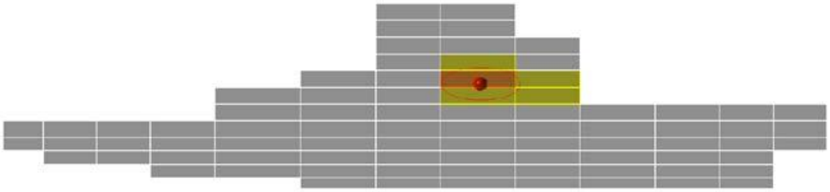


Fig. 8 Damage Extents (Ellipsoid) and SDB Intersection

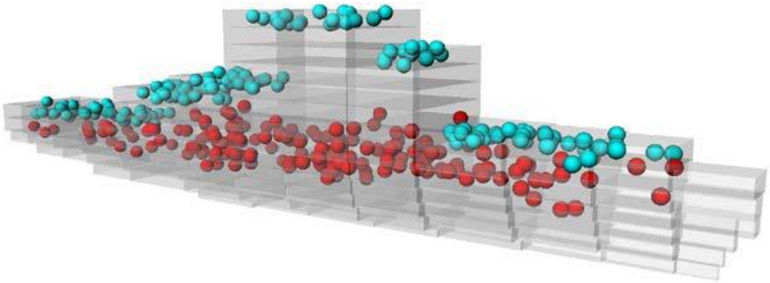
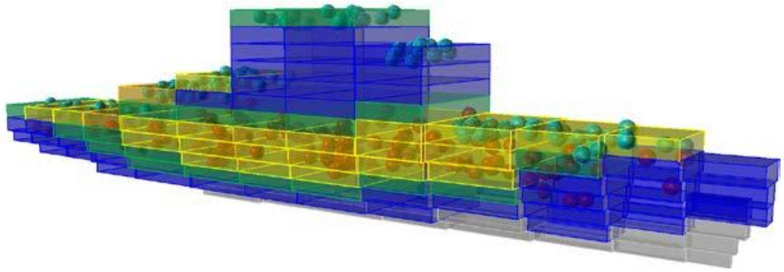


Fig. 9 Sample Anti-ship Cruise Missile Hit Distribution



SDB Probability of Intersection	Color
0	▨
0.01-0.05	🟦
0.06-0.10	🟩
0.11-0.20	🟨
0.21-0.30	🟧
0.31-0.99	🟥
1	⬛

Fig. 11 SDB Probability of Damage Volume Intersection

Distributed power and energy systems and their components can be characterized by their commodity flow (mechanical or electric power, lube oil, seawater, chilled water, glycol coolant, fresh water and data) and their ability to transport, store or convert energy. In its simplest form, this approach includes only the transport of energy or power without explicit consideration of “through” variables like current, flow rate, and speed, or “cross” variables like voltage, pressure and torque. A simple energy flow analysis does not need to consider the relationships between “through” and “across” variables at component nodes. These relationships include resistance, inductance and capacitance and more complex behaviors like pumps curves, engine maps, transformers or heat exchangers. Component or nodal behavior is simply modeled using a matrix of energy flow efficiencies with energy conservation required at all nodes except those identified as sources and sinks. Steady or quasi-steady state is assumed. Components like heat exchangers and electronic systems are assumed to operate at their normal design conditions and temperatures. This simplified approach is consistent with a logical architecture level of detail and can be used efficiently in large system energy commodity flow and architecture optimization for sizing of components and architecture refinement in early stage design.

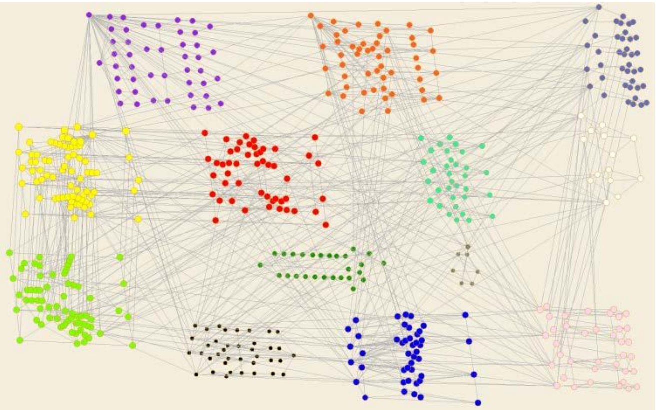


Fig.12 Logical Representation of Notional total-ship system architecture

Once the system logical, physical and operational architecture components are defined, an architecture flow optimization (AFO) can be performed. The AFO is used to reassemble and intersect the architecture components into a total system architecture as represented in Fig.12, to satisfy all operational requirements and constraints, and to insure an optimum energy flow through the entire system of systems. This energy flow can then be used to modify system logical architecture, calculate necessary commodity flows (mechanical, electrical, fluid), size vital components, and ultimately synthesize the total ship design.

We have extended and modified Trapp's (Trapp 2015) linear programming application to optimize 8 plexus (or subsystems) each with its own commodity and dedicated arcs in a total ship system architecture flow optimization (AFO) using the NICOP architecture framework. 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 the 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 to SBDs, as described above; 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 physical solution including the actual commodity flow (LO, SW, CW, electrical, mechanical, EC, Glycol, HVAC) and the sizing of physical components.

The major differences between our AFO formulation and Trapp's flow optimization are:

1. Only energy is explicitly tracked in the AFO as carried by the various commodities. The calculation of commodity flows and component sizing is postponed until post-AFO.
2. Nodal equations do not just consider continuity. They specify the allocation of energy to alternative commodity arcs entering and leaving nodes, although continuity must still be enforced. 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 formulation, particularly in the nodal constraints and energy conservation/partitioning.
3. The number of plexus included in the multiplex model is larger.
4. System architectures (logical, physical and operational) and other input data is extracted directly from a total ship model.

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. This is implemented in a simplex linear programming formation with the following preliminary results.

Figs. 13-19 show an example of energy flow in and out of power and thermal systems using the logical architecture for a sustained speed scenario. This is useful for understanding the AFO, but also for understanding distributed system energy flow in general. In Fig.13, fuel oil (FO) with chemical energy originates in the fuel transfer system from the ship's main fuel storage tanks, flows through fuel oil purifiers to the FO Service Tanks where the FO Service System begins.

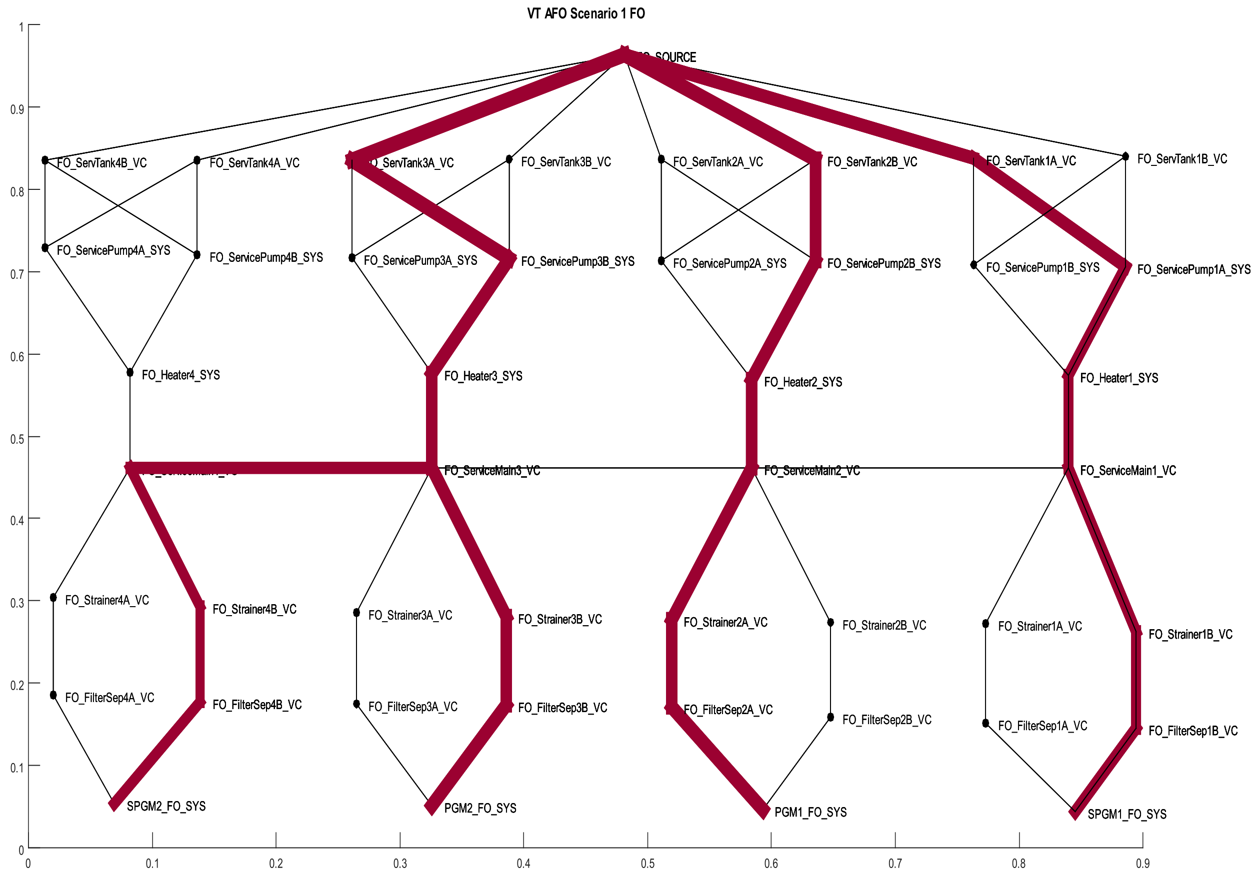


Fig.13 Sustained Speed FO Subsystem Plex Energy Flow

In this result only three service tanks, three pumps and the cross-connect to Zone 4 are used. Other operational, damage and maintenance scenarios may require the use of other FO VCs and these show up in the aggregate (all scenario) system. In this single scenario solution, fuel then flows through strainers and filter/separators to gas turbine PGMs and diesel SPGMs in each zone where energy flows next into the ELEC subsystem plex.

Fig.14 shows the ELEC subsystem. Here the (fuel) energy enters the power generation modules (PGM1&2, SPGM1&2) where it is converted to electric energy and heat. The electric energy flows through switchboards, out to the bus, back in to power conversion modules, and then to propulsion motors and load centers where it is distributed to zonal loads. Note that in this scenario, all PGMs are providing power and all zonal loads and PMMs receive power, but not all arcs, PCMs and LCs are used. These may be required in other scenarios and will then be used in the aggregate system.

Heat from the PGMs goes into the engine exhaust (leaves the ship) and into the lube oil (LO), seawater (SW) and HVAC (through zone air heat) subsystem plexus. These subsystems are shown in Figs. 15 through 18.

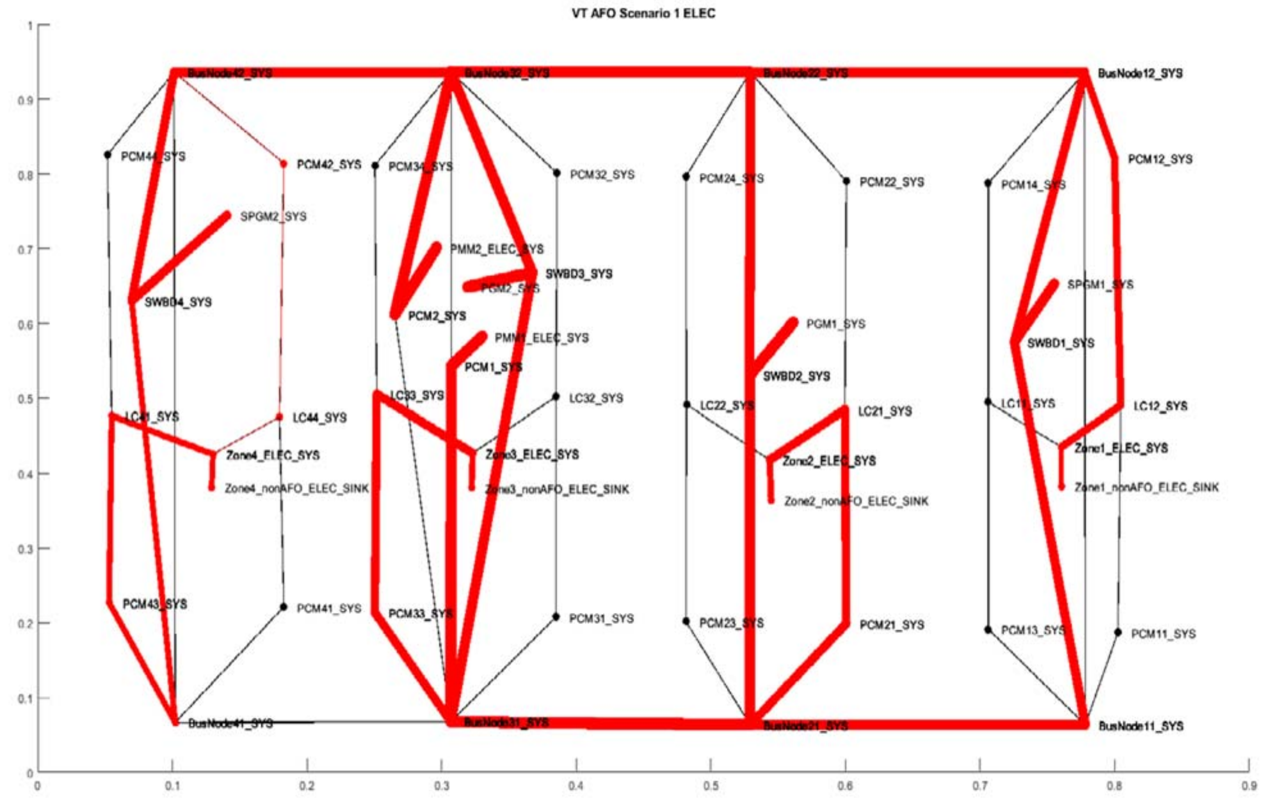


Fig.14 Sustained Speed ELEC Subsystem Plex Heat Flow

In Fig.15, the LO subsystem receives heat from the SPGMs, PGM Synthetic LO subsystem and PMMs, and circulates it through LO sumps, LO pumps, LO coolers and LO filters. Heat removed from the LO coolers passes to the SW subsystem.

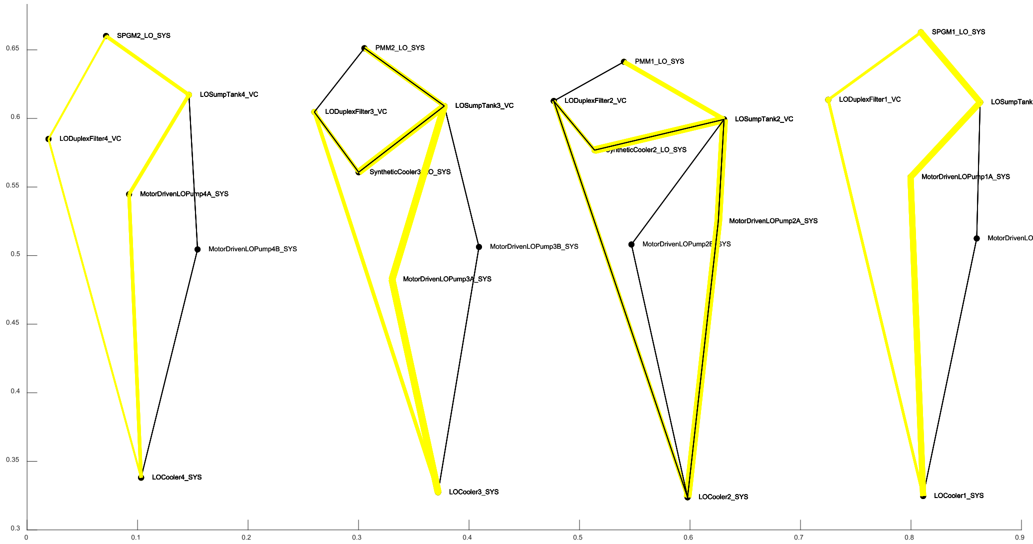


Fig.15 Sustained Speed LO Subsystem Plex Heat Flow

In Fig.16, the SW subsystem receives heat from the LO coolers and HFC/CW subsystems. The SW subsystem is not a loop system as in the LO, CW, HFC, EC and Glycol subsystems.

Seawater is pumped in from seachests, through strainers and pumps to pressurize the SW Main. It flows from the SW main through the LO coolers and HFC condensers and then overboard (out of the ship) into the sea.

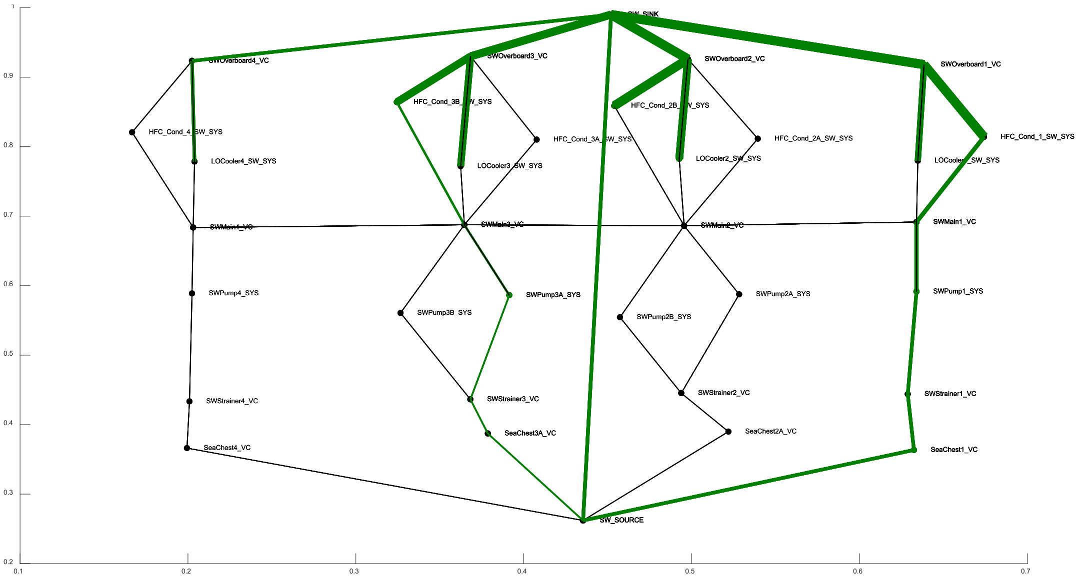


Fig.16 Sustained Speed SW Subsystem Plex Heat Flow

The HVAC subsystem shown in Fig.17 receives air heat from the Zone Air Heat nodes and this heat plus additional aggregate zone heat flows to the HVAC Heat nodes representing multiple unit air coolers where hot air is cooled by CW.

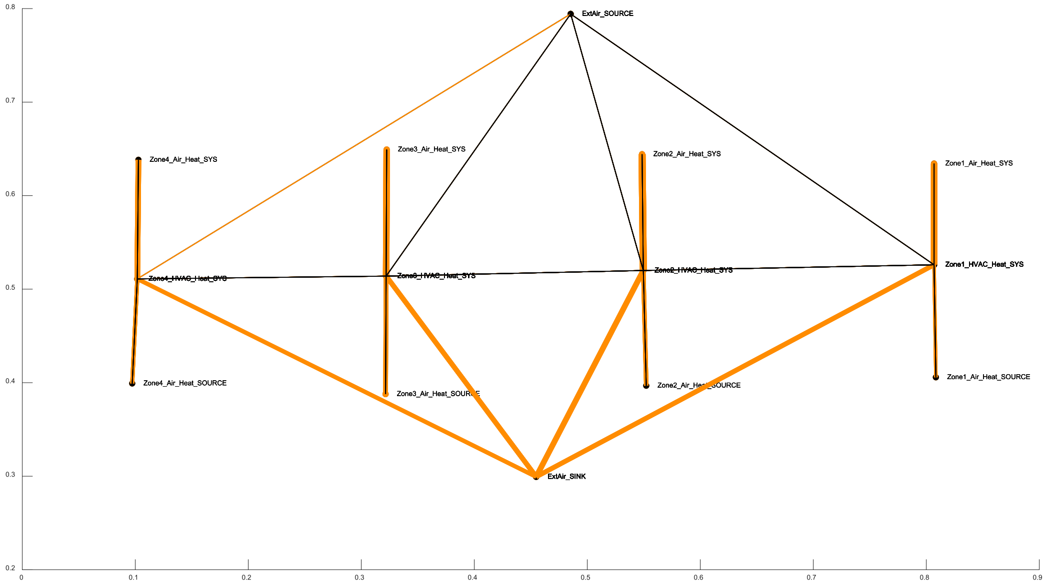


Fig.17 Sustained Speed HVAC Subsystem Plex Heat Flow

The CW subsystem heat flow shown in Fig.18 receives heat at all zonal HVAC nodes and from the electronic cooling (EC) and glycol cooling heat exchangers. This heat flows to the CW return piping, then to the CW coolers where it passes the heat on to the HFC subsystems and then the SW subsystem.

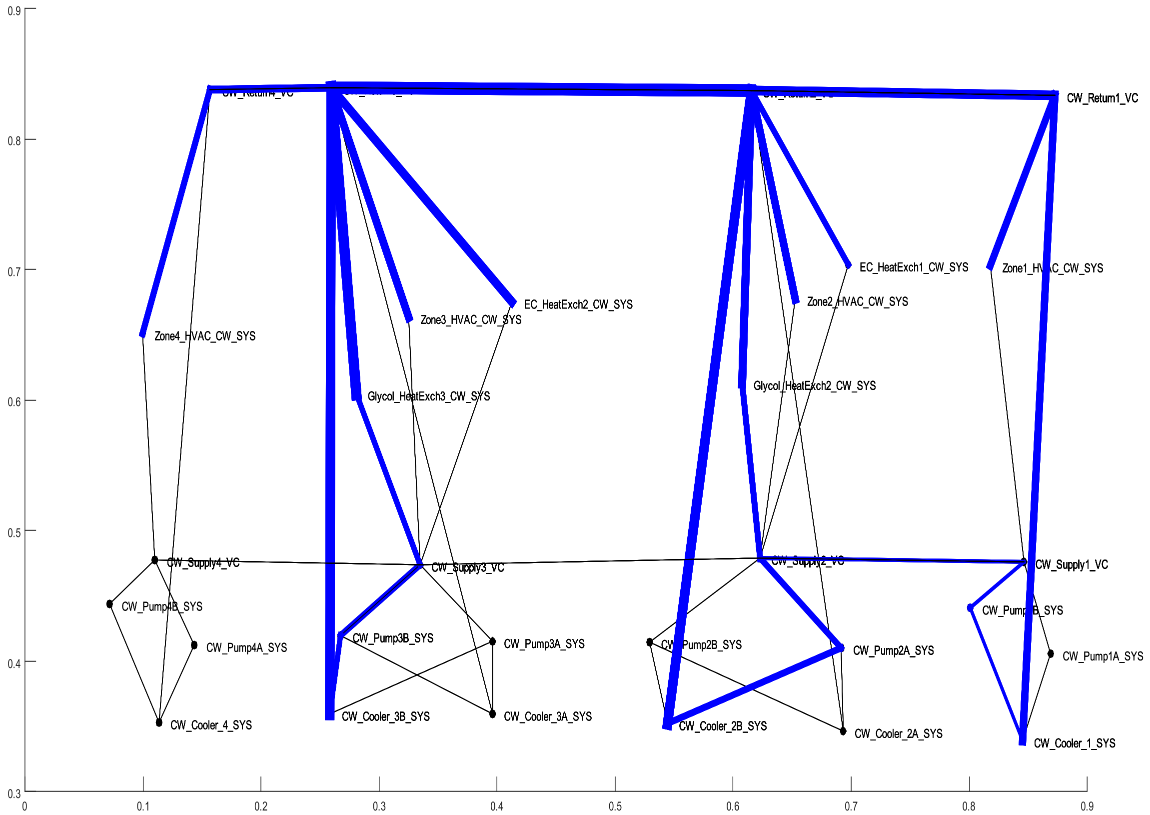


Fig.18 Sustained Speed CW Subsystem Plex Heat Flow

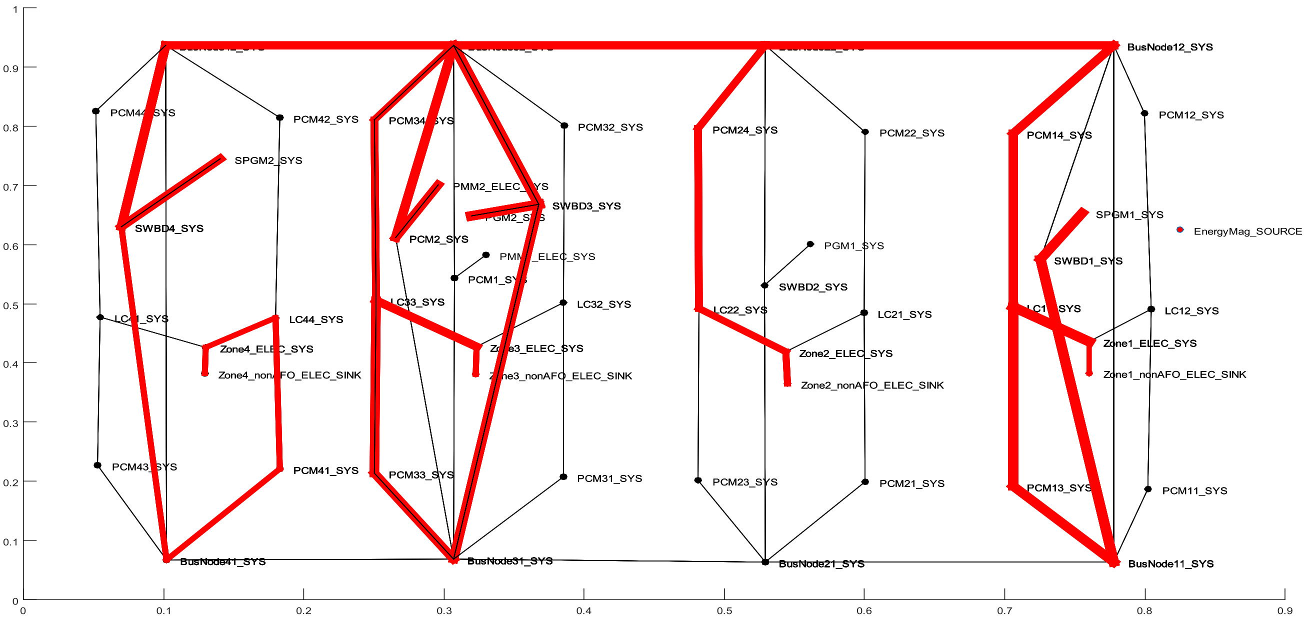


Fig.19 MMR1 Lower Damaged ELEC Subsystem Plex Heat Flow

Fig.19 shows a damage case where main machinery room one MMR1 has been lost and all VCs in MMR1 have been deactivated by setting the flow in and out of each VC to zero. The critical deactivated VC in MMR1 is PGM1 and it can be seen in the ELEC subsystem that the starboard bus which passes through MMR1 lower and PGM1 are deactivated and all ship power for all zones including Zone 2 is provided by SPGM1, PGM2 and SPGM2. Power for Zone 2 comes in from the Port Bus. This power is sufficient to satisfy power and propulsion demands. More than 200 more damage cases similar to this are considered in the aggregate flow analysis.

We see that all the ship energy enters in fuel oil and air heat sources and leaves as propulsion, engine exhaust and HVAC exhaust to the atmosphere, and SW heat overboard. The power generation process is at best about 45% efficient with more than 55% of the fuel chemical energy ending up as heat needing to be removed from the ship. Removing heat from the ship is every bit as important as generating power and in some ways more difficult.

The application of a network architecture framework with an architecture flow optimization (AFO) as a preliminary exploration to ship synthesis has a number of significant advantages:

1) 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.
2) Enables early preliminary general arrangements.
3) Enables early architecture optimization.
4) Enables a more specific consideration of operational architecture scenarios including warfighting damage.
5) Enables early flow-based maintenance, reliability and availability analyses which.
6) Enables early vulnerability and eventually recoverability analyses.
7) Multiple combinations of design variable options can be considered and applied to better understand their total ship impact.

In our fourth year we began work to develop an approach and methods for defining operational architecture and interfaces through capability nodes with the logical architecture. We also began to consider dynamic architecture flow optimization (DAFO) methods to assess system response and recoverability in operational situations (OpSits) with weapon hits and damage, and to adapt our AFO method for application to calculating an overall measure of vulnerability (VAFO). These processes show up in our modified CPES Exploration process, green boxes, shown in Fig. 2. These processes will build on the completed AFO formulation and sizing of the power and energy components to assess their vulnerability and recoverability in more complex and realistic operational scenarios. The DAFO will operate in the time domain in response to operational situations (OpSits) and capability requirements from the operational architecture. The OpSits will be specified as discrete event simulations with conditional branching that depends on the ship's capabilities which will be updated at each time step. Weapon hits specified in the evolving OpSits will be applied to the ship's physical architecture and will affect capabilities including the ship's ability to support combat systems with power and cooling. This is a totally new direction that we believe to be essential is assessing a ship design. An overall measure of vulnerability (OMOV) will also be calculated for the design and used in the final ship synthesis and search of the design space. PhD students Mark Parsons and Mustafa Kara continue to lead this effort.

In the fifth year we began to develop a framework and plan for the DAFO including the **addition of capability nodes and discrete event operational architecture.** 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. Products of our quasi-static AFO include a linear programming formulation of the ship combat, power and energy system (CPES), an optimum system architecture and optimum sizing solution based on t=0+ scenarios. We will continue with the same AFO formulation and t=0+ solution to perform a time-based recoverability analyses in a realistic 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.

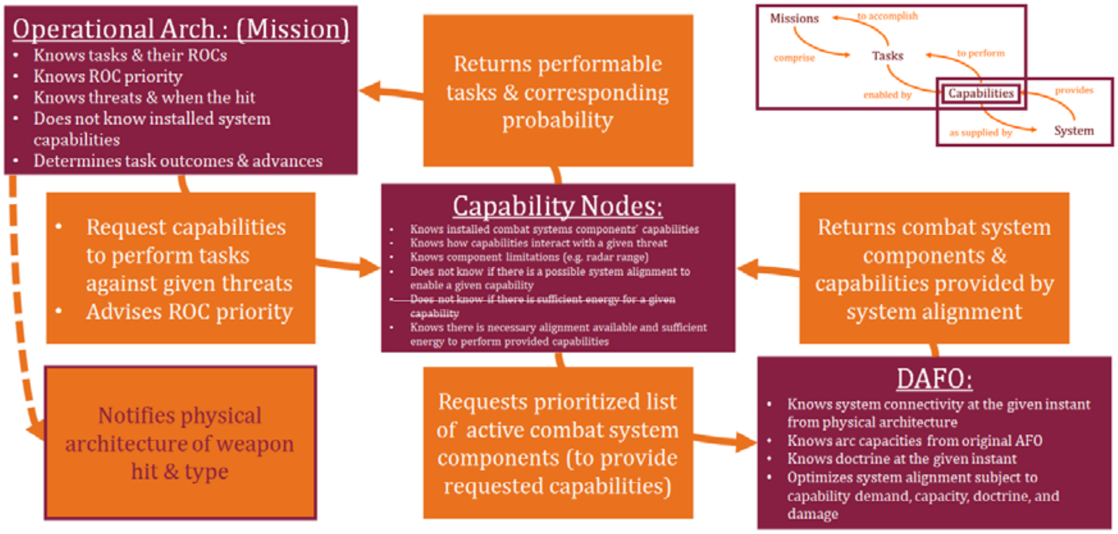
In the current AFO, the operational architecture is limited to scenarios for steady-state steaming conditions (endurance, sustained and battle) and scenarios with single subdivision block damage. Capacity sizing is performed in the logical architecture at its functional utilization intersection with the operational architecture. Since the physical size of components (weight, dimensions, and space requirements) is directly related to capacity, it is also determined at the functional utilization intersection. The aggregate sizing is determined in the AFO and will become an additional constraint set for the DAFO and more realistic time-based operational scenarios specified in a Design Reference Mission (DRM).

The DAFO will be performed with a time increment able to capture the dynamics of the mechanical and fluid systems, but would not consider the full electrical system dynamics such as power stability and transient effects. These would be considered in subsequent concept development feasibility studies.

The following plan for DAFO and operational architecture is as follows:

- Develop a DAFO time-based method and code to consider damage recoverability. Establish operational doctrine and load priorities for different operational conditions and situations. Consider simple models for generator load sharing, load ramps and switching, and temperature increase/limits with loss of cooling.
- Continue to work with MS students to develop and interface with a time-based discrete-event operational situation in the operational architecture, and capability nodes and code in the logical architecture to calculate operational performance as a function of combat system configurations against threats specified by the operational situation. The operational situation will drive the DAFO by specifying a series of time-stepped capability requests to the ship system logical and physical architectures and then applying the answers to the operational situation as illustrated in Figure 20.
- Expand the current AFO to formulate and update an effectiveness objective function at each time step based on the operational situation and load priorities.

- Add a combat system data formulation and scenario that will determine the optimum combat system data flow (0,1) through the logical architecture to support the capability pull from the operational architecture. The DAFO will model combat system usage by using prioritized capability pulls on the system to determine which Vital Components (VCs) are active during the discrete event as illustrated in Figure 21.
- Exercise the DAFO in an LSC design study interfacing with a discrete-event operational scenario. Complete in May 2021.



Operational Arch.: (Mission)
- Knows tasks & their ROCs
- Knows ROC priority
- Knows threats & when the hit
- Does not know installed system capabilities
- Determines task outcomes & advances

Returns performable tasks & corresponding probability

- Request capabilities to perform tasks against given threats
- Advises ROC priority

Capability Nodes:
- Knows installed combat systems components' capabilities
- Knows how capabilities interact with a given threat
- Knows component limitations (e.g. radar range)
- Does not know if there is a possible system alignment to enable a given capability
- ~~Does not know if there is sufficient energy for a given capability~~
- Knows there is necessary alignment available and sufficient energy to perform provided capabilities

Returns combat system components & capabilities provided by system alignment

Notifies physical architecture of weapon hit & type

Requests prioritized list of active combat system components (to provide requested capabilities)

DAFO:
- Knows system connectivity at the given instant from physical architecture
- Knows arc capacities from original AFO
- Knows doctrine at the given instant
- Optimizes system alignment subject to capability demand, capacity, doctrine, and damage

Fig. 20 - DAFO Functions, Capabilities and Operational Architecture Interfaces

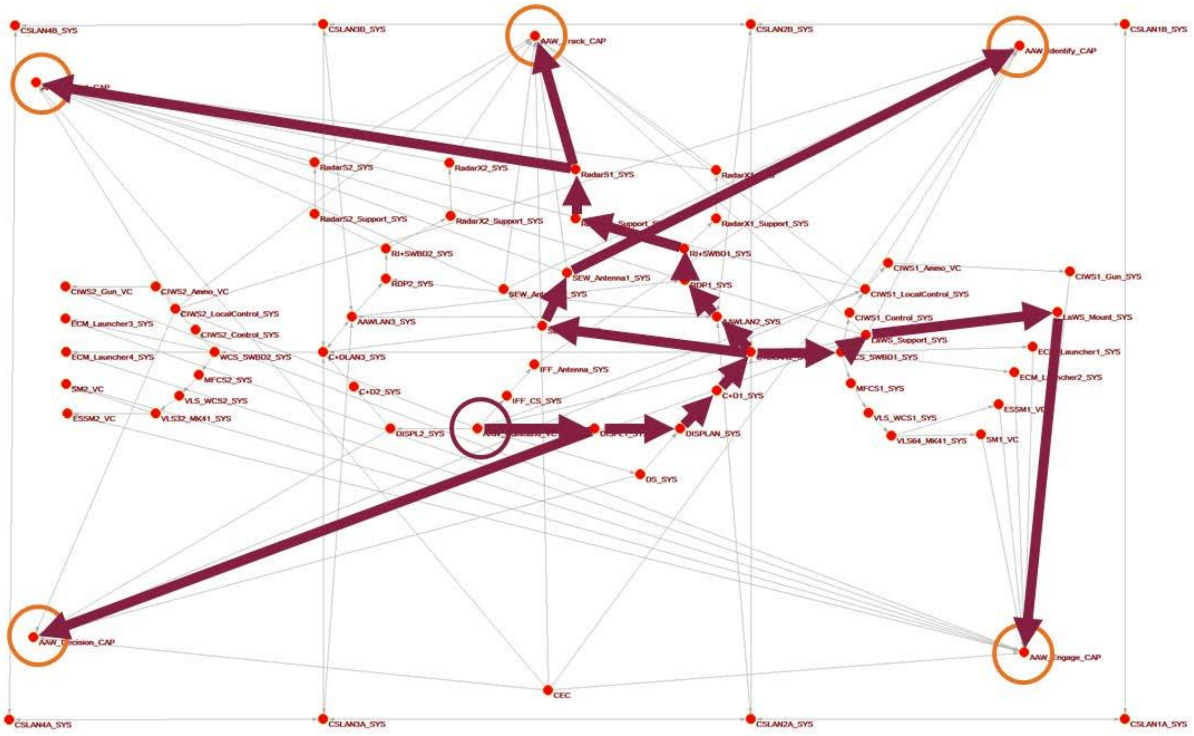


Fig. 21 – Notional Capability Nodes and Data Pull through Combat System Logical Architecture

This expanded Dynamic AFO (DAFO) method will provide a foundation for the development of:

- Time-based operational architecture approaches and tools
- The 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.
- Power Transition load analysis using a Dynamic Architecture Flow Optimization (DAFO).
- Cascading and secondary deactivation analysis.
- Deactivation ship/system recoverability analysis.

In summary, propulsion and distributed system design are proving to be 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.

The interdependence and complexity of ship systems is growing at an accelerated rate. This complexity makes systems 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. 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. Knowledge-based methods have motivated a network architecture-based framework that has value for both knowledge-based and product-based approaches, and for transitioning from one to the other.

The framework, tools and methods developed in this research provide a way ahead to meet the challenges and complexities of future complex and interdependent marine engineering systems within the context of the total ship design.

Specific accomplishments in the five years of our five year plan and schedule with modifications to incorporate more network-based approaches consistent with the NICOP decisions and to support Navy S3D development are as follows:

• Start, Year 1, 16 June 2015 to 15 June 2016

- Begin development of a model to use simplified ship geometry, system architecture and preliminary arrangements to assess system vulnerability. - Complete

- Begin development of weapon damage ellipsoid models using data from more detailed analyses and simplified physics-based approaches. - Complete for AIREX Blast only.

- Use Axis-Aligned Bounding Boxes to model ship subdivision blocks (SDBs) and allocate vital components (VCs) and compartments to these SDBs. - Complete

- Develop a simplified bubble pulse UNDEX model. - Complete

- Begin development of a simplified UNDEX shock and damage model. - Complete

• Year 2, 16 June 2016 to 15 June 2017

- Continue development of simplified UNDEX shock and damage models. - 45%

- Continue development of system network models. – Complete

- Develop Breadth-First Search (BFS) algorithm and code to map physics-based system network architecture to RBD/deactivation diagrams. – 70%

- Continue to develop process and code to extend the architecture flow optimization (AFO) method to a large multi-domain (plex) network system, develop more realistic and rational set of damage and operational constraints, and incorporate the method into a Preliminary Arrangement, Architecture and Vulnerability Model (PAAVM) and process. Collect data from these Architecture Flow Optimizations (AFOs) - 55%

• Year 3, June 2017 to May 2018

- Continue development of simplified UNDEX shock and damage models. - 60%

- Continue baseline architecture flow optimization (AFO) method and code. Apply to FSC design case study. Collect data. – 95%

- Develop Breadth-First Search (BFS) algorithm and code to map physics-based system network architecture to RBD/deactivation diagrams. – 90%

- Begin to modify AFO method to consider load profiles with moderate dynamic load variation and energy storage in a series of time-based flow optimizations. – Start Fall 2018

Year 4, June 2018 to May 2019

- Continue development of simplified UNDEX shock and damage models. - 70%

- Develop Breadth-First Search (BFS) algorithm and code to map physics-based system network architecture to RBD/deactivation diagrams. – Complete

- Develop code to extract LEAPs data to develop RBD/deactivation diagrams. – Complete

- Develop approach and methods for defining operational architecture and interface through capability nodes with the logical architecture. (new in 2019/20 to support S3D development) – 5%

- Begin to develop dynamic architecture flow optimization (DAFO) methods to assess system response and recoverability in operational situations (OpSits) with weapon hits and damage. (new in 2019/20 to support S3D development) - Start Fall 2019

- Begin to adapt AFO method for application to calculating an overall measure of vulnerability (VAFO). - Start Fall 2019

Year 5, June 2019 to May 2020

- Completed plan for DAFO formulation and software including operational architecture and capability nodes.

- Began development of discrete event operational architecture with a basic DRM Operational Scenario for interface with capability nodes and DAFO.

- Began development of capability node logic and software.

In the first year students performed this research as follows:

David Goodfriend, MS OE 2015, completed the baseline system architecture model with vulnerability model interface and related system loss to mission capabilities. He developed an initial Preliminary Arrangements and Vulnerability model. System architecture was input as deactivation block diagrams (DBDs). Damage ellipsoid and preliminary arrangement models and methods were nearly completed and simplified UNDEX models were begun.

In the second year:

- Sean Stark, MS OE 2016, completed an AIREX Blast and Fragmentation damage ellipsoid model using data from more detailed analyses and simple physics-based models.

- Andrew Stevens, MS OE 2016, completed an initial vital component (VC)/compartment assignment model connecting the AABB geometry to the vulnerability model and developed a preliminary arrangement algorithm based on operability and vulnerability that includes system vital component (VC) arrangements.

- Zhaokuan Lu and Nan Si (current PhD students) lead a small team of graduate students to further develop fast UNDEX modeling methods that can be adapted to our damage ellipsoid approach so that we can consider UNDEX threats including shock in our vulnerability assessment. This work is proceeding well, but slowly, on target to be applied in Year 4 or 5, in time for the final modeling and data collection.

- Mark Parsons and Mustafa Kara (PhD students) and Kevin Robinson (USCG MS student) began work on an architecture flow optimization (AFO) method working directly with a multiplex network topology representation of power, energy and combat systems. In Year 1 we used traditional DBDs to model our system architecture for purposes of preliminary arrangement and vulnerability analysis. From this point on, we began with a network topology representation.

• Daniel Snyder (MS student) is began developing a Breadth-First Search (BFS) method and code to map system network architecture to DBD/deactivation diagrams.

• In order to support the need for multiple system network representations, we have completed the development of multiple options of multiple system network models. These include mechanical, electrical, lube oil, salt water, chilled water, electronic cooling, glycol cooling, fuel, AAW, ASW and ASUW systems. We added a zonal ventilation and cooling model in the Fall 2017 and added aggregated electric loads and thermal loads to account for loads that are not explicit in the systems we are modeling.

• We continued to perform ship design case studies for a Future Surface Combatant (FSC).

In the third year:

Zhaokuan Lu and Nan Si (PhD students) continued to develop fast UNDEX modeling methods that can be adapted to our damage ellipsoid approach so that we can consider UNDEX threats including shock in our vulnerability assessment. This work is proceeding well, but slowly, on target to be applied in Year 5, in time for the final modeling and data collection.

• Mark Parsons and Mustafa Kara (PhD students) and Kevin Robinson, MS OE 2018, completed the baseline architecture flow optimization (AFO) model.

• Daniel Snyder (MS student) continues developing a Breadth-First Search (BFS) method and code to map system network architecture to DBD/deactivation diagrams. It is nearly complete.

• Nick Stinson (MS student) began to integrate the AFO sizing approach with our ship synthesis model.

• We continued to perform ship design case studies for a Future Surface Combatant (FSC) in our undergraduate and graduate student design classes and projects.

In the fourth year:

• Zhaokuan Lu and Nan Si (PhD students) continued to develop fast UNDEX modeling methods that can be adapted to our damage ellipsoid approach so that we can consider UNDEX threats including shock in our vulnerability assessment. This work is proceeding well, but slowly. The shock modeling is on target to be applied in Year 5, in time for the final modeling and data collection. Hull UNDEX damage model work will likely need to continue for another year.

• Mark Parsons and Mustafa Kara (PhD students) continued to refine and test the baseline architecture flow optimization (AFO) model, including a frigate (FFGX) design application in addition to the previous FSC design. They also began work to develop an approach and methods for defining operational architecture and interfaces through capability nodes with the logical architecture, to develop dynamic architecture flow optimization (DAFO) methods to assess system response and recoverability in operational situations (OpSits) with weapon hits and damage, and to adapt our AFO method for application to calculating an overall measure of vulnerability (VAFO).

- David Berrow and Alan Shane, distance-learning OE MS students, supported Mark in planning operational architecture and capability models.

- Daniel Snyder (MS student) completed his Breadth-First Search (BFS) method and code to map system network architecture to DBD/deactivation diagrams. He completed his thesis and graduated with an MSOE.

- Nick Stinson (MS student) integrated the AFO approach and our ship synthesis model with emphasis on power and energy system flow and sizing. He completed his thesis and graduated with an MSOE.

- We continued to perform ship design case studies, this year for a guided-missile Frigate (FFGX) in our undergraduate and graduate student design classes and projects using the methods developed in this research.

In the fifth year:

- Zhaokuan Lu completed the development of his shock modeling method and software, and successfully defended his PhD dissertation. Nan Si's hull UNDEX damage model work is not yet complete and is proceeding, but very slowly.

- Mark Parsons (PhD student) continued work to develop an approach and methods for defining operational architecture and interfaces through capability nodes with the logical architecture, to develop dynamic architecture flow optimization (DAFO) methods to assess system response and recoverability in operational situations (OpSits) with weapon hits and damage.

- David Berrow and Alan Shane, distance-learning OE MS students, supported Mark in planning operational architecture and capability models.

All of the specific objectives of our research have been completed, but the goal of answering our specific questions relating early stage design and survivability, particularly considering battle damage recovery, has not been fully met. We have demonstrated a significant impact of considering vulnerability in early-stage design, but the consideration of recoverability will require the development and design application of a DAFO tool. A framework for DAFO has been completed, but an additional year is required for its development and simple application.

What opportunities for training and professional development did the project provide?

Summer 2017 – Worked with NSWCPD NREIP interns on summer project related to this project.

Summer 2018 – Have begun work with both NSWCPD and NSWCCD NREIP interns on summer project that includes implementation of this project in US Navy design tools. Our PhD student Marks Parsons is a NSWCCD summer employee leading the NSWCCD effort.

Summer 2019 - Our PhD student Marks Parsons is again a NSWCCD summer employee. This year he is focusing on incorporating operational architecture capabilities within the LEAPS framework. This is totally in line with his graduate research developing an approach and methods for defining operational architecture and interfaces through capability nodes with the logical architecture. Alan Shane, a NAVSEA 05D3 employee and distance learning student is also supporting this effort.

Summer 2020 - Our PhD student Marks Parsons is again a NSWCCD summer employee. He continues to focus on incorporating operational architecture capabilities within the LEAPS framework. This is totally in line with his graduate research developing an approach and methods for defining operational architecture and interfaces through capability nodes with the logical architecture. Alan Shane, a NAVSEA 05D3 employee and distance learning student is also supporting this effort.

How were the results disseminated to communities of interest?

Dr. Brown gave a SNAME Webinar on the basic process and methods of this research and has completed Chapter 1 of a new SNAME Marine Engineering text that introduces the entire Marine Engineering and ship design process in the same system network context as developed in this research. Mark Parsons is planning for a follow-on webinar in the Fall 2020.

What do you plan to do during the next reporting period to accomplish the goals and objectives?

We have submitted a white paper to ONR to provide sufficient one-year funding for Mark Parsons to complete his DAFO formulation and application.

Honors: What honors or awards were received under this project in this reporting period?

Dr. Brown won the SNAME Webb medal in the first year of this project.

Technology Transfer

Throughout the duration of this project we have worked closely with the ONR S3D/Electric Ship research project and have adapted our goals and objectives to support their development whenever possible. Mark Parsons who is also an NSWCCD employee in the tools group has been applying our process and methods wherever possible in his LEAPS work. David Goodfriend, an early graduate student in this research, was also hired by NSWCCD and used much of our preliminary arrangements and subdivision block approach in his Navy project work.

Students

6 students have worked on the project during the reporting period. Zhaokuan Lu completed his PhD in Aerospace Engineering and Mark Parsons completed an MS in Ocean Engineering .