Modeling Distributed Naval Ship Systems Using Architecture Flow Optimization

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ABSTRACT

Successful future surface combatants in the US Navy must embrace the growing integration and interdependency of propulsive and combat systems. Traditionally, the development of Hull, Mechanical and Electrical systems has been segregated from the development of weapons and sensors. However, with the incorporation of high energy weapons into future ship configurations, ship design processes must evolve to embrace the concept of a "System of Systems" being the only way to achieve affordable capability in our future fleets.

This thesis bridges the gap between the physical architecture of components within a ship and the way in which they are logically connected to model the energy flow through a representative design and provide insight into sizing requirements of both system components and their connections using an Architecture Flow Optimization (AFO).

This thesis presents a unique method and tool to optimize naval ship system logical and physical architecture considering necessary operational conditions and possible damage scenarios. The particular and unique contributions of this thesis are: 1) initially only energy flow is considered without explicit consideration of commodity flow (electric, mechanical, chilled water, etc.), which is calculated in post-processing; 2) AFO is applied to a large and complex naval surface combatant system of systems, demonstrating its scalability; 3) data necessary for the AFO is extracted directly from a naval ship synthesis model at a concept exploration level of detail demonstrating its value in early stage design; and 4) it uses network-based methods which make it adaptable to future knowledge-based network analysis methods and approaches.

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GENERAL AUDIENCE ABSTRACT

The US Navy faces a future where their ships will be required to perform a greater number and increasingly more diverse mission set while the resources provided to them dwindle. Traditionally, propulsive, electrical and weapons systems onboard ships have been segregated in their development, however, with the incorporation of high energy weapons into future ship configurations, the ship design processes must evolve to incorporate these interdependent power consumers. To take advantage of emerging technologies in a resource constrained environment, the future fleet of the US Navy must incorporate the concept of a "System of Systems" early in the ship design process.

This thesis correlates the energy available onboard a ship to how it can be distributed to components in the execution of required missions. Additionally, this thesis provides insight into the sizing requirements of intermediary and auxiliary components using an Architecture Flow Optimization (AFO) by only analyzing energy flow without considering the commodity flow (electricity, mechanical power, chilled water, etc.) which can be calculated post optimization. Using network-based methods allows the AFO to be adaptable to future knowledge-based network analysis methods and approaches while using data directly from a naval ship synthesis model enables the AFO to be scaled to incorporate a large and complex system of systems proving its value to early stage design.

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1 Introduction and Motivation

Naval ship design is one of the most complex and challenging endeavors attempted by engineers. A ship must operate in an unforgiving environment, while performing a mission and keeping the crew inside safe. To accomplish this, ships must be able to function in a multitude of different domains and be far more versatile than almost any other vehicle. Figure 1 shows a simplified ship design hierarchy which must be considered when designing a naval ship (A. Brown, Marine Engineering 2018).

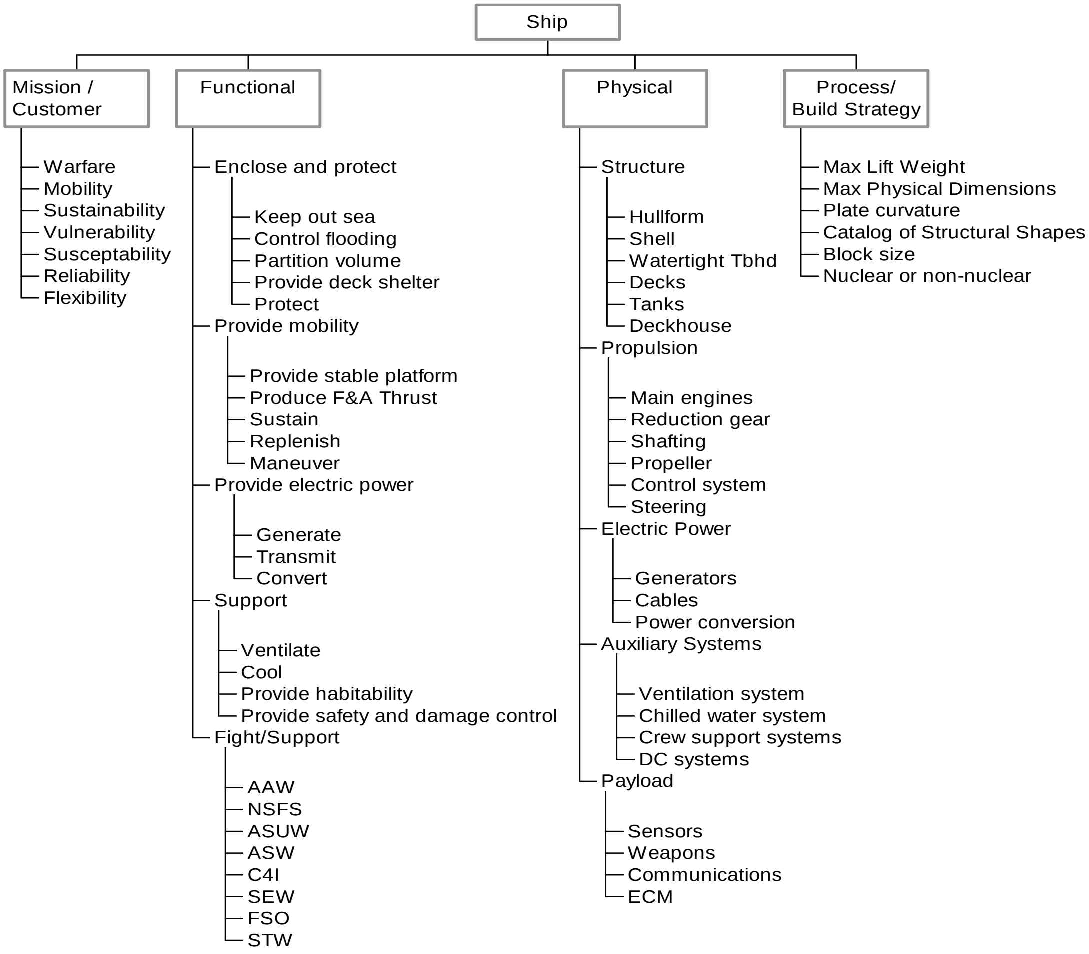


Figure 1 - Naval Ship Domain Hierarchy (A. Brown, Marine Engineering 2018)

Adding to the complexity of this hierarchy is the fact that power, propulsion and combat system design tasks and systems are becoming increasingly interdependent due to future plans for high energy weapons and sensors. The primary coupling for this interdependence is electric power and thermal management. Because of this interdependence, naval architects, marine engineers and combat system engineers must be in lockstep throughout the design process if the design is to be affordable, feasible and effective. This requires new tools and new attitudes!

This mindset for producing larger ships with additional capability at additional cost is at odds with the challenges associated with the fiscal realities of the modern world. The next generation of surface combatants will be asked to provide greater capabilities with fewer financial resources and thus require designers to think differently in search of a solution (Andrews 2003).

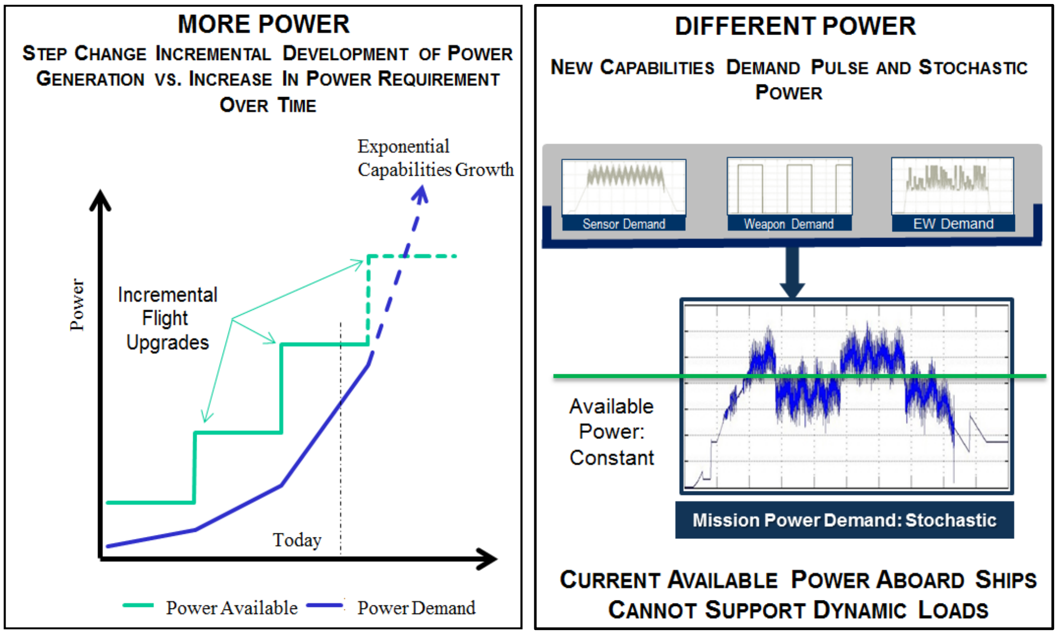
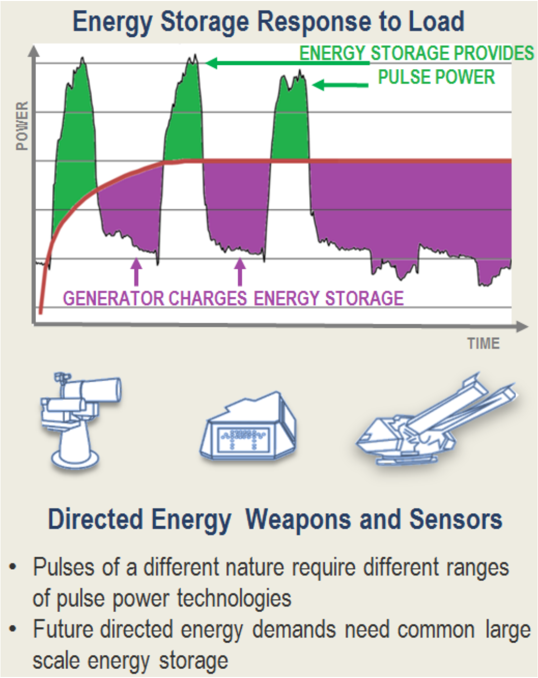


Figure 2 – More and Different Power Requirements over Time (Markle 2018)



- Pulses of a different nature require different ranges of pulse power technologies
- Future directed energy demands need common large scale energy storage

Figure 3 - Need for Energy Storage (Markle 2018)

This thesis introduces an innovative method of analyzing and optimizing total ship system energy flow for a representative ship design in a variety of user-defined scenarios, to reasonably estimate and optimize the effectiveness and affordability of a ship's system architecture and assess its ability to support high energy weapons systems in both normal and extemporaneous operational scenarios. By analyzing the quantity of energy flow and the required routing of energy to sustain operational requirements, the driving components of a design can be assessed for compatibility and the supporting power and energy systems can be sized and assessed for suitability within the design.

This is a big problem! Using a network architecture approach and framework to Integrate Combat, Power and Energy systems (CPES), the feasibility of a design can be decomposed, analyzed and improved early in the design process for both steady state and dynamic states in various operational environments and scenarios.

Automating this flow optimization to incorporate it in a total-ship set-based design process can ensure that system operability, survivability and affordability are designed into a ship during the early stages of ship design. The process presented in this thesis will describe and discuss the development of an architecture flow optimization tool that may be applied to a full design space of representative designs and subsequently used in the Concept and Requirements Exploration (C&RE) for a naval ship, particularly a naval surface combatant.

1.1 Architecture Framework

This section discusses the decomposition of ship systems' architecture into an architecture framework with three domains: Logical, Physical and Operational as shown in Figure 4.

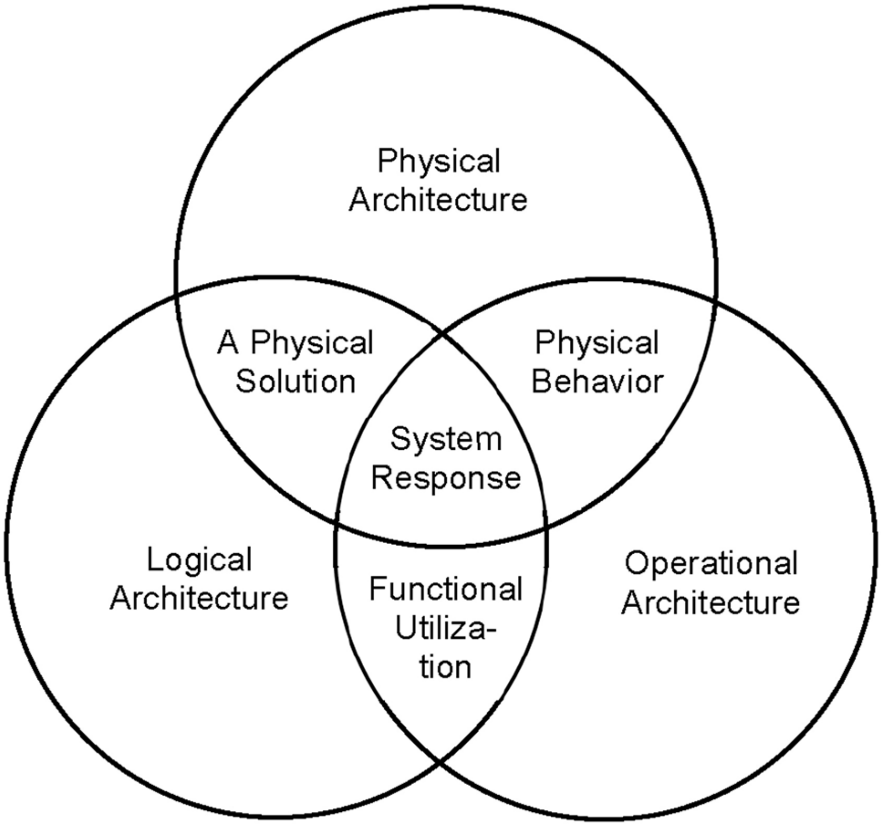


Figure 4 - Architecture Framework (Brefort, et al. 2017)

The physical architecture describes the ship spatial arrangement and the physical characteristics of system vital components and their inter-connecting media (pipes, cable, and shafting). Within the physical architecture are constraining relationships. These relationships describe how a potential design is impacted and limits the weight, space, stability and physical arrangement of potential vital components which can be placed onboard. These constraints are discussed in greater detail in Section 1.2 when discussing preliminary arrangements.

The logical architecture lists vital components and defines how these components are connected and dependent on each other. In a network representation of logical architecture, vital components are represented as nodes and connectivity is represented as arcs or edges (A. Brown, Marine Engineering 2018).

The operational architecture defines the missions, operational situations (OpSits) or scenarios, tasks and operational environment for the ship and ship systems. At the system level, this can be represented in many ways, such as electrical loads as shown in Figure 2, as required ship propulsion power, as damage resulting from weapon hits, as loss of components due to operational reliability, as hull flooding or as explosion shock effects. Systems must often be reconfigured to respond to these effects and this reconfiguration itself is part of the operational architecture (Markle 2018).

1.1.1 Logical Architecture of Ship Systems or Network Plexus

The mechanical (MECH) subsystem or plex shown in Figure 5Figure 6 transports energy as torque and shaft rotation from its initial conversion to mechanical energy (from chemical or electrical energy) in its application for propulsion. In the case study used in this thesis, the MECH plex is part of an Integrated Power System (IPS) where electrical energy is converted into propulsion mechanical energy in an electrical propulsion motor or propulsion motor module (PMM).

Figure 5 - Mechanical Plex Logical Architecture (A. Brown, Marine Engineering 2018)

The electric power (ELEC) subsystem or plex converts chemical energy from the Fuel Oil (FO) plex to electric energy with by-products of LO heat, HVAC heat and engine exhaust. The electrical plex is the most complex and most critical to the concept of an IPS ship. The electrical energy produced is used to provide propulsive power via the MECH system and to provide the electrical energy necessary to support high energy combat systems. Allowing the power generated to be used flexibly and applied to the warfare area most crucial to the situation at the moment.

Figure 6 shows a four-zone, P&S bus, electrical distribution architecture. This four-zone template is reflected throughout the other systems being modeled. Future versions of the ELEC plex will include stored energy and the ability to draw excess power as needed and store energy when power is in available in excess (A. Brown, Marine Engineering 2018).

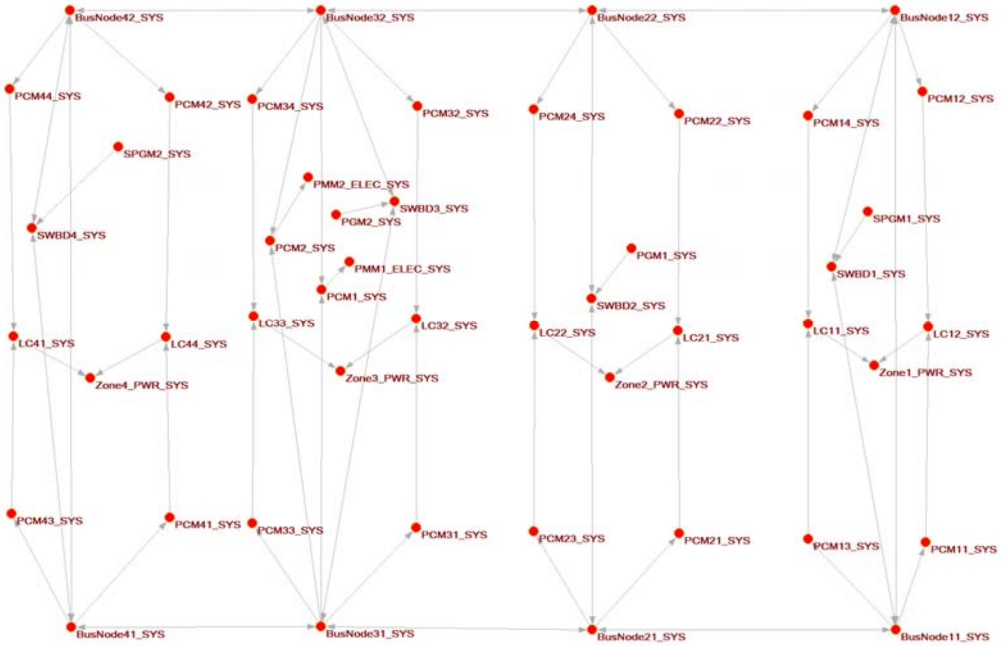


Figure 6 - Electrical Plex Logical Architecture (A. Brown, Marine Engineering 2018)

The Fuel Oil (FO) subsystem or plex transports chemical energy to the ELEC and MECH subsystems where it can be converted into mechanical or electrical energy. The FO subsystem as shown in Figure 7 draws fuel from a fuel source, through a transfer system, service tanks, and service system via a series of pumps and heaters. The FO pumps and heaters require electric power from their zonal electric systems which produce heat deposited into their zonal HVAC system (A. Brown, Marine Engineering 2018).

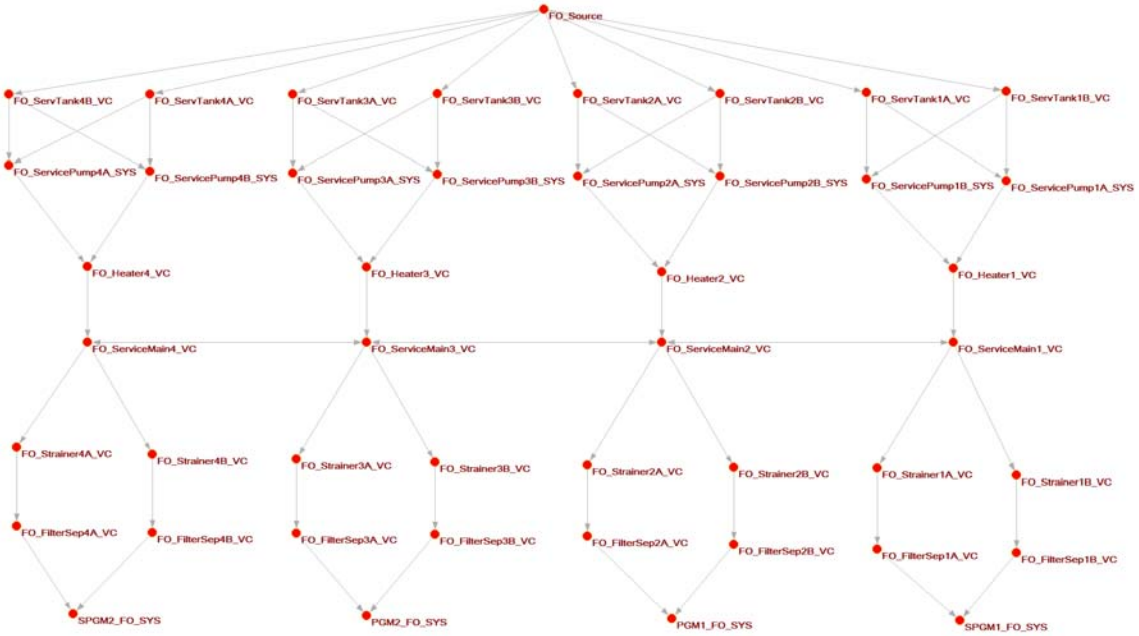


Figure 7 - Fuel Oil Plex Logical Architecture (A. Brown, Marine Engineering 2018)

The Lube Oil (LO) subsystem or plex is used both to lubricate the machinery operating throughout the ship and to carry thermal energy away from machinery to be transferred out of the ship by the SW system as shown in Figure 8. LO is circulated from sump tanks through strainers to the machinery and on to the SW cooler. LO pumps draw electrical energy from their zonal electric system and produce HVAC heat into their zonal HVAC system (A. Brown, Marine Engineering 2018).

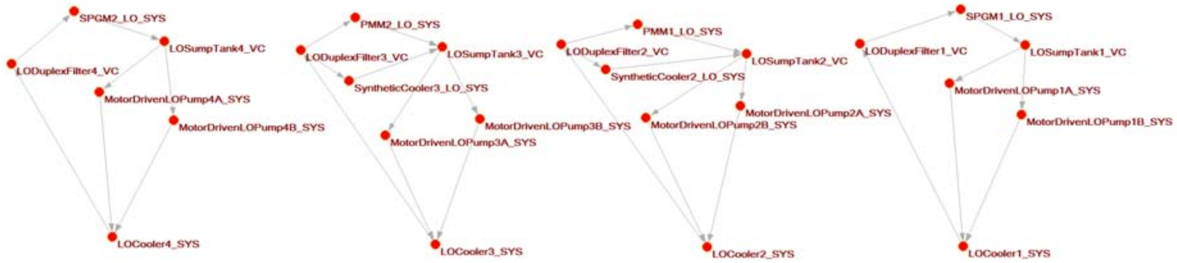


Figure 8 - Lube Oil Plex Logical Architecture (A. Brown, Marine Engineering 2018)

The Chill Water (CW) subsystem or plex transports chilled water throughout the ship to the four zones as shown in Figure 9. CW is circulated throughout the ship by pumps which require electric energy to operate and produces HVAC heat. CW acts as the primary means of cooling throughout the ship via distributed systems and consolidates the heat collected by the Electronic Cooling, Glycol and HVAC systems via a series of heat exchangers. CW then deposits the consolidated energy from these systems into the Hydroflurocarbon system. (A. Brown, Marine Engineering 2018).

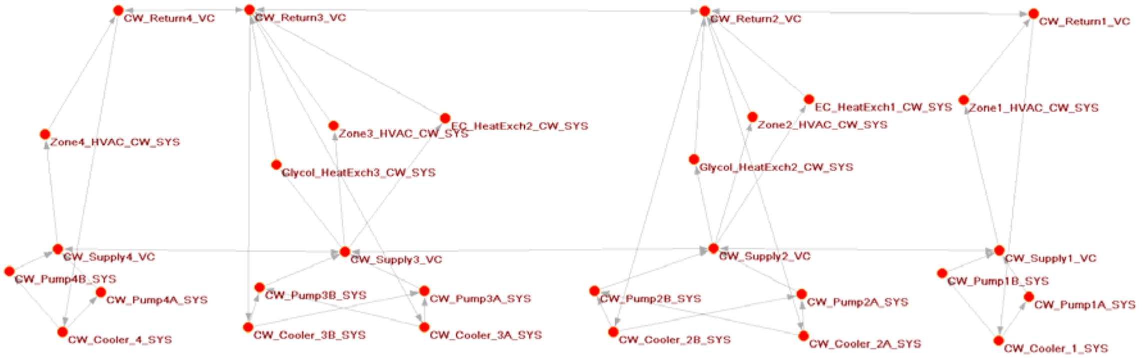


Figure 9 - Chill Water Plex Logical Architecture (A. Brown, Marine Engineering 2018)

The hydrofluorocarbon (HFC) subsystem or plex is the intermediary between the Salt Water (SW) plex and the CW plex as shown in Figure 10. The HFC plex collects thermal energy from the CW plex and transfers it into the SW plex via coolers and compressors. The compressors used in the HFC system receive their electric energy from zonal electrical nodes and deposit their byproducts into the zonal HVAC plex as thermal energy (A. Brown, Marine Engineering 2018).

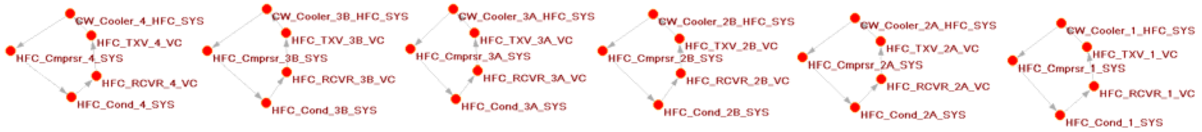


Figure 10 - Hydrofluorocarbon Logical Architecture (A. Brown, Marine Engineering 2018)

The Salt Water (SW) subsystem or plex shown in Figure 11 carries sea water from the external ocean (SW Source) through the ship collecting thermal energy from the LO and HFC systems and dispose of the thermal energy outside the ship via SW overboard (SW Sinks). SW is moved throughout the ship via a series of strainers and pumps which draw electric energy from the zonal electric components and produce thermal heat which goes into the zonal HVAC system when in operation (A. Brown, Marine Engineering 2018).

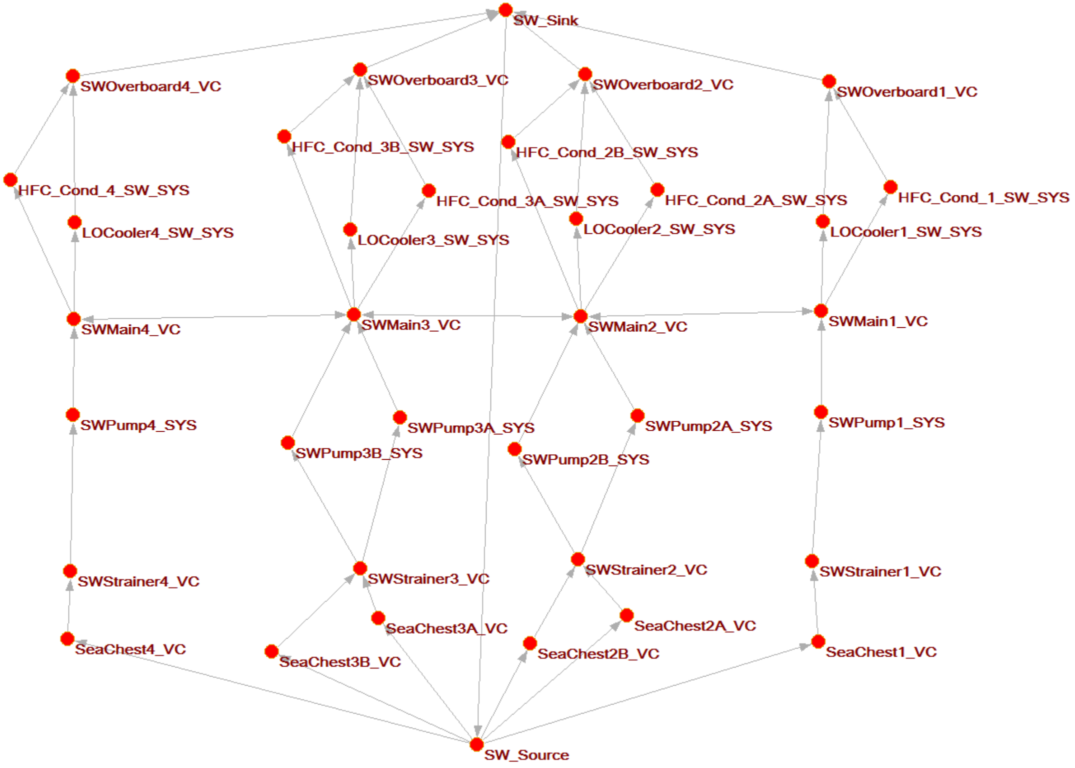


Figure 11 - Salt Water Plex Logical Architecture (A. Brown, Marine Engineering 2018)

The Electronic Cooling (EC) and Glycol sub systems and plexus shown in Figure 12 and Figure 13 respectively provide cooling for components that require a specialized system for high energy and sensitive equipment. EC uses deionized water to cool sensitive electronic equipment. Both systems circulate their fluid through heat exchangers, expansion tanks and circulation pumps which draw electric energy from the zonal electric system and disperse heat into the zonal HVAC system (A. Brown, Marine Engineering 2018).

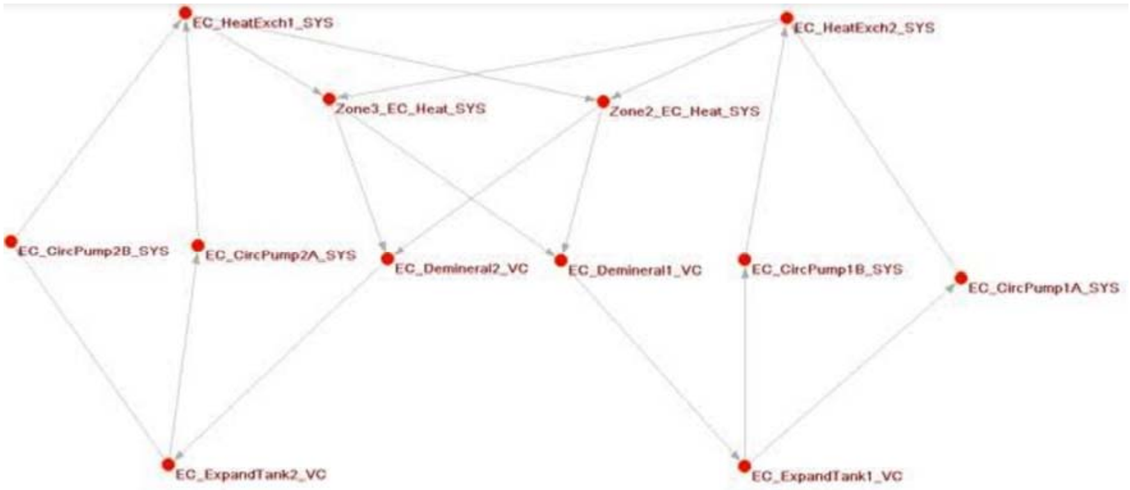


Figure 12 - Electronic Cooling Logical Architecture (A. Brown, Marine Engineering 2018)

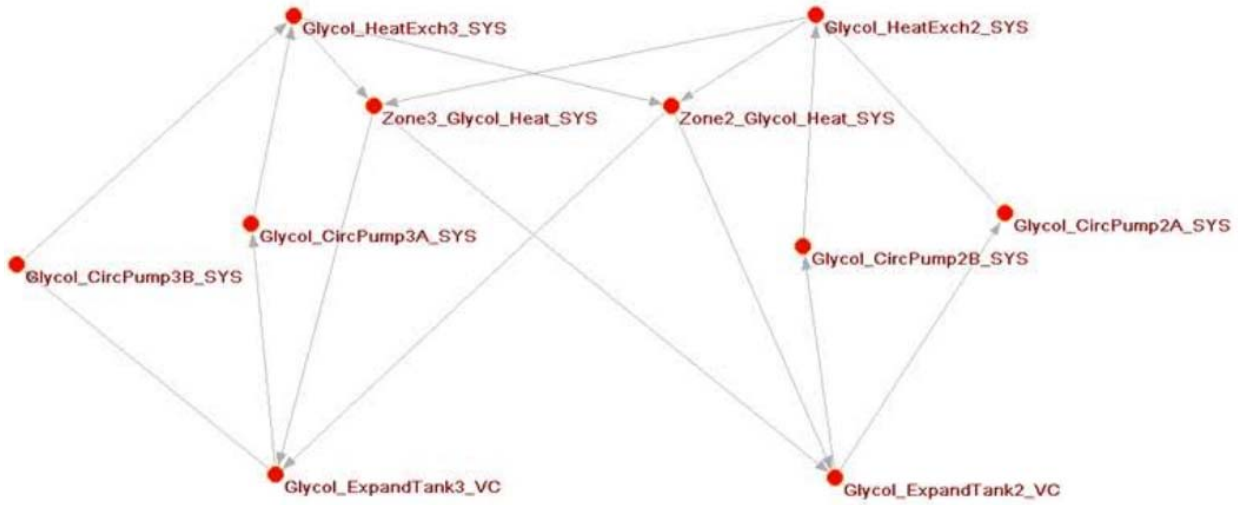


Figure 13 - Glycol Plex Logical Architecture (A. Brown, Marine Engineering 2018)

The Heating, Ventilation and Cooling (HVAC) subsystem or plex collects thermal energy in the air and either deposits it outside the ship to the external air or into the CW system via heat exchangers. The HVAC plex shown in Figure 14 is a four zonal system whose ventilation fans receive electrical energy from the zonal electric network (A. Brown, Marine Engineering 2018).

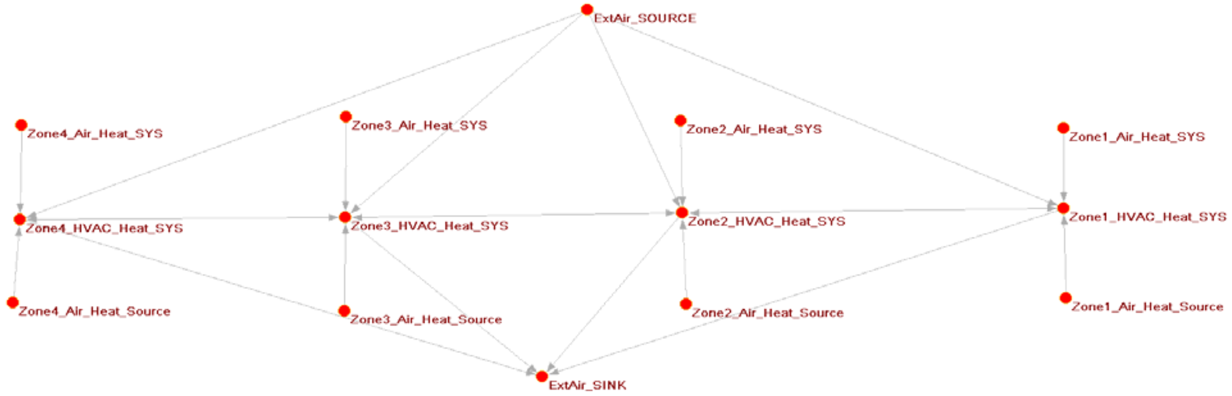


Figure 14 - HVAC Plex Logical Architecture (A. Brown, Marine Engineering 2018)

The machinery control (CONT) subsystem or plex shown in Figure 15 transports control and monitoring data between components throughout the ship. The CONT components require electrical energy to operate and radiate heat into the air and eventually the HVAC system. The data connectivity between the control network components is modeled as 1's or 0's, carrying information or not. The control plex provides ship-wide control for all mechanical and electrical components and can be monitored and accessed through displays and consoles throughout the ship. The control plex and the combat system plexus (AAW shown in Figure 16) function in a similar way (A. Brown, Marine Engineering 2018).

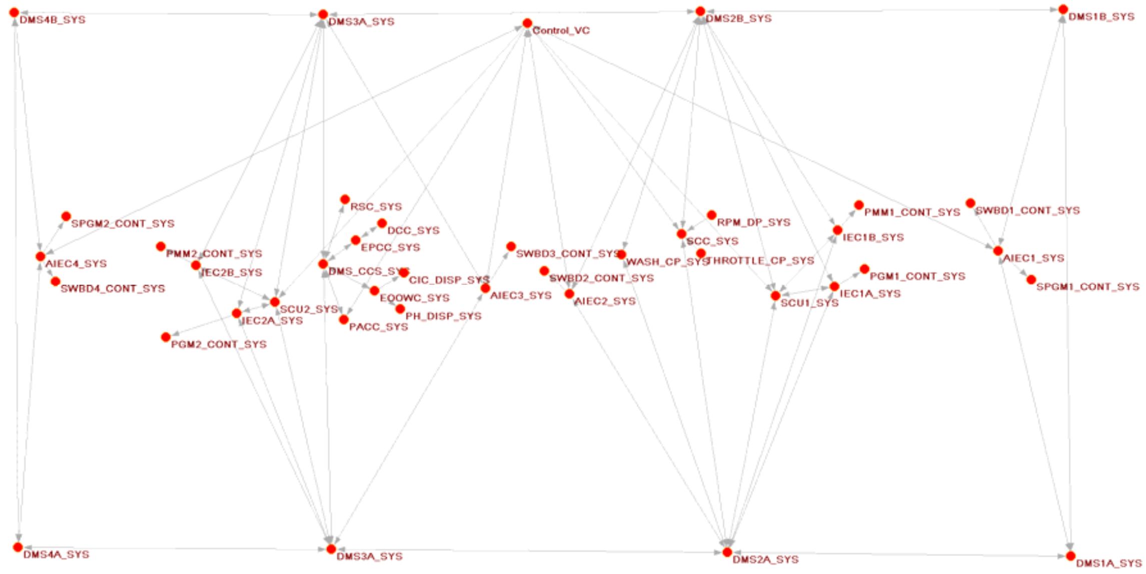


Figure 15 - Control Plex Logical Architecture (A. Brown, Marine Engineering 2018)

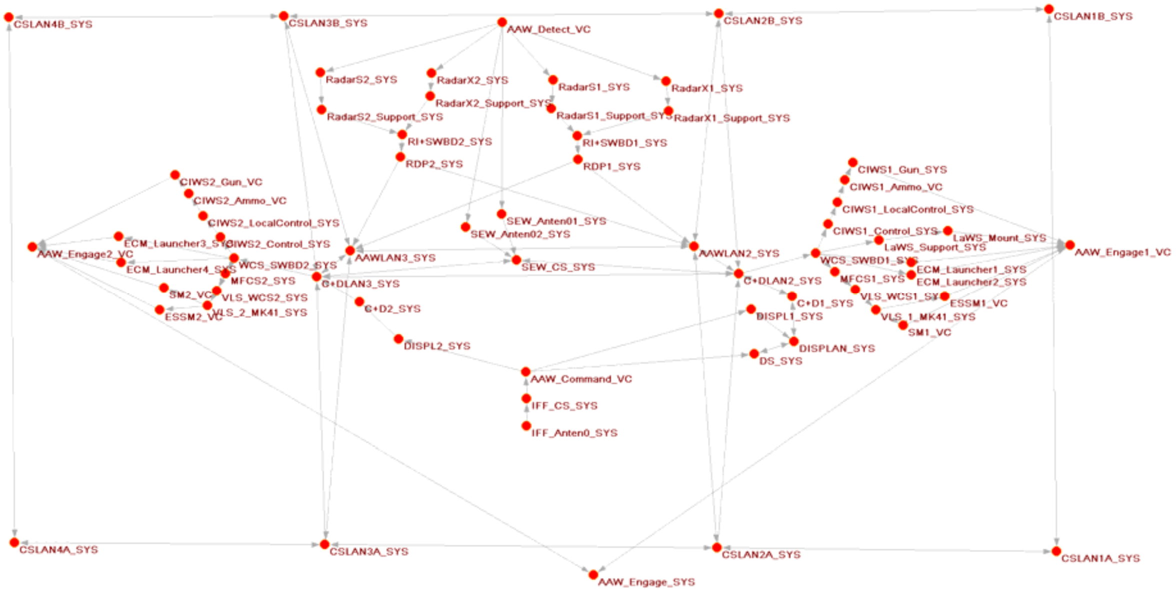


Figure 16 - Anti-Air Warfare Logical Architecture (A. Brown, Marine Engineering 2018)

Considering each of the individual plexus on their own allows designers to build very precise and detailed models for each of these systems, but fails to accurately project how impacts in one system affect the ability of another to contribute to the completion of the mission. Figure 17 is a logical representation of the total system of system plexus inside a ship and illustrates the interconnectedness between the plexus and how reliant each of them are on the other to function properly (A. Brown, Marine Engineering 2018).

An Integrated Power System (IPS) ship is an excellent example of the interdependency illustrated in Figure 4 and Figure 17 as components have tangible attributes, are located within the physical ship and are generally dependent upon each other to operate properly. The IPS ship is the focus of this thesis but the methods used here can also be applied to non-IPS ships.

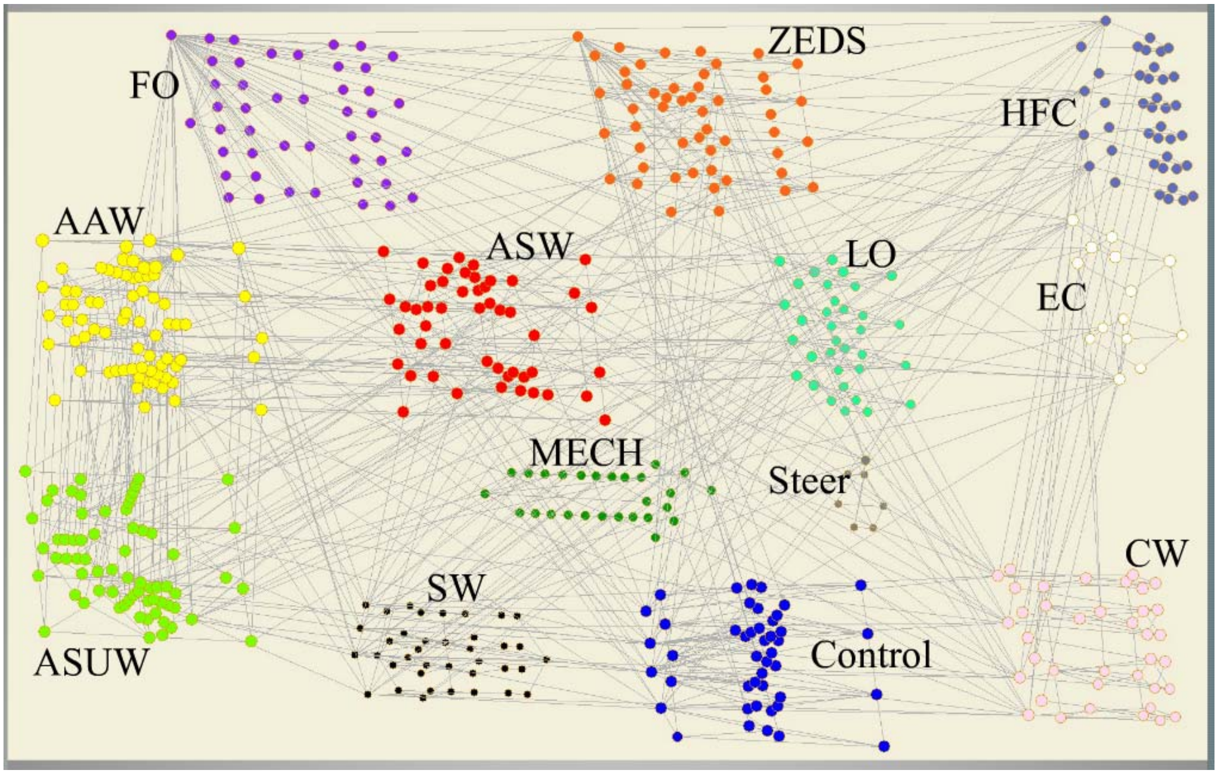
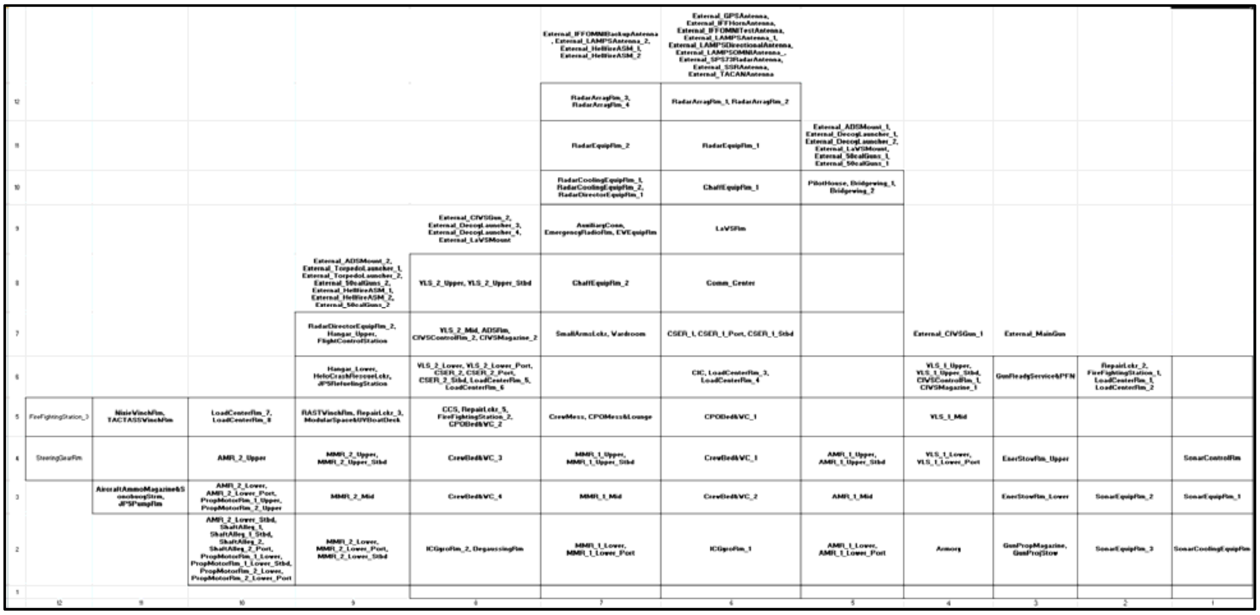


Figure 17 - Notional IPS Ship System Architecture (A. Brown, Marine Engineering 2018)

1.1.2 Physical Architecture

Within the logical architecture, physical components are represented as nodes within the ship. These nodes are assigned to compartments which are assigned to subdivision blocks which have a physical location within the ship as seen in Figure 18 (not to scale) and Figure 19. The connections between these nodes are called arcs and edges and represent the physical ties between components such as cables or piping similar to the configuration shown in Figure 20.



						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					
12						RadarArrayRm_3, RadarArrayRm_4	RadarArrayRm_1, RadarArrayRm_2					
11						RadarEquipRm_2	RadarEquipRm_1	External_ADSMount_1, External_DecoyLauncher_1, External_DecoyLauncher_2, External_LaVSMount, External_50calGuns_1, External_50calGuns_1				
10						RadarCoolingEquipRm_1, RadarCoolingEquipRm_2, RadarDirectorEquipRm_1	ChaffEquipRm_1	PilotHouse, Bridgewing_1, Bridgewing_2				
9					External_CIWSGun_2, External_DecoyLauncher_3, External_DecoyLauncher_4, External_LaVSMount	AuxiliaryConn, EmergencyRadioRm, EVEquipRm	LaVSRm					
8				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	ChaffEquipRm_2	Comm_Center					
7				RadarDirectorEquipRm_2, Hangar_Upper, FlightControlStation	VLS_2_Mid, ADSRm, CIWSControlRm_2, CIWSMagazine_2	SmallArmsLckr, Wardroom	CSER_1, CSER_1_Port, CSER_1_Stbd		External_CIWSGun_1	External_MainGun		
6				Hangar_Lower, HeloCrashRescueLckr, JP5RefuelingStation	VLS_2_Lower, VLS_2_Lower_Port, CSER_2, CSER_2_Port, CSER_2_Stbd, LoadCenterRm_5, LoadCenterRm_6		CIC, LoadCenterRm_3, LoadCenterRm_4		VLS_1_Upper, VLS_1_Upper_Stbd, CIWSControlRm_1, CIWSMagazine_1	GunReadyService&PFN	RepairLckr_2, FireFightingStation_1, LoadCenterRm_1, LoadCenterRm_2	
5	FireFightingStation_3	NixieWinchRm, TACTASSWinchRm	LoadCenterRm_7, LoadCenterRm_8	RASTWinchRm, RepairLckr_3, ModularSpace&UVBoatDeck	CCS, RepairLckr_5, FireFightingStation_2, CPOBed&WC_2	CrewMess, CPOMess&Lounge	CPOBed&WC_1		VLS_1_Mid			
4	SteeringGearRm		AMR_2_Upper	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_Lower, VLS_1_Lower_Port	EnerStowRm_Upper		SonarControlRm
3		AircraftAmmoMagazine&SonobuoyStrm, JP5PumpRm	AMR_2_Lower, AMR_2_Lower_Port, PropMotorRm_1_Upper, PropMotorRm_2_Upper	MMR_2_Mid	CrewBed&WC_4	MMR_1_Mid	CrewBed&WC_2	AMR_1_Mid		EnerStowRm_Lower	SonarEquipRm_2	SonarEquipRm_1
2			AMR_2_Lower_Stbd, ShaftAlley_1, ShaftAlley_1_Stbd, ShaftAlley_2, ShaftAlley_2_Port, PropMotorRm_1_Lower, PropMotorRm_1_Lower_Stbd, PropMotorRm_2_Lower, PropMotorRm_2_Lower_Port	MMR_2_Lower, MMR_2_Lower_Port, MMR_2_Lower_Stbd	ICGyroRm_2, DegaussingRm	MMR_1_Lower, MMR_1_Lower_Port	ICGyroRm_1	AMR_1_Lower, AMR_1_Lower_Port	Armory	GunPropMagazine, GunProjStow	SonarEquipRm_3	SonarCoolingEquipRm
1												
	12	11	10	9	8	7	6	5	4	3	2	1

Figure 18 – Compartments in Physical Architecture (A. Brown, Marine Engineering 2018)

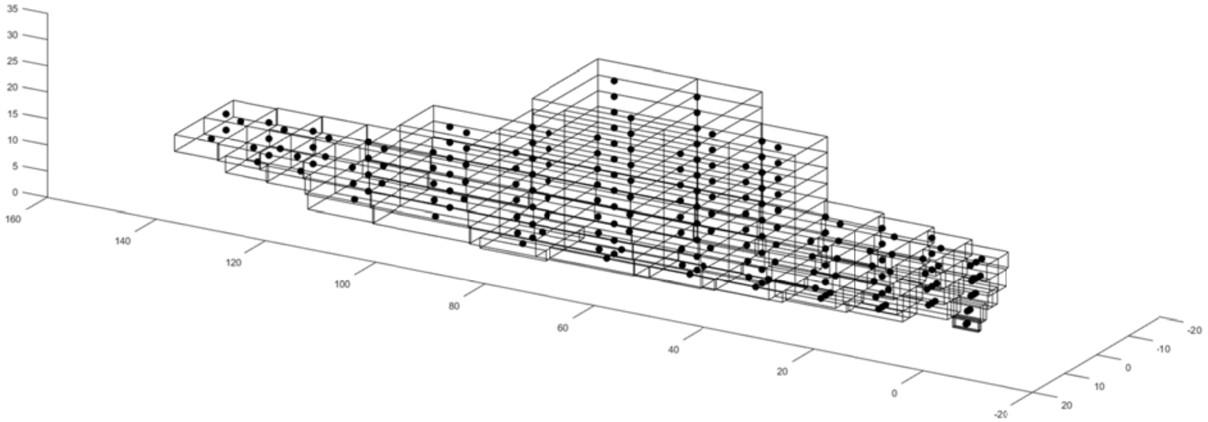


Figure 19 - 3D View of SDB Nodes

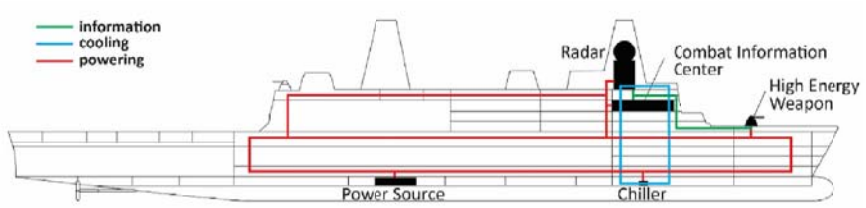


Figure 20 - Routing of Arcs between Nodes in a Distributed System (Brefort, et al. 2017)

1.2 Concept and Requirements Exploration (C&RE)

The Virginia Tech C&RE process shown in Figure 21 is initiated with an Initial Capabilities Document (ICD). In this document are specified required operational capabilities (ROCs), a list of the ship's expected operational situations (OpSits) and a Concept of Operations (CONOPS). Baseline and goal capabilities for the design are established in these documents. The combat, power and energy distributed systems (CPES) development process is shown in Figure 22 with an overlay of the architectural framework discussed in Section 1.1 and shown in Figure 4. CPES is a subset of the C&RE where an enhanced system engineering approach must be applied to design key systems which will drive the remainder of the design and architecture. In a future naval ship, this may include high energy weapons systems such as lasers and rail guns.

Arrangements and vulnerability of components and systems are highly interdependent. As components are placed throughout the ship, each location is more or less vulnerable to certain types of adversary weapons and understanding this can guide the location of compartment and components to minimize their vulnerability.

Referring to Figure 22, the CPES process begins with mission definition and the search for technologies and systems to provide required mission capabilities. Design options are identified and organized using design variables (DVs). In CPES design these include combat systems (AAW, ASW, ASUW) and power and energy systems (PSYS). Basic logical architectures must be developed for each of these DVs as shown in Figure 5 to Figure 16. Data for these systems and components including capacities, weight, space and power requirements is organized in a Machinery Equipment List (MEL) and Combat System Equipment List (CSEL). A hullform exploration is performed and a 3D hullform and deckhouse including subdivision and eventually subdivision blocks (SDBs) is generated as a representative design for a particular combination of system options. A preliminary arrangement is performed assigning ship compartments and their associated system vital components (VCs) to (SDBs). This is the initial physical architecture and it is intersected with the logical architecture through the assignment of VCs to SDBs. The ship synthesis model (SSM) (Figure 23) assembles the ship and organizes the necessary data required by the AFO.

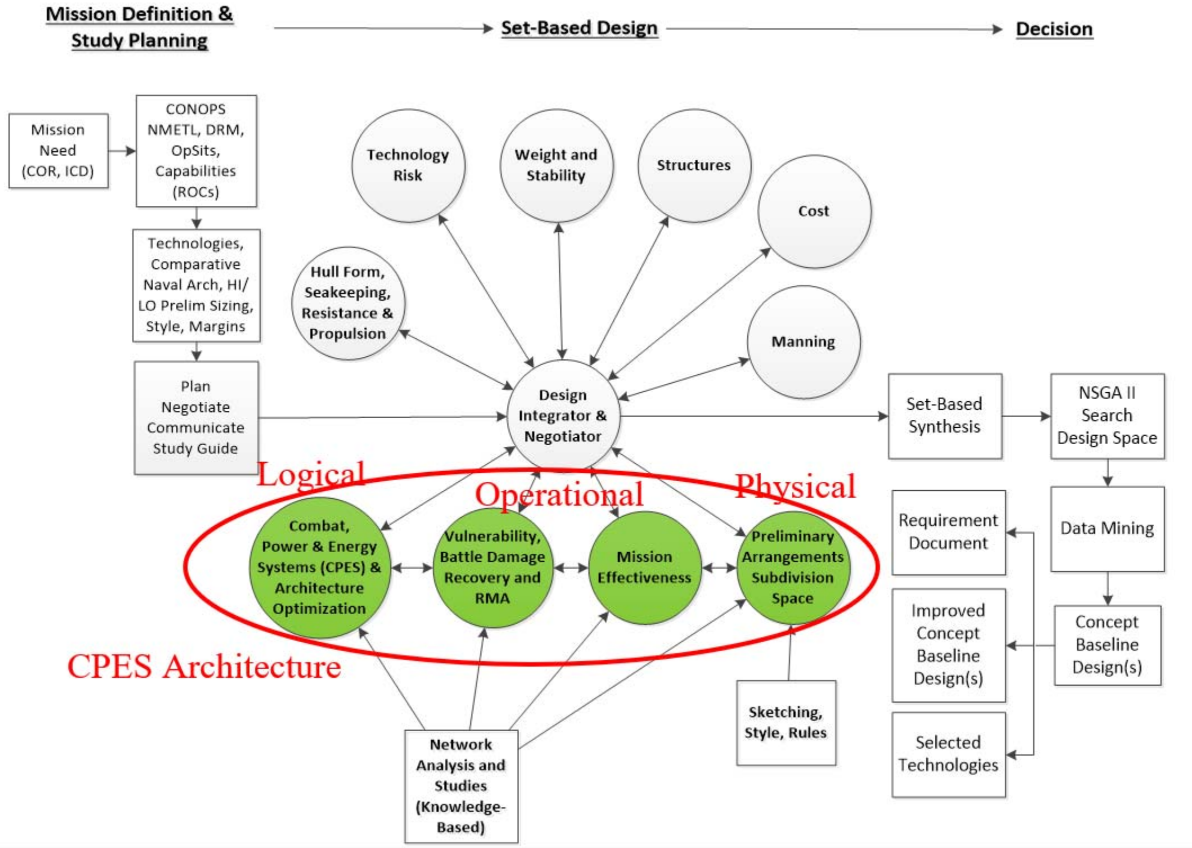


Figure 21 - Virginia Tech C&RE (A. Brown, Marine Engineering 2018)

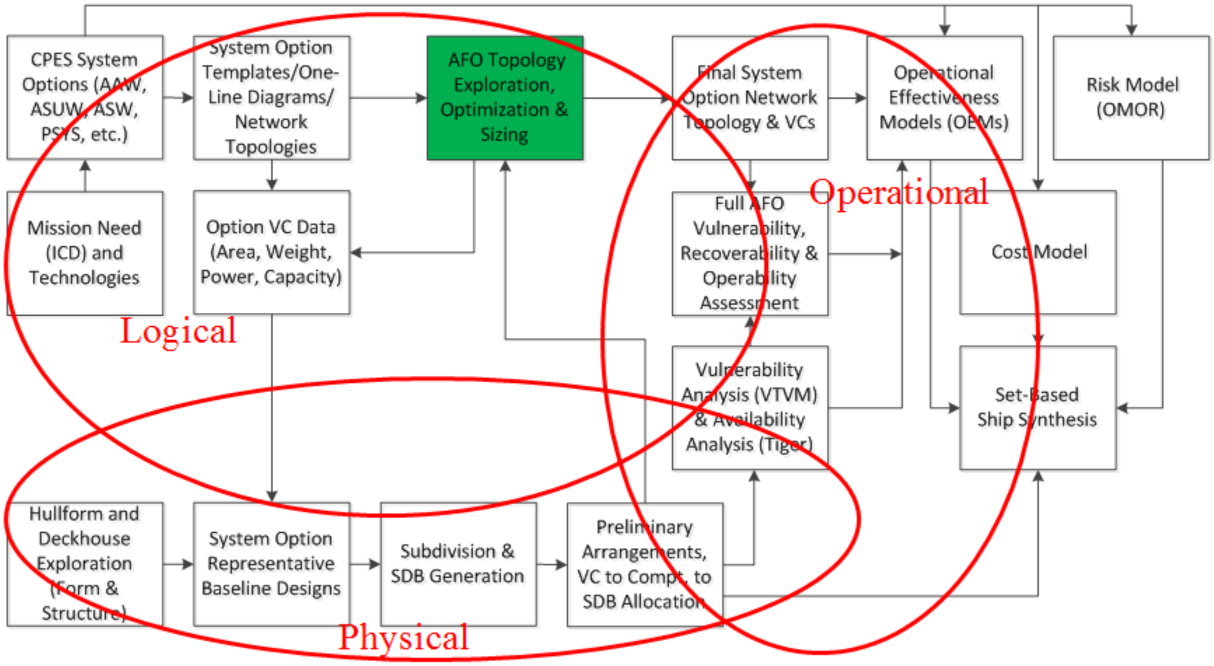
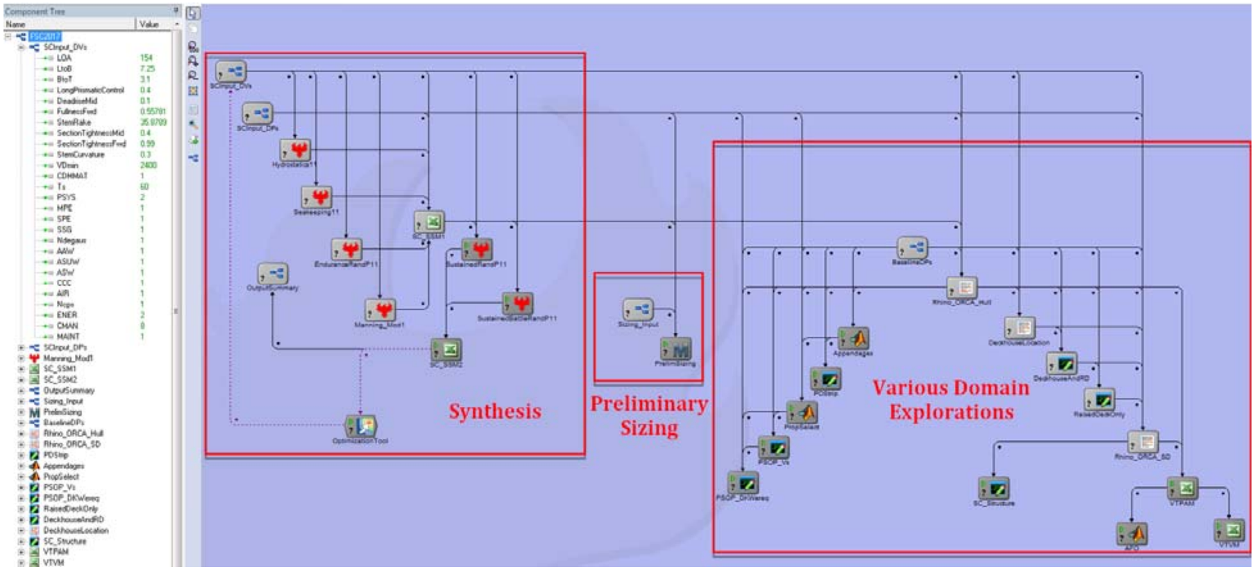


Figure 22 - CPES design process using architectural framework



Name	Value
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SCInput_DVs	
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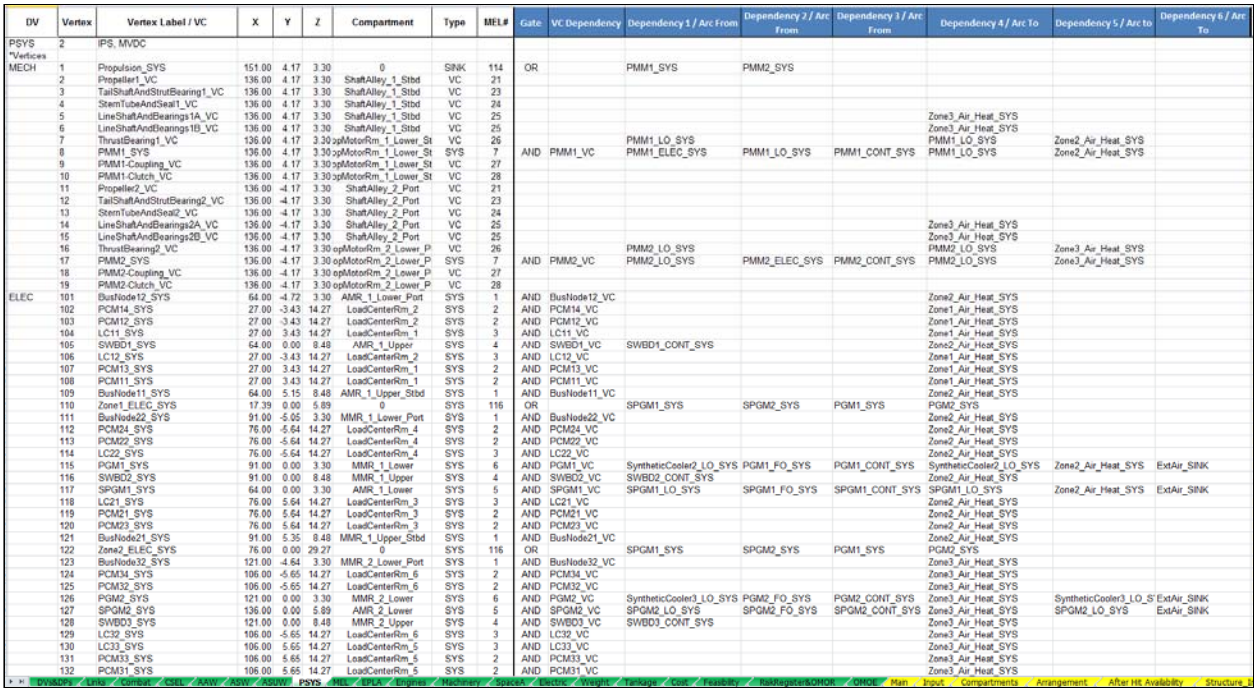
LtoB	7.25
BtoT	3.1
LongPrismaticControl	0.4
DeadriseMid	0.1
FullnessFwd	0.55781
StemRake	35.8709
SectionTightnessMid	0.4
SectionTightnessFwd	0.99
StemCurvature	0.3
VDmin	2400
CDHMAT	1
Ts	60
PSYS	2
MPE	1
SPE	1
SSG	1
Ndegaus	1
AAW	1
ASUW	1
ASW	1
CCC	1
AIR	1
Ncps	1
ENER	2
CMAN	0
MAINT	1
SCInput_DPs	
Manning_Mod1	
SC_SSM1	
SC_SSM2	
OutputSummary	
Sizing_Input	
PrelimSizing	
BaselineDPs	
Rhino_ORCA_Hull	
Rhino_ORCA_SD	
PDSimp	
Appendages	
PropSelect	
PSOP_Vs	
PSOP_DKWeeq	
RaisedDeckOnly	
DeckhouseAndRD	
DeckhouseLocation	
SC_Structure	
VTPAM	
VTVM	

Figure 23 - Ship Synthesis & Exploration Model Environment (SSM)

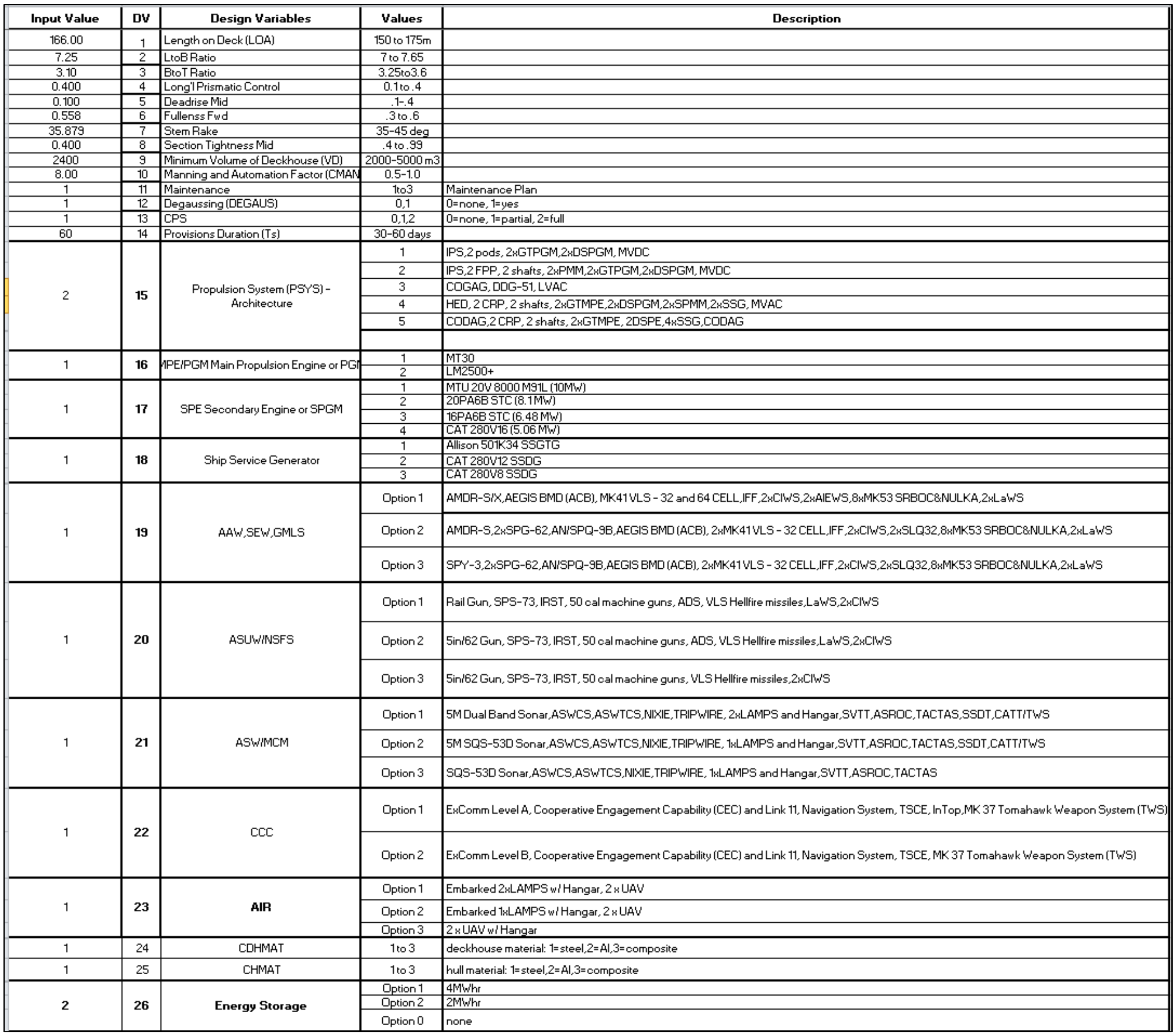


DV	Vertex	Vertex Label / VC	X	Y	Z	Compartment	Type	MEL#	Gate	VC Dependency	Dependency 1 / Arc From	Dependency 2 / Arc From	Dependency 3 / Arc From	Dependency 4 / Arc To	Dependency 5 / Arc to	Dependency 6 / Arc To
PSYS	2	IPS, MVDC														
*Vertices																
MECH	1	Propulsion_SYS	151.00	4.17	3.30	0	SINK	114	OR		PMM1_SYS	PMM2_SYS				
	2	Propeller1_VC	136.00	4.17	3.30	ShaftAlley_1_Stbd	VC	21								
	3	TailShaftAndStrutBearing1_VC	136.00	4.17	3.30	ShaftAlley_1_Stbd	VC	23								
	4	SternTubeAndSeal1_VC	136.00	4.17	3.30	ShaftAlley_1_Stbd	VC	24								
	5	LineShaftAndBearings1A_VC	136.00	4.17	3.30	ShaftAlley_1_Stbd	VC	25						Zone3_Air_Heat_SYS		
	6	LineShaftAndBearings1B_VC	136.00	4.17	3.30	ShaftAlley_1_Stbd	VC	25						Zone3_Air_Heat_SYS		
	7	ThrustBearing1_VC	136.00	4.17	3.30	ɔpMotorRm_1_Lower_St	VC	26			PMM1_LO_SYS			PMM1_LO_SYS	Zone2_Air_Heat_SYS	
	8	PMM1_SYS	136.00	4.17	3.30	ɔpMotorRm_1_Lower_St	SYS	7	AND	PMM1_VC	PMM1_ELEC_SYS	PMM1_LO_SYS	PMM1_CONT_SYS	PMM1_LO_SYS	Zone2_Air_Heat_SYS	
	9	PMM1-Coupling_VC	136.00	4.17	3.30	ɔpMotorRm_1_Lower_St	VC	27								
	10	PMM1-Clutch_VC	136.00	4.17	3.30	ɔpMotorRm_1_Lower_St	VC	28								
	11	Propeller2_VC	136.00	-4.17	3.30	ShaftAlley_2_Port	VC	21								
	12	TailShaftAndStrutBearing2_VC	136.00	-4.17	3.30	ShaftAlley_2_Port	VC	23								
	13	SternTubeAndSeal2_VC	136.00	-4.17	3.30	ShaftAlley_2_Port	VC	24								
	14	LineShaftAndBearings2A_VC	136.00	-4.17	3.30	ShaftAlley_2_Port	VC	25						Zone3_Air_Heat_SYS		
	15	LineShaftAndBearings2B_VC	136.00	-4.17	3.30	ShaftAlley_2_Port	VC	25						Zone3_Air_Heat_SYS		
	16	ThrustBearing2_VC	136.00	-4.17	3.30	opMotorRm_2_Lower_P	VC	26			PMM2_LO_SYS			PMM2_LO_SYS	Zone3_Air_Heat_SYS	
	17	PMM2_SYS	136.00	-4.17	3.30	opMotorRm_2_Lower_P	SYS	7	AND	PMM2_VC	PMM2_LO_SYS	PMM2_ELEC_SYS	PMM2_CONT_SYS	PMM2_LO_SYS	Zone3_Air_Heat_SYS	
	18	PMM2-Coupling_VC	136.00	-4.17	3.30	opMotorRm_2_Lower_P	VC	27								
	19	PMM2-Clutch_VC	136.00	-4.17	3.30	opMotorRm_2_Lower_P	VC	28								
ELEC	101	BusNode12_SYS	64.00	-4.72	3.30	AMR_1_Lower_Port	SYS	1	AND	BusNode12_VC				Zone2_Air_Heat_SYS		
	102	PCM14_SYS	27.00	-3.43	14.27	LoadCenterRm_2	SYS	2	AND	PCM14_VC				Zone1_Air_Heat_SYS		
	103	PCM12_SYS	27.00	-3.43	14.27	LoadCenterRm_2	SYS	2	AND	PCM12_VC				Zone1_Air_Heat_SYS		
	104	LC11_SYS	27.00	3.43	14.27	LoadCenterRm_1	SYS	3	AND	LC11_VC				Zone1_Air_Heat_SYS		
	105	SWBD1_SYS	64.00	0.00	8.48	AMR_1_Upper	SYS	4	AND	SWBD1_VC	SWBD1_CONT_SYS			Zone2_Air_Heat_SYS		
	106	LC12_SYS	27.00	-3.43	14.27	LoadCenterRm_2	SYS	3	AND	LC12_VC				Zone1_Air_Heat_SYS		
	107	PCM13_SYS	27.00	3.43	14.27	LoadCenterRm_1	SYS	2	AND	PCM13_VC				Zone1_Air_Heat_SYS		
	108	PCM11_SYS	27.00	3.43	14.27	LoadCenterRm_1	SYS	2	AND	PCM11_VC				Zone1_Air_Heat_SYS		
	109	BusNode11_SYS	64.00	5.15	8.48	AMR_1_Upper_Stbd	SYS	1	AND	BusNode11_VC				Zone2_Air_Heat_SYS		
	110	Zone1_ELEC_SYS	17.39	0.00	5.89	0	SYS	116	OR		SPGM1_SYS	SPGM2_SYS	PGM1_SYS	PGM2_SYS		
	111	BusNode22_SYS	91.00	-5.05	3.30	MMR_1_Lower_Port	SYS	1	AND	BusNode22_VC				Zone2_Air_Heat_SYS		
	112	PCM24_SYS	76.00	-5.64	14.27	LoadCenterRm_4	SYS	2	AND	PCM24_VC				Zone2_Air_Heat_SYS		
	113	PCM22_SYS	76.00	-5.64	14.27	LoadCenterRm_4	SYS	2	AND	PCM22_VC				Zone2_Air_Heat_SYS		
	114	LC22_SYS	76.00	-5.64	14.27	LoadCenterRm_4	SYS	3	AND	LC22_VC				Zone2_Air_Heat_SYS		
	115	PGM1_SYS	91.00	0.00	3.30	MMR_1_Lower	SYS	6	AND	PGM1_VC	SyntheticCooler2_LO_SYS	PGM1_FO_SYS	PGM1_CONT_SYS	SyntheticCooler2_LO_SYS	Zone2_Air_Heat_SYS	ExtAir_SINK
	116	SWBD2_SYS	91.00	0.00	8.48	MMR_1_Upper	SYS	4	AND	SWBD2_VC	SWBD2_CONT_SYS			Zone2_Air_Heat_SYS		
	117	SPGM1_SYS	64.00	0.00	3.30	AMR_1_Lower	SYS	5	AND	SPGM1_VC	SPGM1_LO_SYS	SPGM1_FO_SYS	SPGM1_CONT_SYS	SPGM1_LO_SYS	Zone2_Air_Heat_SYS	ExtAir_SINK
	118	LC21_SYS	76.00	5.64	14.27	LoadCenterRm_3	SYS	3	AND	LC21_VC				Zone2_Air_Heat_SYS		
	119	PCM21_SYS	76.00	5.64	14.27	LoadCenterRm_3	SYS	2	AND	PCM21_VC				Zone2_Air_Heat_SYS		
	120	PCM23_SYS	76.00	5.64	14.27	LoadCenterRm_3	SYS	2	AND	PCM23_VC				Zone2_Air_Heat_SYS		
	121	BusNode21_SYS	91.00	5.35	8.48	MMR_1_Upper_Stbd	SYS	1	AND	BusNode21_VC				Zone2_Air_Heat_SYS		
	122	Zone2_ELEC_SYS	76.00	0.00	29.27	0	SYS	116	OR		SPGM1_SYS	SPGM2_SYS	PGM1_SYS	PGM2_SYS		
	123	BusNode32_SYS	121.00	-4.64	3.30	MMR_2_Lower_Port	SYS	1	AND	BusNode32_VC				Zone3_Air_Heat_SYS		
	124	PCM34_SYS	106.00	-5.65	14.27	LoadCenterRm_6	SYS	2	AND	PCM34_VC				Zone3_Air_Heat_SYS		
	125	PCM32_SYS	106.00	-5.65	14.27	LoadCenterRm_6	SYS	2	AND	PCM32_VC				Zone3_Air_Heat_SYS		
	126	PGM2_SYS	121.00	0.00	3.30	MMR_2_Lower	SYS	6	AND	PGM2_VC	SyntheticCooler3_LO_SYS	PGM2_FO_SYS	PGM2_CONT_SYS	Zone3_Air_Heat_SYS	SyntheticCooler3_LO_S	ExtAir_SINK
	127	SPGM2_SYS	136.00	0.00	5.89	AMR_2_Lower	SYS	5	AND	SPGM2_VC	SPGM2_LO_SYS	SPGM2_FO_SYS	SPGM2_CONT_SYS	Zone3_Air_Heat_SYS	SPGM2_LO_SYS	ExtAir_SINK
	128	SWBD3_SYS	121.00	0.00	8.48	MMR_2_Upper	SYS	4	AND	SWBD3_VC	SWBD3_CONT_SYS			Zone3_Air_Heat_SYS		
	129	LC32_SYS	106.00	-5.65	14.27	LoadCenterRm_6	SYS	3	AND	LC32_VC				Zone3_Air_Heat_SYS		
	130	LC33_SYS	106.00	5.65	14.27	LoadCenterRm_5	SYS	3	AND	LC33_VC				Zone3_Air_Heat_SYS		
	131	PCM33_SYS	106.00	5.65	14.27	LoadCenterRm_5	SYS	2	AND	PCM33_VC				Zone3_Air_Heat_SYS		
	132	PCM31_SYS	106.00	5.65	14.27	LoadCenterRm_5	SYS	2	AND	PCM31_VC				Zone3_Air_Heat_SYS		

Figure 24 - Ship Synthesis & Exploration Model Environment (SSM) Worksheets

1.2.1 Ship Synthesis Model (SSM)

The Ship Synthesis Model (SSM) shown in Figure 23 and Figure 24 is a repository and integration tool for all components and information pertaining to a design. Referring to the worksheet tabs in Figure 24 starting with DVs&DPs, Design Variables (DVs) are utilized to define characteristics and key architectural decisions in the physical, logical and operational domains. DV's are bound by either a continuous range of potential values or assigned discrete integer values for evaluation as shown in Figure 25 which is the input for the IPS case study described in Chapter 4. Physically, DVs modify the hull form and select specific components and large pieces of machinery for inclusion in the design. Logically, DVs determine which logical architecture is utilized for evaluation within each of the warfighting areas and power and energy systems.



Input Value	DV	Design Variables	Values	Description
166.00	1	Length on Deck (LOA)	150 to 175m	
7.25	2	LtoB Ratio	7 to 7.65	
3.10	3	BtoT Ratio	3.25to3.6	
0.400	4	Long'l Prismatic Control	0.1 to .4	
0.100	5	Deadrise Mid	.1-.4	
0.558	6	Fullenss Fwd	.3 to .6	
35.879	7	Stem Rake	35-45 deg	
0.400	8	Section Tightness Mid	.4 to .99	
2400	9	Minimum Volume of Deckhouse (VD)	2000-5000 m3	
8.00	10	Manning and Automation Factor (CMAN	0.5-1.0	
1	11	Maintenance	1to3	Maintenance Plan
1	12	Degaussing (DEGAUS)	0,1	0=none, 1=yes
1	13	CPS	0,1,2	0=none, 1=partial, 2=full
60	14	Provisions Duration (Ts)	30-60 days	
2	**15**	Propulsion System (PSYS) - Architecture	1	IPS,2 pods, 2xGTPGM,2xDSPGM, MVDC
			2	IPS,2 FPP, 2 shafts, 2xPMM,2xGTPGM,2xDSPGM, MVDC
			3	COGAG, DDG-51, LVAC
			4	HED, 2 CRP, 2 shafts, 2xGTMPE,2xDSPGM,2xSPMM,2xSSG, MVAC
			5	CODAG,2 CRP, 2 shafts, 2xGTMPE, 2DSPE,4xSSG,CODAG
1	**16**	PE/PGM Main Propulsion Engine or PG	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
1	24	CDHMAT	1 to 3	deckhouse material: 1=steel,2=Al,3=composite
1	25	CHMAT	1 to 3	hull material: 1=steel,2=Al,3=composite
2	**26**	**Energy Storage**	Option 1	4MWhr
			Option 2	2MWhr
			Option 0	none

Figure 25 - SSM DV Input Worksheet for Chapter 4 Case Study

Design Parameters (DPs) are stored in the same SSM sheet as the DV's and specify other parameter values that remain constant for all designs.

Data from response surface models (RSMs) which approximate response characteristics based on DV and DP values are collected in the Links worksheet. RSM's included in the analysis of a representative design are developed in Hullform and other explorations shown in Figure 23 and rapidly calculate data for the design including hydrostatic and seakeeping characteristics, resistance and propulsion power requirements for the hull at various speeds, and manning requirements.

The Engines worksheet contains manufacturer's engine and generator set data including weight, volume, footprint area, maximum continuous rating, specific fuel consumption, and inlet and exhaust requirements. This information is available to be extracted based on the DV values chosen for the design.

The Combat System Equipment List (CSEL) worksheet provides data for Combat System components physical and operational characteristics including weight, volume, arrangeable area and power requirements for both cruise and battle conditions. Based upon the DVs selected, this information is populated into other areas of the SSM for analysis and assessment of their impact on the design.

The Machinery Equipment List (MEL) performs a similar function as the CSEL. The MEL contains a list of 125 component types which are available for estimating the design's machinery characteristics and specifying its energy flow characteristics in a coefficient matrix. Based on the PSYS and engine DV values selected, data will populate the PSYS worksheet architecture template in the PSYS worksheet for use in the design. Engine data is first pulled into the MEL and then loaded into the PSYS worksheet.

The PSYS tab contains multiple architecture templates for use in a network architecture evaluation. The PSYS tab is populated from the MEL tab with data pertaining to the physical, operational and logical properties of the components. The PSYS table specifies the logical architecture for all power and energy system options and subsystems including components (nodes), explicit arcs between nodes of the same plex, implicit dependencies or arcs to nodes of different plexus and assigned compartments in the physical architecture. Baseline component data from the MELs is resized based on the AFO and the resulting component characteristics are stored in another template in the PSYS worksheet. Electric loads are also determined in the AFP and stored in the PSY worksheet. This data and worksheet are critical to the AFO. Figure 24 shows a sample of the PSYS data.

Combat system logical architectures are specified in three worksheets: Anti-Air Warfare (AAW), Anti-Surface Warfare (ASUW), and Anti-Submarine Warfare (ASW). Each of these worksheets contains architectures (nodes and arcs) for three options or levels of capability. Each of these worksheets are populated from the CSEL worksheet based on the DV options specified.

The Combat and Machinery worksheets consolidate information from the PSYS and Combat System tabs for evaluation including SWBS weights, SSCS space and electric power requirements. These results and the manning estimate from the Manning RSM are used to calculate electrical loads, balance the ship and assess its feasibility for space, power, weight/buoyancy and stability.

The Electric worksheet calculates electric loads and heat loads for all components in the ship not explicitly considered in the AFO. It then calculates auxiliary machinery room volume and final manning for the ship.

The SpaceA and Tankage worksheets calculate volume and arrangeable area available in the ship and the space required for non-AFO systems and tankage. The tankage worksheet also calculates endurance range and life-cycle fuel requirements and data. The Weights worksheet calculates and sums weights and estimated and estimated COGs to assess their impact on stability and seakeeping.

Cost, effectiveness (OMOE), risk (OMOR) and Feasibility are calculated and assessed in the remaining SSM worksheets.

1.2.2 Preliminary Arrangements Model (VTPAM)

VTPAM calculates ship space and area requirements, creates subdivision within the hull and deckhouse considering the number of damage control zones specified, and generates subdivision blocks (SDBs) in the 3D geometry (Figure 26). It calculates SDB hit probabilities for a series of warfighting scenarios and then assigns compartments to SDBs based on operability priorities and preferences, available area, and SDB hit probability. This process results in a preliminary arrangement concept of compartments assigned to SDBs in “two and a half dimensions” as shown in Figure 18.

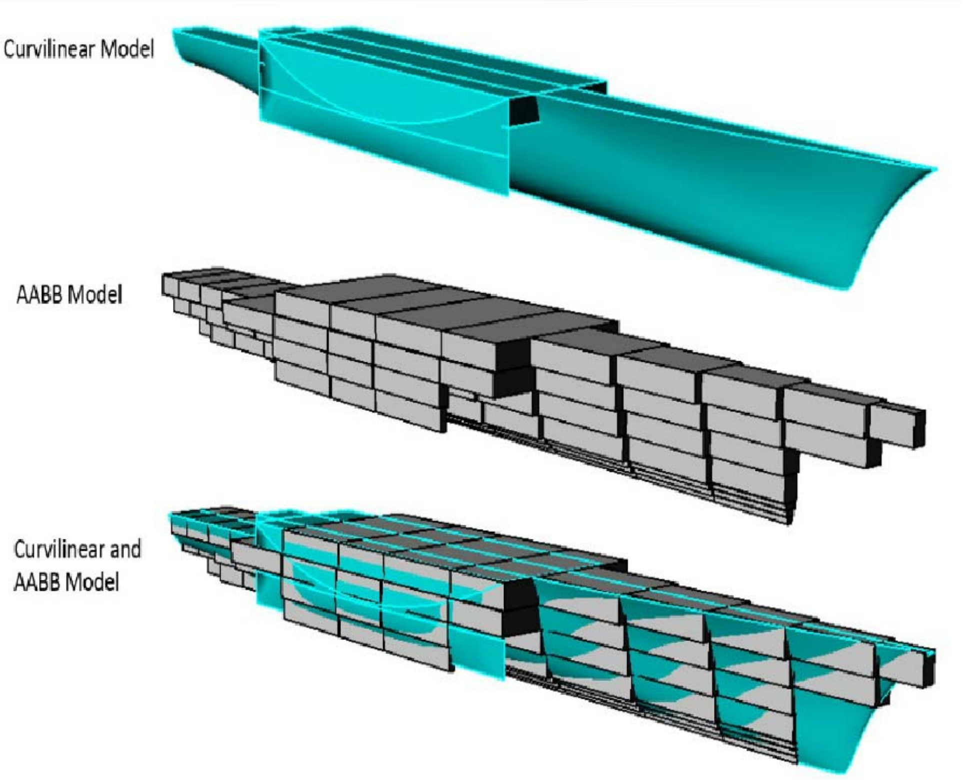


Figure 26 - AABBs overlaid with Curvilinear hull example (Goodfriend 2015)

Vital Components (VCs) are assigned to compartments in the SSM PSYS and Combat System worksheets. This compartment assignment is mapped to the SDB physical architecture effectively assigning VCs to SDBs and locating all VCs within the ship.

1.3 Thesis Outline

Chapter 1 discusses the motivation for this research and introduces the Architecture Framework, and the VT Concept and Requirements Exploration (C&RE) and CPES processes with their related tools including the SSM and VTPAM. This provides the context and input required for the AFO which is presented in the remaining chapters.

Chapter 2 provides a brief introduction to the mathematical foundations of the optimization process and the basics of linear programing (LP), network flow and non-simultaneous multi-commodity flow as developed as applied by Trapp.

Chapter 3 describes the AFO including its fundamental equations and application to ship system design.

Chapter 4 presents a case study and discusses the results of a network flow optimization.

Chapter 5 describes conclusions about the AFO and how it can be integrated into the Virginia Tech C&RE ship design process. It also provides recommendations for further analysis, development and study.

2 Network Optimization

The purpose of an optimization is to define and select the best feasible solution from a set of potential solutions. Optimization techniques have been long-used in transportation networks such as shipping or air travel and widely used in manufacturing and the flow of inventory through production lines (Ashish, Chapter 5 Network Flows 2008). Telecommunications companies have also incorporated network flow to manage the transfer of information across a network, to analyze the ability to expand a network and to study the impacts of capability loss and network mesh adaptability (Konak 2006), (Chinneck 2017), (MIT 2016). Our application is to the design of naval ship systems.

2.1 Linear Programming

While, linear programming and optimization methods date back at least as far as Euler and Fourier (Sierksma 2001), their practical application in modern real world problems began in earnest during and immediately following World War II with the incorporation of powerful computing techniques (McCallum 2001). Fundamentally, a linear program seeks to minimize or maximize an objective function which is constrained by a set of linear equations. Mathematically, a linear programming problem can be described as:

$$\text{Minimize: } C_x x \tag{2-1}$$

$$\text{Subject To: } \mathrm{Ax} \leq \mathrm{b} \tag{2-2}$$

where: x is a decision or flow variable and C_x represents the objective coefficient or cost associated with the decision variable. For each potential solution to decision variable x, the solution must conform to the set of constraints Ax ≤ b which ensure the solution remains in the feasible region (Ashish, Chapter 3: Linear Programs 2008).

2.2 Network Flow Optimization (NFO)

A network flow problem is a common application for optimization in the telecommunication and shipping industries (Ashish, Chapter 5 Network Flows 2008). The purpose is to move a commodity or set of commodities through a network.

The problem is set up by connecting a set of points called Nodes with a set of lines, called Arcs. Nodes can be any one of three different types: source nodes, called “Sources”, which provide a commodity to the network, sink nodes, called, “Sinks”, which require a commodity from the network and transient nodes which allow energy to pass through the nodes (Leon 2006), (IBM 2014).

A very simple example of a NFO problem is illustrated in Figure 27 and further quantified in Table 1. Nodes are represented by a single number located at the circles and arcs are represented by a numbered pair which connects the nodes. Arcs are always labeled with the “from” node first and the “to” node second.

In this example, Nodes 1 & 5 represent sources of a commodity with quantities 5 and 10 respectively being provided to the network. Nodes 2 and 6 represent sinks of the commodity which must be removed from the network. Nodes 3 and 4 represent transient nodes which, again, must achieve a net in/out flow of zero for continuity.

Each arc is associated with a specified cost per unit flow through that arc and bound by a given capacity. In the minimum cost flow problem, the goal of the solution is to minimize the cost of flow from the source nodes, through the network and ultimately delivering the appropriate quantity of the commodity to the sink nodes.

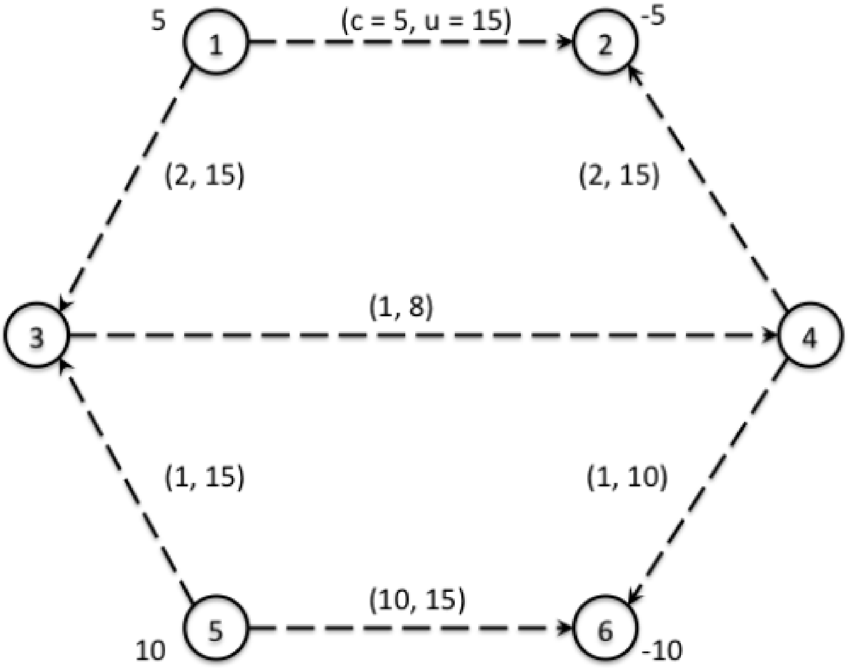
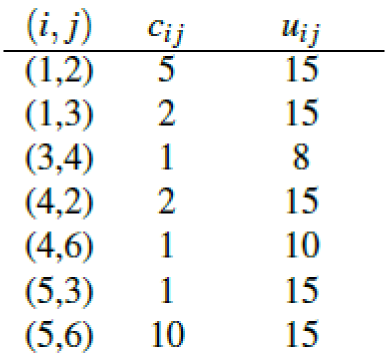


Figure 27 - Simple Network Optimization Problem (Trapp 2015)

Table 1 - Simple network Flow Optimization Edges (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

Mathematically we describe this NFO problem with a set of cost functions, capacity limits, nodal continuity, and flow direction equations as shown below, with the results of the optimization shown in Figure 28 and quantified in Table 2.

$$min. \quad \sum_{(i,j)\in E} c_{ij}\, x_{ij} \qquad (i,j) \in E \tag{2-3}$$

$$s.t. \quad x_{ij} \le u_{ij} \qquad (i,j) \in E \tag{2-4}$$

$$and \quad \sum_{(i,j)\in E} x_{ij} - \sum_{(i,j)\in E} x_{ji} = b_i \qquad (i,j) \in E \qquad i \in N \tag{2-5}$$

$$and \quad x_{ij} \ge 0 \qquad (i,j) \in E \tag{2-6}$$

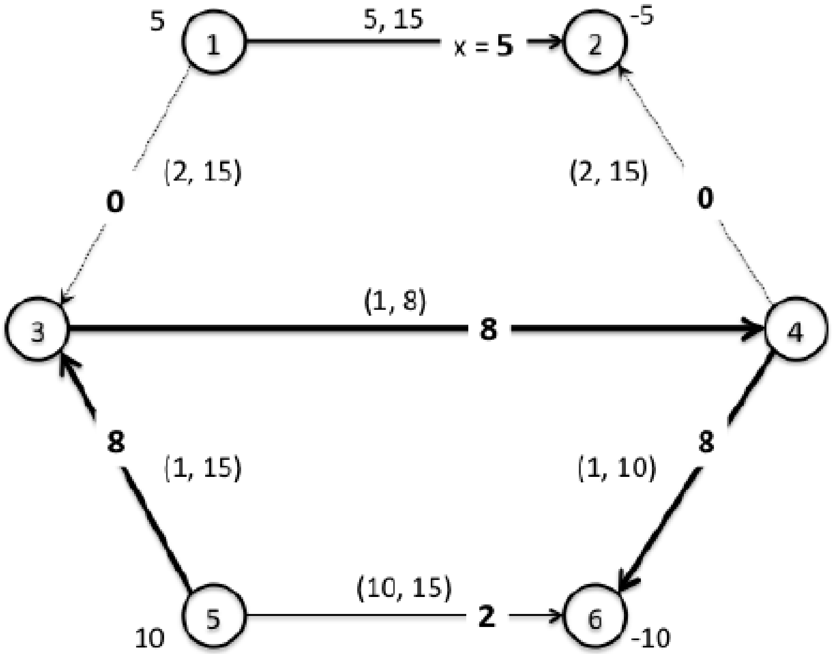
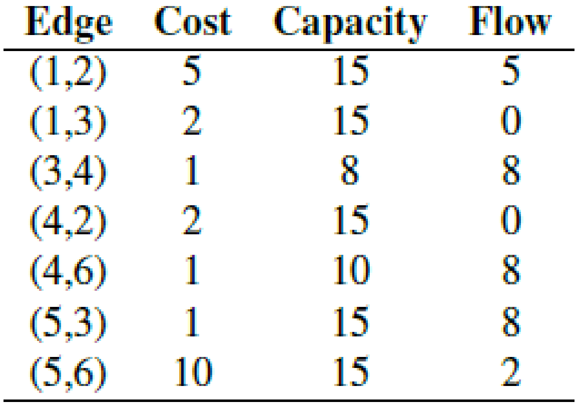


Figure 28 - Simple Network Flow Optimization Solution (Trapp 2015)

Table 2 - Solution Values Simple Network Flow Optimization (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

The optimization tool selected a combination of arc flows which minimized the total cost of the system as prescribed in the Objective (Cost) statement. Very simply the source and sink requirements of nodes 1 and 2 were satisfied using their direct arc connection (1,2). However, the source and sink requirements for nodes 5 and 6 would be optimally satisfied by splitting the flow into two different paths.

Without arc capacities, the network would have directed the entirety of the flow from node 5, to node 6 through transient nodes 3 and 4 for a total cost of 30 with 10 units transiting the path of arcs (5,3) (3,4) and (4,6). The upper bound capacity on for arc (3,4) prevented this as only 8 units of flow could flow this arc. Because of this restriction, 8 units were directed along the path of (5,3) (3,4) and (4,6) with the remaining two units transiting directly via arc (5,6) resulting in a contributed objective cost of this routing of 44. (Trapp 2015).

2.3 Multi Commodity Flow

A Multi Commodity Flow (MCF) network optimization furthers the capabilities of the traditional NFO by allowing multiple commodities to transit from node to node simultaneously via the same arcs. In the same way as the NFO, each commodity (k) can be assigned its own cost/objective coefficient as well as limits on the quantities which can transit each arc. Mathematically the differences between the traditional NFO and the MCF can be seen below with the addition of commodity (k) (Trapp 2015).

$$\boldsymbol{min.} \quad \sum_{(k)\,\in\,K} \quad \sum_{(i,j)\,\in\,E} c_{ij}^{k}\, x_{ij}^{k} \qquad (i,j) \in E \quad k \in K \tag{2-7}$$

$$\boldsymbol{s.t.} \quad \sum_{(k)\,\in\,K} \quad x_{ij}^{k} \leq u_{ij} \qquad (i,j) \in E \quad k \in K \tag{2-8}$$

$$\boldsymbol{and} \quad \sum_{(i,j)\,\in\,E} x_{ij}^{k} \; - \; \sum_{(i,j)\,\in\,E} x_{ji}^{k} = b_i \qquad (i,j) \in E \quad i \in N \quad k \in K \tag{2-9}$$

$$\boldsymbol{and} \quad x_{ij}^{k} \geq 0 \qquad (i,j) \in E \quad k \in K \tag{2-10}$$

2.4 Non-Simultaneous Multi Commodity Flow

A Non-Simultaneous Multi Commodity Flow (NSMCF) allows the designer to change the formulation of the traditional MCF in a couple of ways. Using NSMCF the objective function being minimized can be changed from a flow minimization to an arc capacity minimization. Rather than looking at arcs as having exclusively upper bounds and lower bounds, their values can be incorporated into the objective functions and decision variables (Trapp 2015).

Additionally, the incorporation of NSMCF allows for multiple scenarios to be evaluated for a single network architecture. The NSMCF allows the objective function to be an aggregate capacity, or equal to the capacity of the arc with the greatest capacity required in any given scenario. This optimization is possible due to the formulation of the NSMCF which permits only one commodity to flow at a time. In application to the AFO, the number of flows equates to the number scenarios being evaluated and thus, each scenario is allowed to be run through the network one at a time with the greatest flow capacity being represented in the objective function.

$$x_{ij}^{k} \leq U_{ij} \qquad (i,j) \in E \qquad k \in K \tag{2-11}$$

In the equations above, U_{ij} would replace x_{ij}^{k} in the objective function and represent the greatest capacity required through the given arc (i,j) in any scenario. Using the NSMCF process, the (k) variable no longer represents different commodities but a specified flow situation for the given scenario. The incorporation of this scenario concept through a network optimization will be expanded upon to show how flow of a commodity though a system, system within a ship, or an entire ship itself maybe optimized to accommodate desired operational conditions and/or casualty conditions to pieces of equipment (Trapp 2015).

The generic equations governing the flow through the network in the specified scenarios are:

$$\mathbf{min.} \quad \sum_{(k)\,\in\,K} \quad \sum_{(i,j)\,\in\,E} c_{ij}\; U_{ij} \qquad (i,j) \in E \tag{2-12}$$

$$\mathbf{s.t.} \quad x_{ij}^{k} \leq U_{ij} \qquad (i,j) \in E \quad k \in K \tag{2-13}$$

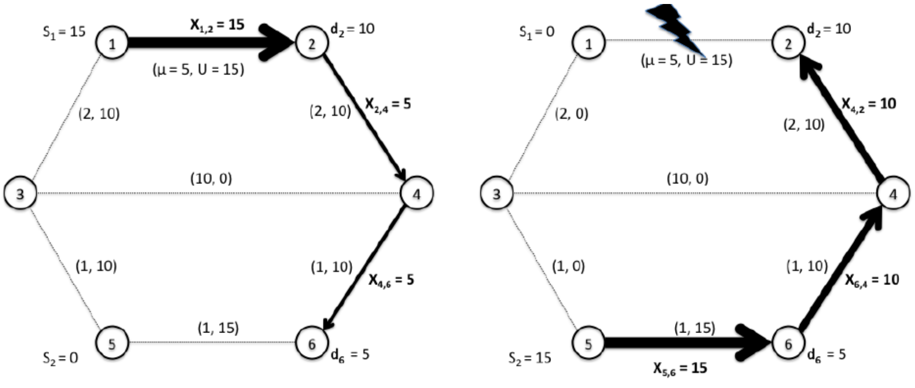
$$\mathbf{and} \quad \sum_{(i,j)\,\in\,E} x_{ij}^{k} \; - \; \sum_{(i,j)\,\in\,E} x_{ji}^{k} = b_i \qquad (i,j) \in E \quad i \in N \quad k \in K \tag{2-14}$$

$$\boldsymbol{and} \quad x_{m}^{k} = 0 \qquad (i,j) \in E \quad k \in K \quad m \in M \tag{2-15}$$

Where M represents a desired set of damaged arcs in which flow is not allowed to pass (Trapp 2015). This damaged set of arcs can be expanded to include nodes by stating if a node is damaged and unavailable to act as a transient node in the system, the flow of all arcs to and from that node is zero, effectively eliminating the desired node from the system.

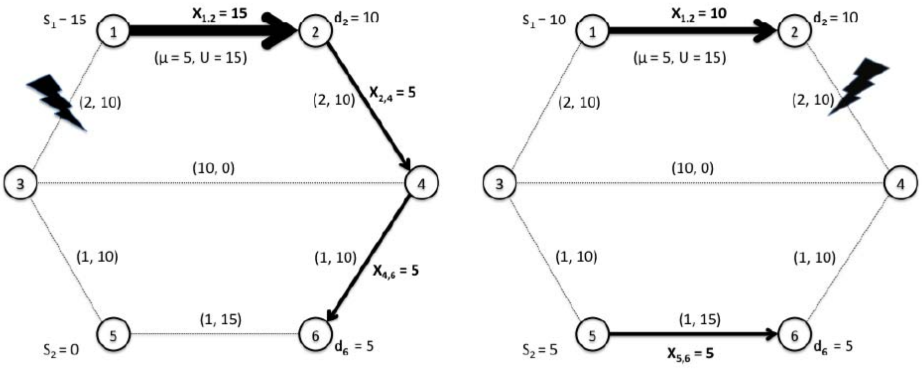
Using the generic equations (2-12) through (2-15) and considering the network problem in Figure 27, this problem can be analyzed for any number of degraded or specified operating conditions. An M-1 ("M minus one") requirement considers the aggregate of the required network where the flow in one arc at a time is set to zero or deactivated. In the Figure 27 network, allowing the sources at nodes 1 and 5 to be scalable sources results in eight specified scenarios, one for the original network with all arcs available for use and separate scenarios for the loss of each arc in the network, seven damaged arc scenarios in total. Figure 29 through Figure 32 show the solution flows in each scenario and how the commodity would travel from nodes 1 and 5 and provide energy to nodes 2 and 6. (Trapp 2015)

Figure 33 shows the aggregate solution for Figure 28. This solution represents the arc's aggregate capacity to support the network over the full set of scenarios. This technique can also be used to eliminate unnecessary arcs from a network while providing the user confidence that an optimal solution still exists and can satisfy the required network flow for all damage scenarios. In this case, node 3 is unused through the series of scenarios and can be eliminated from the network along with the arcs going to and from it (Trapp 2015).



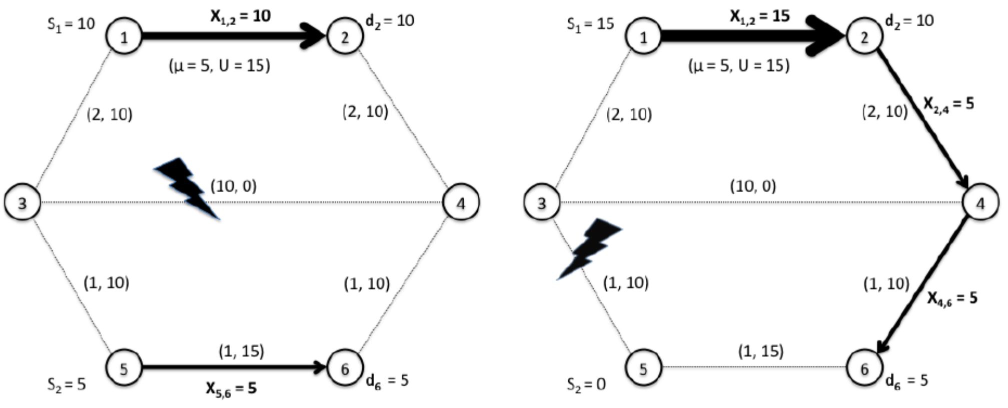
(a) #0: No Loss (b) #1: Loss of Edge (1,2)

Figure 29 - NSMCF Solution-No Damage & Loss of Arc 1 (Trapp 2015)



(c) #2: Loss of Edge (1,3) (d) #3: Loss of Edge (2,4)

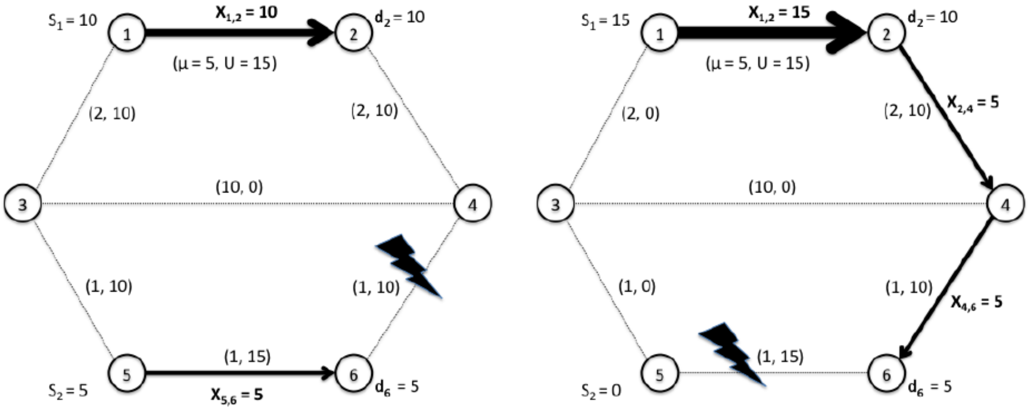
Figure 30 - NSMCF Solution-Damaged Arcs 2& 3 (Trapp 2015)



(a) #4: Loss of Edge (3,4)

(b) #5: Loss of Edge (3,5)

Figure 31 - NSMCF Solution-Damaged Arcs 4 & 5 (Trapp 2015)



(c) #6: Loss of Edge (4,6)

(d) #7: Loss of Edge (5,6)

Figure 32 - NSMCF Solution-Damaged Arcs 6 & 7 (Trapp 2015)

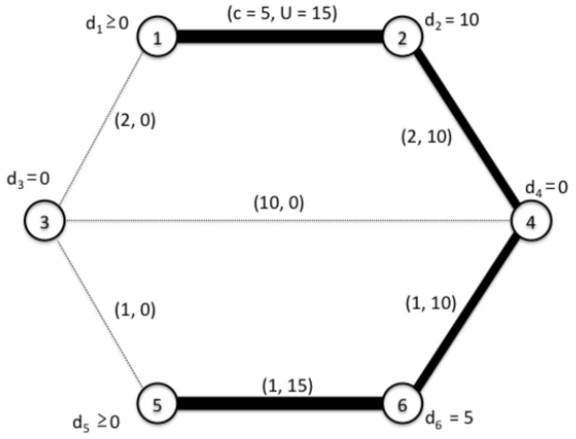


Figure 33 - NSMCF M-1 Network Solution (Trapp 2015)

2.5 Trapp’s Incorporation of NSMCF into IEP design for Survivability

Trapp introduced the idea of using this NSMCF network optimization method to design the Integrated Engineering Plant (IEP) shown in Figure 34. Trapp considered two interrelated plexus, electrical and thermal systems, modeled as a single multiplex system, optimizing the multiplex network to minimize cost with constraints for operational flexibility and survivability (Trapp 2015).

Arguably the most insightful outcome of his dissertation, was how variable arc costs could be calculated. Correlating material cost to the flow capacity using standard material and a linear approximation multiplied by the length of the arc allowed for a cost function to be created which was tied directly to the commodity flow required to pass through the arcs. Trapp applied this technique to both domains and was able to demonstrate how a physical commodity flow through a representative logical architecture could be optimized using NSMCF as shown in Figure 35 and Figure 36 (Trapp 2015).

In these figures, Trapp demonstrates how survivability could be designed into a notional ship’s logical architecture and subsequently optimized for capacity. Simulating the loss of both an electrical edge and a cooling edge on each side of the IEP configuration, the system was able to adapt to the new network, adjust the capacities and flows of each commodity through their respective networks and achieve the necessary cooling and propulsive power delivered to the motor. Using the NSMCF method, the aggregate flow for the network using only these two scenarios would be equal to the capacity required for each side of the IEP. For additional redundancy and to build in increased reserve capacity, additional casualty constraints could be implemented and assessed for feasibility.

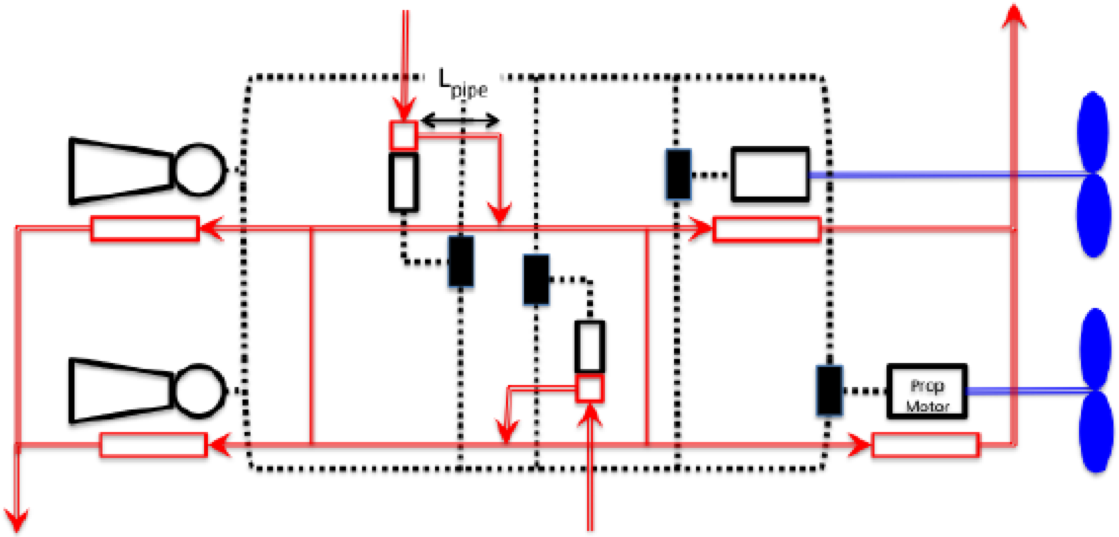


Figure 34 - Trapp's IEP Logical Architecture (Trapp 2015)

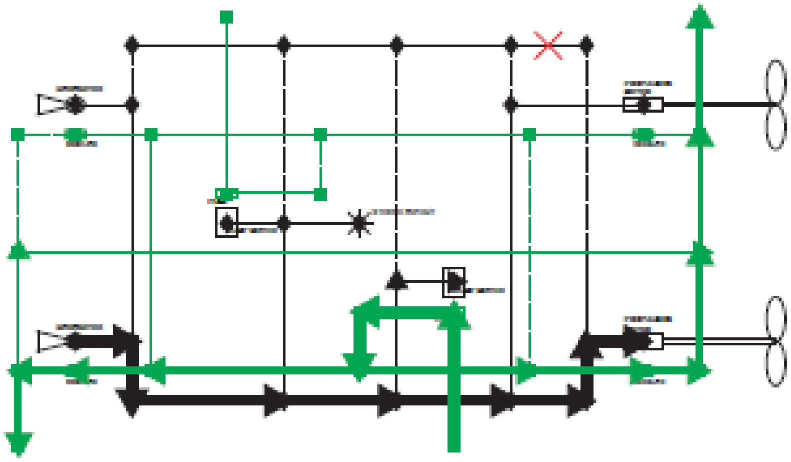


Figure 35 - Trapp's IEP loss of Electrical Edge 11 (Trapp 2015)

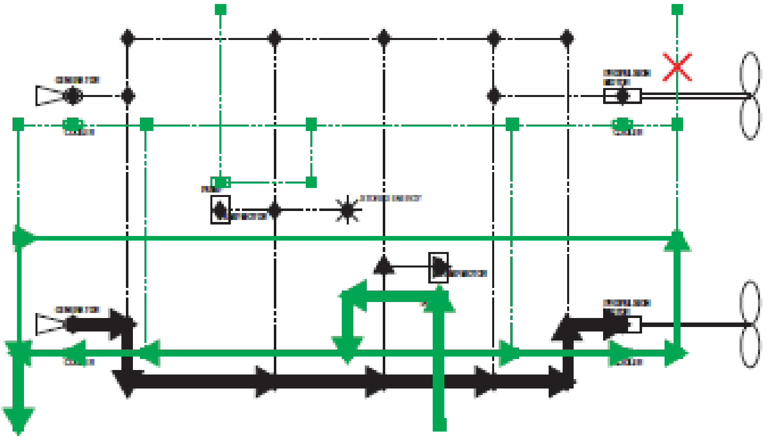


Figure 36 - Trapp's IEP loss of Cooling Edge 12

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2.6 IBM ILOG CPLEX

IBM ILOG CPLEX Optimization studio (CPLEX) is a commercially available software optimization package capable of quickly solving robust algorithms, tailored for businesses and data scientists. Capable of solving linear programming, mixed integer linear programing (MILP), quadratic and quadratically constrained programming models, CPLEX provided platform to develop a representative model of the ship's architecture and opportunities to expand the method of optimization in the future if desired (IBM 2014).

Through the CPLEX interactive optimizer, only a text file is required to begin the MILP optimization. Using MATLAB, the required information pertaining to the representative design (DVs, PSYS, AAW, ASUW, ASW, VTPAM) is read from the SSM and organized into a linear programming equation acceptable for CPLEX, more detailed information on this process is discussed in Section 3.10.

CPLEX is capable of solving the problem several ways including a primal simplex optimizer for strictly linear equations, a network optimizer for large embedded networks and a MILP optimizer when discrete integer components are included. For the purposes of this thesis MILP method was used but was aided by a review of how CPLEX read and optimized problems via the primal simplex and network methods. Each method connects nodes via arcs while constraining those connections by conservation of energy at each node, placing upper or lower bounds on each arc and in some cases dictating what the flow to a node/through an arc is required to be. Through this setup, CPLEX will carry a commodity through a network from a source to a sink at the least cost for the objective function (IBM 2014)

Outputs from CPLEX are provided in a text file which is read by MATLB. The outputs from CPLEX detail the value of the objective function from the optimized network and show details about each constraint and decision variable. While the objective function seeks to minimize the aggregate capacity required to support the network, valuable information can be obtained through the extraction of individual scenarios, including the ability to produce meaningful visualizations of the network. Evaluation of the results from each scenario verify the M-1 condition and all other constraints were successfully applied to the problem and add confidence the network has been optimized successfully.

3 Network Architecture Flow Optimization (AFO) of Steady State Shipboard Operations

In this thesis, Trapp's method of applying NSMCF to represent two domains of an IEP system is expanded to include not only Electrical energy and cooling, but all ship Vital Components (VCs) and systems. Using a representative ship and ship system descriptions from the SSM including data, baseline system logical architecture, preliminary arrangement and operational scenarios, it is possible to perform an architecture flow optimization (AFO) and define an initial system design with response solution that includes logical, physical (VC locations) and operational (scenario) architectures. The definition of the physical solution is effectively completed in two steps: 1) complete an architecture flow optimization considering energy and data flow in all subsystems with VC locations; and 2) transform the energy solution into a physical solution including actual commodity flow (LO, SW, CW, electrical, mechanical) and the sizing of physical components. The first step of this process is the primary focus of this thesis.

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

1. Only energy is explicitly tracked in the AFO as carried by the various commodities (fluid, mechanical, electrical). Commodities carry energy in separate arcs. 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 leaving nodes and in some cases actually determine the (electric) input energy required to support the transport of commodities carrying energy leaving nodes. Of course continuity must still be enforced.
3. The number of plexus included in the multiplex model is much larger and essentially unlimited.
4. System architectures (logical, physical and operational) are extracted and defined from a ship design synthesis model (SSM) in an architecture framework.

3.1 Transport of Energy by Commodities

The architecture flow optimization (AFO) in this thesis explicitly considers only energy transported through the ship's systems or plexus by various flow commodities including mechanical, electrical, lube oil (LO), seawater (SW), chilled water (CW), electronic cooling deionized water (EC) glycol coolant (Glycol) and heating ventilation and cooling (HVAC) as described in Section 3.2.2. These commodities do not interact directly with one another but transfer their energy from one to the other via nodal connectivity and energy conversion. A node may have a single commodity transiting the node or could have multiple inputs and outputs of multiple commodities using multiple "Ports". This requires a different formulation of the optimization problem from Trapp's NSMCF formulation, particularly in the nodal constraints and energy conservation/partitioning. This will be discussed in Section 3.6. Connections between nodes of a common plex and commodity are described using explicit arcs, while connections between nodes of a different plex and commodity are described using dependencies or implicit arcs.

3.2 Nodes

Logical subsystem network architectures as described in Section 1.1.1 are assembled into a multiplex system. The basic components of this logical architecture are nodes and arcs with nodes representing vital components and arcs representing the media (pipes, cables, shafts) for distributing commodity flows (mechanical, electrical, LO, etc.) which carry energy. As stated, the AFO considers energy flow only without direct consideration of commodity flow, but energy flows have separate arcs by commodity in their own subsystems or plexus and only interact at vital components or nodes. The commodity flow necessary to support the optimized energy flow is calculated post-AFO. The plexus are interconnected at a few nodes that manage multiple commodities such as a Power Generation Modules and heat exchangers, but primarily they are interconnected through zonal electric power and zonal heat nodes which all plexus have in common as will be discussed.

Network nodes generally represent vital components (VCs). The behavior of each node is intended to model the behavior of their related VC and is specified by the data provided for each VC and VC type in the SSM. This data is contained in coefficient matrices in both the MEL and the CSEL.

3.2.1 Terminal Nodes

Terminal nodes are sources or sinks where energy either enters the multiplex network or where energy leaves the network. Energy enters from the FO_Source node and the non-AFO thermal heat nodes. The FO_Source node represents FO storage tanks onboard the ship and non-AFO thermal heat nodes are heat sources from external transmission (solar heat) into the ship and from equipment and personnel in the ship that are not explicitly considered in the AFO multiplex. The non-AFO thermal heat sources are segregated by ship damage control zones of which there are four in the representative design used in this thesis. Energy leaves the ship most directly as mechanical power through the propellers, but energy also leaves the ship as thermal energy carried ultimately by either the SW plex through the SW_Sinks and overboards, through the HVAC system via the ship's ventilation plex into the external air, or by engine exhaust into the atmosphere. Energy exiting the ship as propulsion power is required for various operations in the required scenarios and is constrained to be greater than or equal to the required power specified in the SSM. In the current model, there are three different propulsion power requirements calculated for the representative hullform to attain certain ship speeds. These power requirements are for sustained speed, which is the ship's maximum achievable continuous speed with margin, battle speed which is the ship's maximum achievable continuous speed with margin during high power combat operations, and endurance speed which is the specified speed at which the ship will cruise or transit for purposes of calculating endurance range. SW and External Air sinks do not have a specified amount of energy they must remove, however. Due to nodal continuity constraints, these nodes will receive energy from the ship that must be expelled out of the multiplex system so heat value of these sinks in based on continuity.

3.2.2 Zonal Electric and Heat Load Nodes

Some VC nodes require electric power or fuel to operate as defined in the SSM, and since their operation is not 100% efficient, they produce heat which must be removed into one of the thermal plexus. These power and thermal loads include both static loads (constant when the VC is operating) and flow-dependent loads (loads that depend on other energy flows entering or leaving their nodes). Static load components are usually specified by ship DV's. Examples of static loads include combat system components, engines and ship non-AFO loads. Flow-dependent loads include electric-driven pumps. A CW pump is an example of a flow dependent component/node. The electric power required by the pump is directly related to the quantity of thermal energy passing through the pump node carried by the chilled water commodity that must be pumped.

3.2.3 Continuity Nodes

Explicitly connecting all multiplex components that require electric power to the electric system, or explicitly connecting all components needing to expel heat into their compartment air to the HVAC system, would require a large number of additional explicit arcs and paths, greatly complicating the AFO. Instead, these components are connected implicitly to zonal continuity nodes that provide power from the electric system or receive heat into the HVAC system with no other function. These nodes are not sources or sinks or actual VCs, but just continuity nodes providing important interfaces between many components in all plexus and the electric and HVAC systems. Examples include: Zone1_ELEC_SYS and Zone1_Air_Heat_SYS.

Other continuity nodes are actual VCs and maintain conservation of energy based on the arcs entering and exiting the node, but they do not require power to operate. They may lose heat to the zonal air. Energy enters the nodes on incoming arcs and this total incoming energy is partitioned to outgoing commodity arcs based on the node type and its corresponding coefficient matrix values. Examples of this type of node include load centers, power conversion modules, switchboards, filters, reduction gear, shafting, etc.

3.3 Other Constraints

Each arc may have upper and lower flow constraints. All arcs have a lower bound of zero flow, functionally stating that energy cannot flow backwards from the head of the arc to the tail. In situations where energy may be required go both ways between nodes, parallel arcs are specified. These arc pairs may be combined into a single “edge”, but only arcs are used in our AFO formulation.

The only arcs which are currently restricted by an upper bound in our AFO are the power outputs from engines and power generation modules. The capacity of engine and PGM nodes to provide energy to either the mechanical or the electrical plexus is limited by the engine’s maximum continuous rating (MCR) and specified in SSM design variables (DVs). The MCR is a manufacture’s limit on the safe continuous operating capability of the engine and should be considered by the designer when selecting a physical architecture to model. All other arcs and components are free to scale up to the optimal level as determined by the optimizer. This limit is actually the only energy flow constraint in the model and sets the overall system capacity which should match the operating conditions modeled more simply in the SSM.

3.4 Assumptions

Each node considered in the network is physically placed at the geometric center of the SDB of which it is associated based on the VTPAM preliminary arrangement of the representative ship design. This link to the physical architecture provides a rough estimate of the length of the arcs associated with the nodal connections. The distance between nodes is calculated to be the summation of the difference in their X, Y and Z locations.

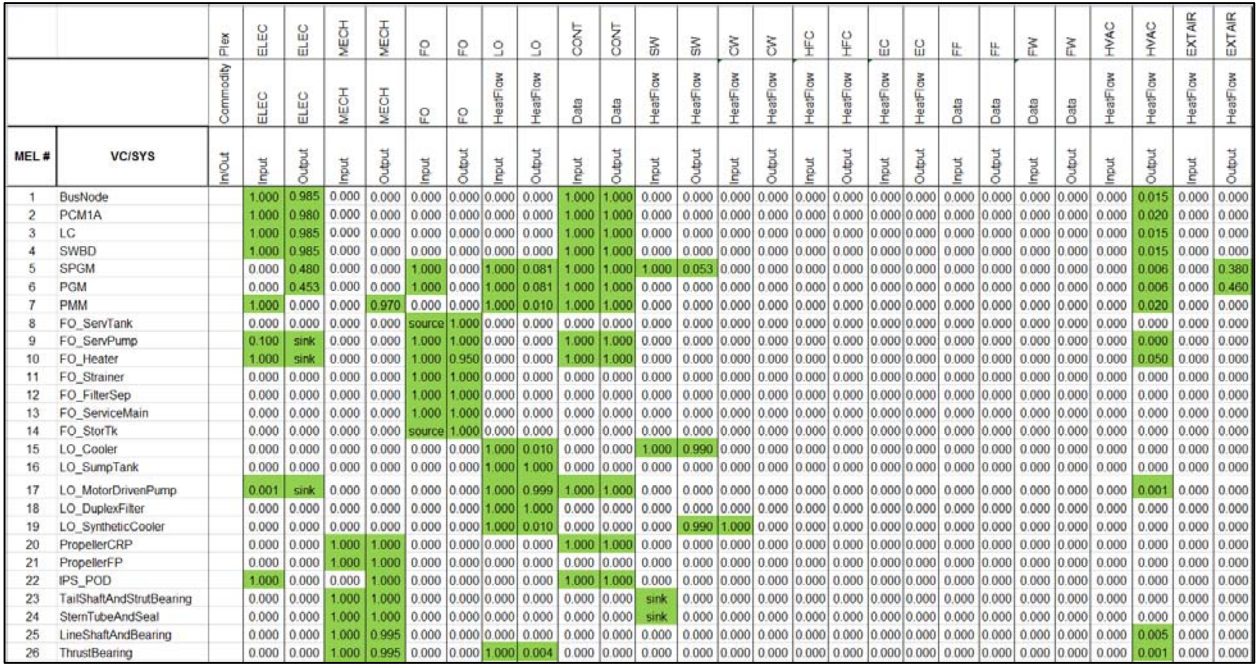
Energy losses through the arc media (pipe, cable, shafting) are not considered directly in the energy flow optimization. Instead these losses (fluid friction, mechanical friction and electrical resistance) are estimated and applied at the nodes where energy is distributed to the air heat zonal nodes and ultimately to the HVAC plex.

3.5 Nodal Models, Power Conversion and Plex Interaction

In early stage ship design and within the AFO, a simple energy flow analysis is conducted which does not directly consider “through variables” such as electrical current, flow rate and speed, or “cross variables”, such as voltage, pressure and torque. Only power transmission (energy) is considered. This allows each node modeled in steady state to be represented by a simple energy flow efficiency matrix. The matrices used in the AFO are located in the MEL and CSEL where each node type in the two equipment lists is represented by a vector detailing how a node may accept energy from various commodities into its ports and how the sum of that energy should be distributed to outgoing arcs from the nodal outgoing ports. (A. Brown, Marine Engineering 2018).

A sample of the MEL is shown in Table 3. Of the energy entering a Load Center or Bus Node (MEL# 1&3), 98.5% of the energy entering that node leaves that node via an ELEC arc, while 1.5% of the energy that enters the node is converted into thermal heat which enters the HVAC system. Similarly, a Power Conversion Module (MEL#2) directs 98% of the energy entering back into the ELEC plex while 2% of the total energy is converted to heat.

Table 3 - Sample of ELEC & MECH MEL



		Plex	ELEC	ELEC	MECH	MECH	FO	FO	LO	LO	CONT	CONT	SW	SW	CW	CW	HFC	HFC	EC	EC	FF	FF	FW	FW	HVAC	HVAC	EXTAIR	EXTAIR
		Commodity	ELEC	ELEC	MECH	MECH	FO	FO	HeatFlow	HeatFlow	Data	Data	HeatFlow	HeatFlow	HeatFlow	HeatFlow	HeatFlow	HeatFlow	HeatFlow	HeatFlow	Data	Data	Data	Data	HeatFlow	HeatFlow	HeatFlow	HeatFlow
MEL #	VC/SYS	In/Out	Input	Output	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		1.000	0.985	0.000	0.000	0.000	0.000	0.000	0.000	1.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.015	0.000	0.000
2	PCM1A		1.000	0.980	0.000	0.000	0.000	0.000	0.000	0.000	1.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.020	0.000	0.000
3	LC		1.000	0.985	0.000	0.000	0.000	0.000	0.000	0.000	1.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.015	0.000	0.000
4	SWBD		1.000	0.985	0.000	0.000	0.000	0.000	0.000	0.000	1.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.015	0.000	0.000
5	SPGM		0.000	0.480	0.000	0.000	1.000	0.000	1.000	0.081	1.000	1.000	1.000	0.053	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.006	0.000	0.380
6	PGM		0.000	0.453	0.000	0.000	1.000	0.000	1.000	0.081	1.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.006	0.000	0.460
7	PMM		1.000	0.000	0.000	0.970	0.000	0.000	1.000	0.010	1.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.020	0.000	0.000
8	FO_ServTank		0.000	0.000	0.000	0.000	source	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
9	FO_ServPump		0.100	sink	0.000	0.000	1.000	1.000	0.000	0.000	1.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10	FO_Heater		1.000	sink	0.000	0.000	1.000	0.950	0.000	0.000	1.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.050	0.000	0.000
11	FO_Strainer		0.000	0.000	0.000	0.000	1.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12	FO_FilterSep		0.000	0.000	0.000	0.000	1.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
13	FO_ServiceMain		0.000	0.000	0.000	0.000	1.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
14	FO_StorTk		0.000	0.000	0.000	0.000	source	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
15	LO_Cooler		0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.010	0.000	0.000	1.000	0.990	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
16	LO_SumpTank		0.000	0.000	0.000	0.000	0.000	0.000	1.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
17	LO_MotorDrivenPump		0.001	sink	0.000	0.000	0.000	0.000	1.000	0.999	1.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000
18	LO_DuplexFilter		0.000	0.000	0.000	0.000	0.000	0.000	1.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
19	LO_SyntheticCooler		0.000	0.000	0.000	0.000	0.000	0.000	1.000	0.010	0.000	0.000	0.000	0.990	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
20	PropellerCRP		0.000	0.000	1.000	1.000	0.000	0.000	0.000	0.000	1.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
21	PropellerFP		0.000	0.000	1.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
22	IPS_POD		1.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	1.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
23	TailShaftAndStrutBearing		0.000	0.000	1.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	sink	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
24	SternTubeAndSeal		0.000	0.000	1.000	1.000	0.000	0.000	0.000	0.000	0.000	0.000	sink	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
25	LineShaftAndBearing		0.000	0.000	1.000	0.995	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.000	0.000
26	ThrustBearing		0.000	0.000	1.000	0.995	0.000	0.000	1.000	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000

Figure 37 and Figure 38 show a notional bus node and the generic nodal continuity model for Bus Nodes in the ELEC plex. In this case, there may be multiple electrical arcs leaving the same node. Because of this, the formulas enforcing these efficiencies are written in such a way that the ELEC energy output is a summation of all the electronic arcs leaving the nodes, however, the thermal energy radiated from each of these nodes remains fixed and represents a single arc. Figure 39 shows the model and nodal efficiencies of a Power Conversion Module (PCM).

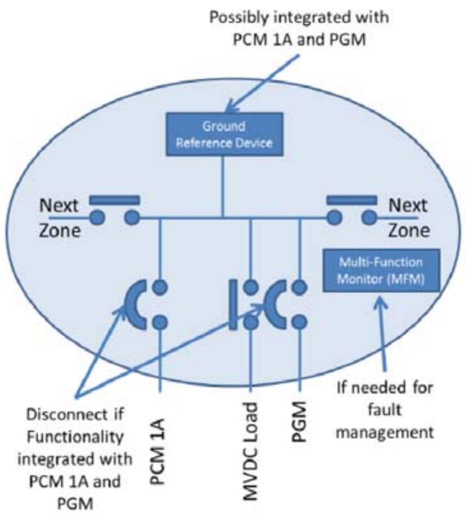


Figure 37 - Notional Bus Node Schematic (Doerry 2016)

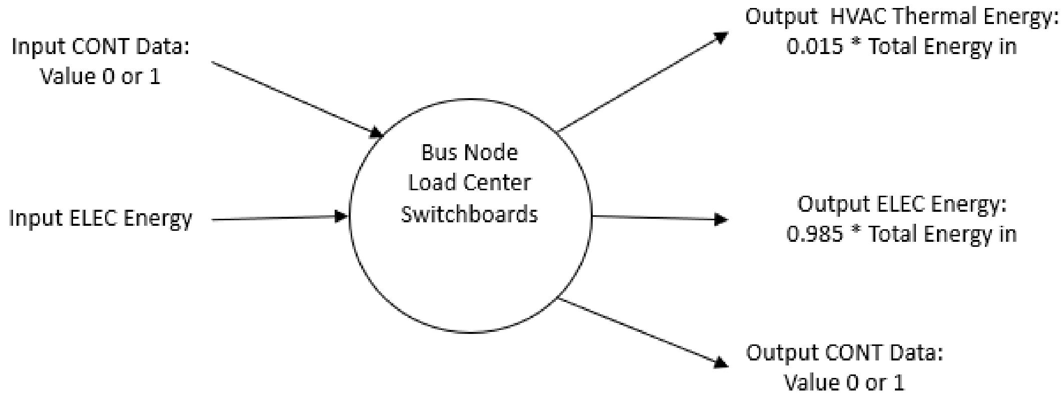


Figure 38 - Nodal Efficiency for Bus Nodes, Load Centers, Switchboards

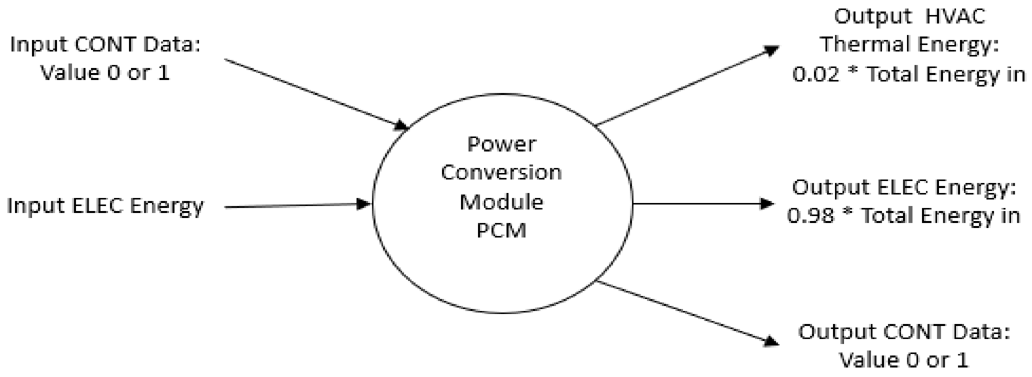


Figure 39 - Nodal Efficiency for Power Conversion Module

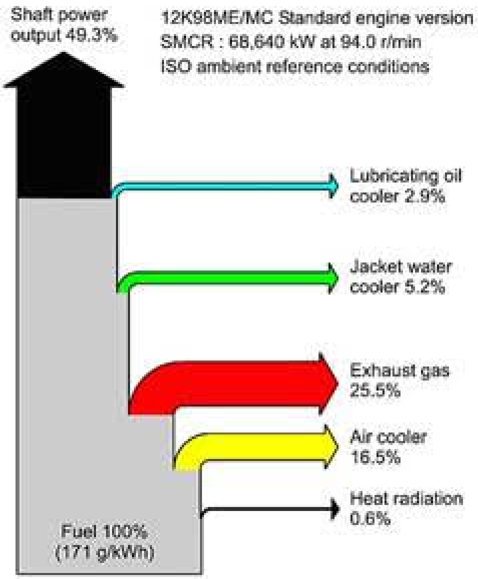


Figure 40 - Energy Flow through a PGM (Man Diesel 2014)

Table 3 and Figure 40 illustrate how 100% of the chemical energy entering a diesel engine (similar to MEL #5) may be parsed to outgoing arcs where energy is sent to the Mechanical plex, LO Plex, HVAC system (compartment air) and out of the ship via the exhaust system to the atmosphere. An important point of emphasis is that the output of the diesel into the Mechanical or Electrical plexus is limited by the manufacturers MCR, which places a limit on how much this component can contribute to the useful work required to be completed by that plex. The fuel input energy flow is the energy that must be extracted from the fuel and input into the AFO. This represents a pull from the engine driven by scenario speed/power requirements but limited by the engine MCR. The actual fuel commodity flow would be calculated post-AFO considering the engine specific fuel consumption (SFC) at load from the engine performance map.

In an Integrated Propulsion system, diesel generators are generally preferred to provide power when low levels of energy are required due to their increased fuel efficiency when compared to a gas turbine, especially at partial loads. However, both are required as Gas Turbine Generators can reach higher levels of electrical output while remaining lighter and smaller than a comparable diesel generator would be (A. Brown, Marine Engineering 2018).

Diesel Generator sets in the AFO are referred to as Secondary Power Generation Modules (SPGM, Figure 41), while the Gas Turbines are simply referred to as Power Generation Modules (PGM, Figure 42).The simplified nodal energy flow for the SPGM is shown in Figure 43 with the PGM energy model being shown in Figure 44. Coefficients from the Table 3 MEL specify the energy which must be carried by each of the arcs leaving the node and are not indicative of the flow quantity itself. The flow required to carry this quantity of energy via the specified commodity is calculated post-AFO.

Figure 41 - Caterpillar Diesel Generator Set C280-16 (A. Brown, Marine Engineering 2018)

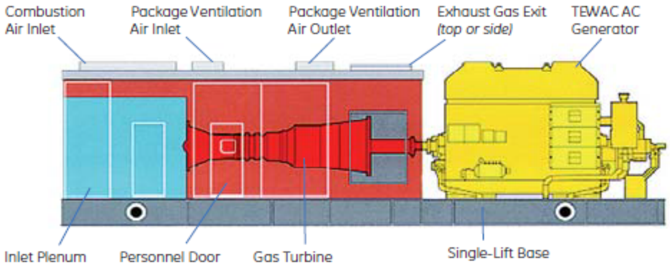


Figure 42 - Gas Turbine Generator Set Example (A. Brown, Marine Engineering 2018)

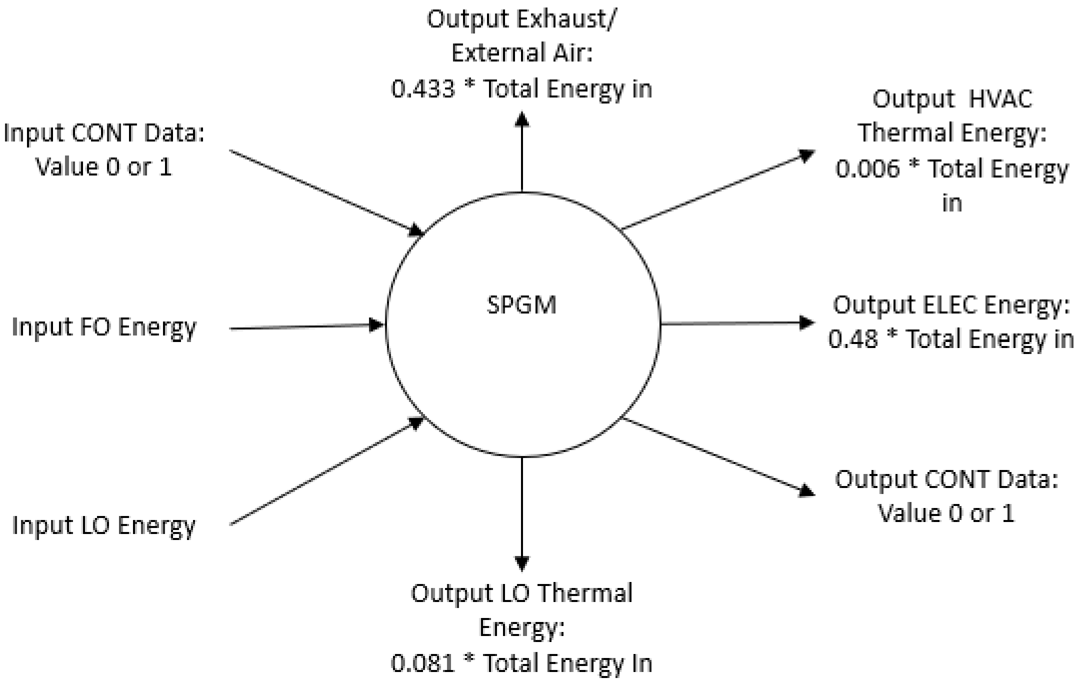


Figure 43 - Nodal Model for SPGM & SSDG (MEL #5)

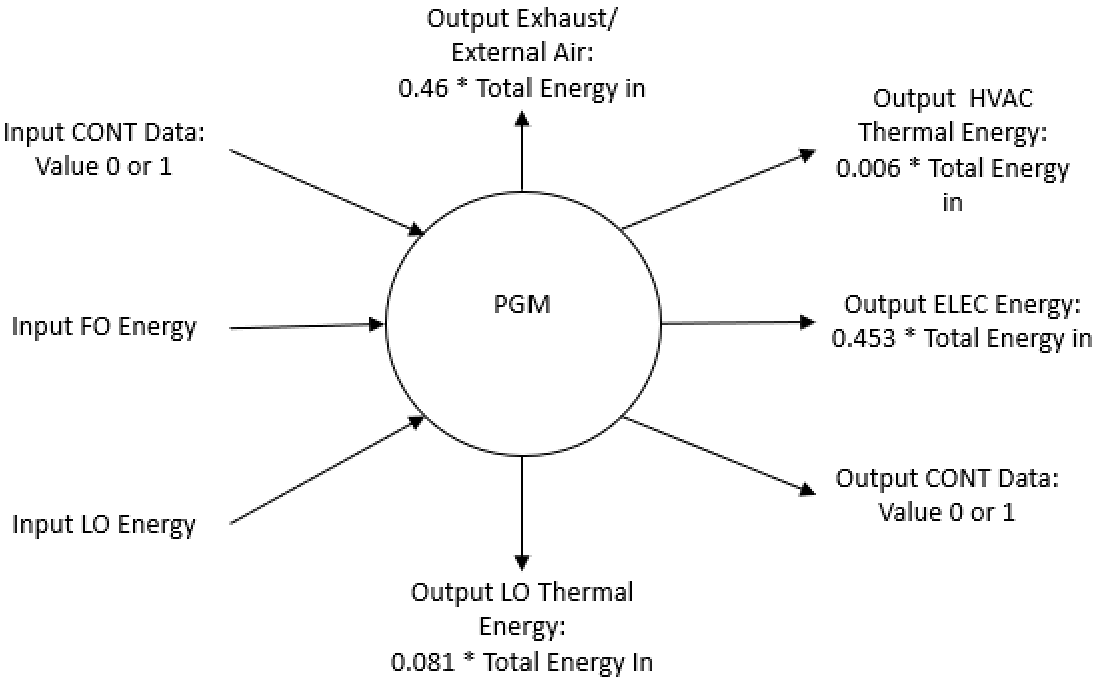


Figure 44 - Nodal Model for PGM (MEL #6)

The Propulsion Motor Module (PMM) shown in Figure 45 takes electrical energy and converts it primarily to MECH energy which is then passed through the MECH plex for propulsion in an IPS ship. Figure 46 shows the nodal model for the Propulsion Motor Module (PMM) based on coefficients from Table 3. Heat from the conversion of ELEC energy to MECH energy leaves the node as air heat in the HVAC plex or subsystem and lube oil heat in the LO plex.

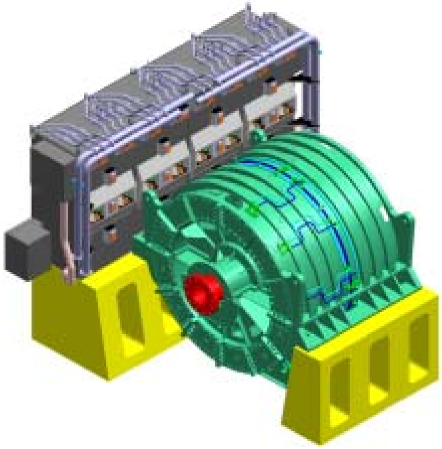


Figure 45 - Notional Propulsion Motor Module (PMM) (A. Brown, Marine Engineering 2018)

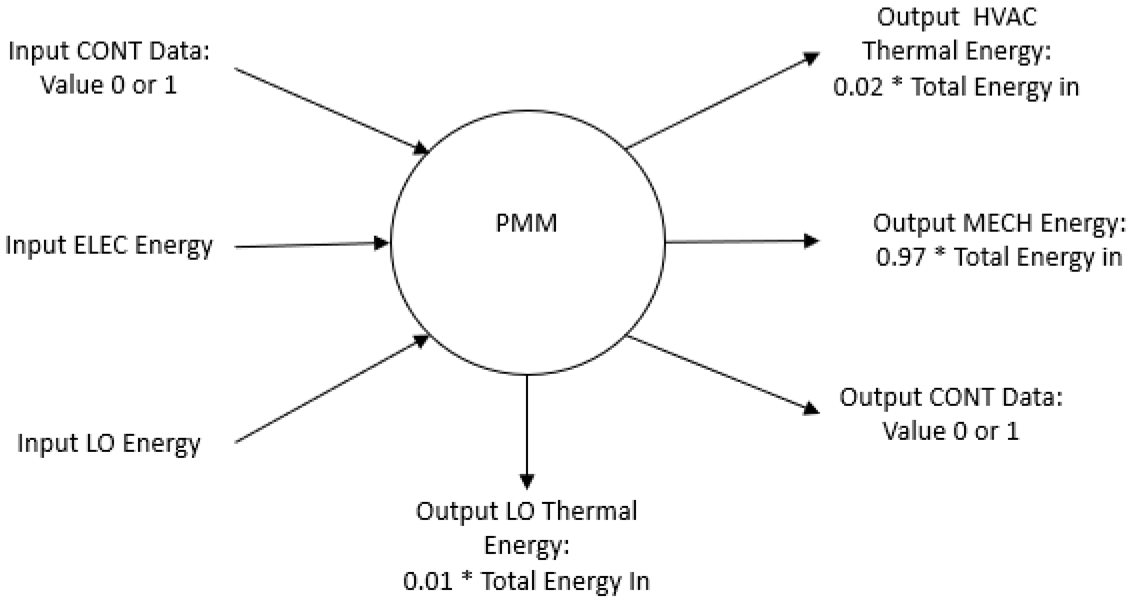


Figure 46 - Nodal Model for PMM

Within the MECH plex are numerous nodes which affect the power ultimately delivered to the propeller. These nodes include line shaft bearings, couplings, thrust bearings and seals which all have a similar model to that of a line shaft bearing shown in Figure 47. These are examples of continuity nodes discussed in Section 3.2.3. Each of these nodes remove a small percentage of the incoming energy from the MECH plex and output that energy to a zonal air heat node discussed in Section 3.2.2 to be cooled by the ship HVAC subsystem or plex. These losses represent a portion of the mechanical losses of the propeller drive train

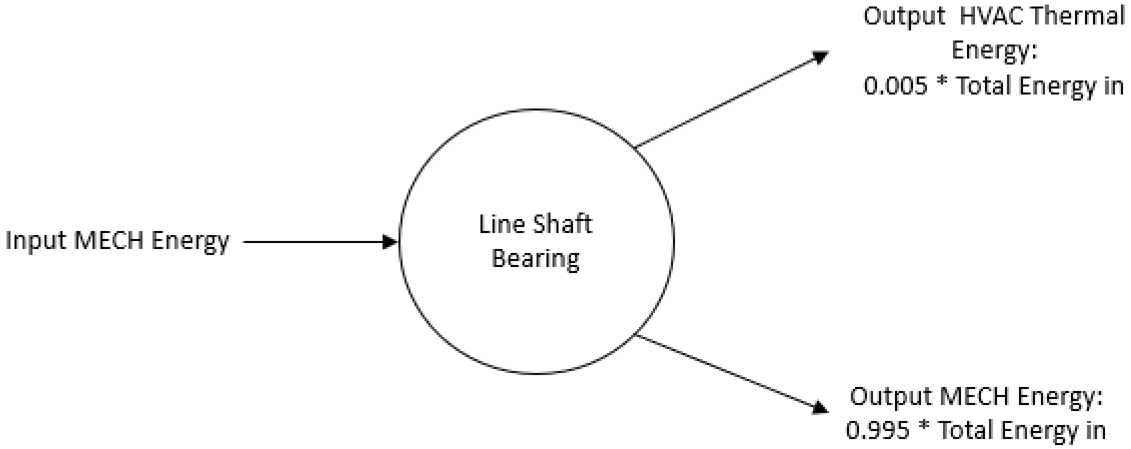


Figure 47 - Nodal Model for a Line Shaft Bearing

Throughout the ship, there are coolers found in each of the thermal plexus. Each of these is modeled similarly to the LO cooler shown in Figure 48 and Figure 49. These nodes include LO Coolers, LO Synthetic Coolers, CW-HFC Condensers, EC Heat Exchangers, Glycol Heat Exchangers and CW-HVAC Coolers.

This nodal model illustrates how LO heat entering the cooler transfers to a SW cooling arc that leaves the LO Cooler. A trace amount of energy must remain in the LO plex to maintain the loop arc integrity and circulate back around the system. This requirement ensures that both fixed and variable costs are considered within the plex and that the complete logical loop representation and intervening nodes are included in the AFO solution. Otherwise cold side arcs and nodes are deleted by the AFO since they are not required.

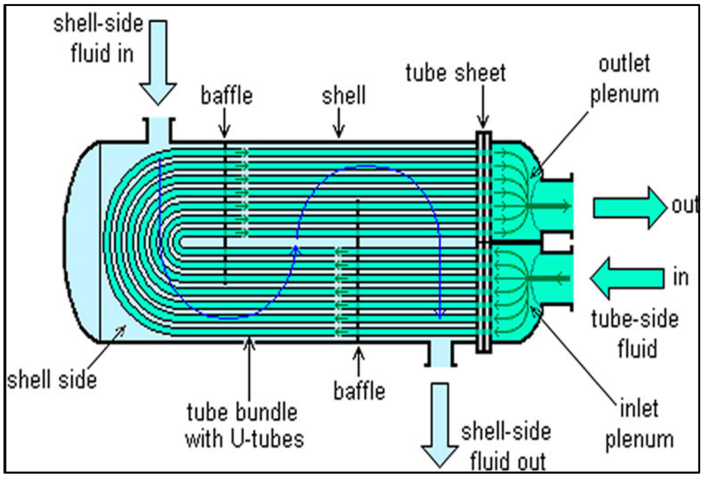


Figure 48 - Basic Heat Exchanger (A. Brown, Marine Engineering 2018)

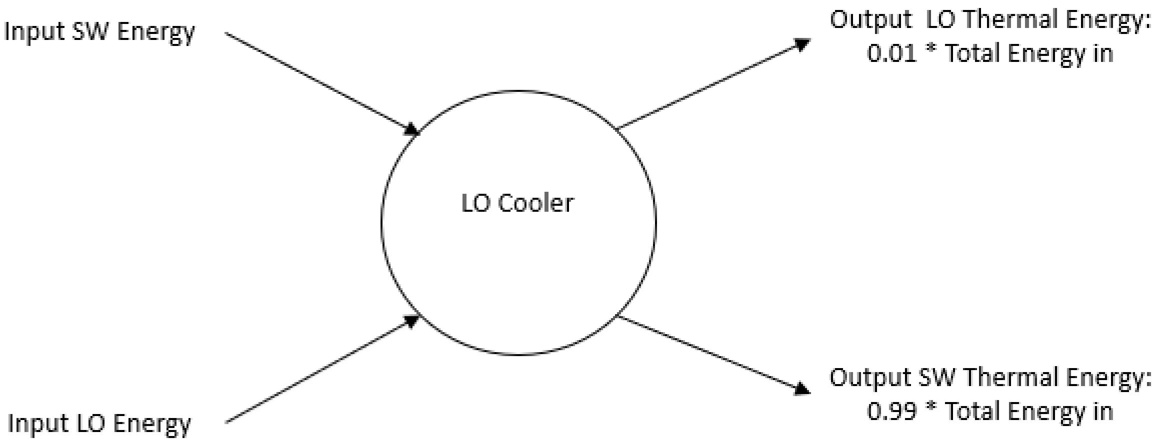


Figure 49 - Nodal Model for LO Cooler

Two different types of electric-driven pumps are modeled in the AFO. One with a static electric load and the other with an electric load dependent on the energy flow which must be processed through the node, called flow-dependent pumps, both described in Section 3.2.2. Figure 50 illustrates a common model for several flow-dependent nodes including a LO Motor Driven pump, SW Service pumps, CW Pumps, HFC Compressors, Glycol circulation pumps and EC circulation pumps.

At these nodes, the quantity of energy entering the node's port from the node's assigned plex is determined within CPLEX for the scenario being evaluated. This quantity is then multiplied by a coefficient located in the MEL to determine the ELEC energy required by the pump to process the previously determined amount of energy through the node. The total input energy is then distributed to the outgoing arcs by following the output coefficients for that node in the MEL like other standard nodes.

Static electric load pumps are determined by the DV's chosen and have an electric load specified in the MEL. Examples of these include FO system pumps, Fire pumps, AFFF pumps, and steering gear hydraulic pumps.

Other static electrical loads include control and combat system items where the load may be based on operating condition (cruise, sustained or battle). The entire electric load required by CS and control nodes is assumed to become heat which must be removed by either the HVAC, CW, EC or Glycol cooling plexus as shown in Figure 51.

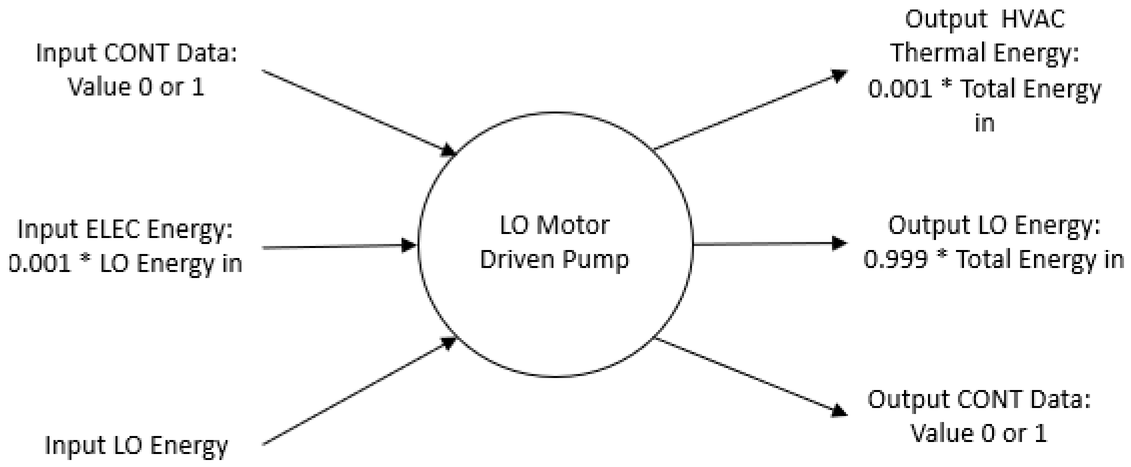


Figure 50 - Nodal Model for LO Motor Driven Pump and other Flow dependent VC's

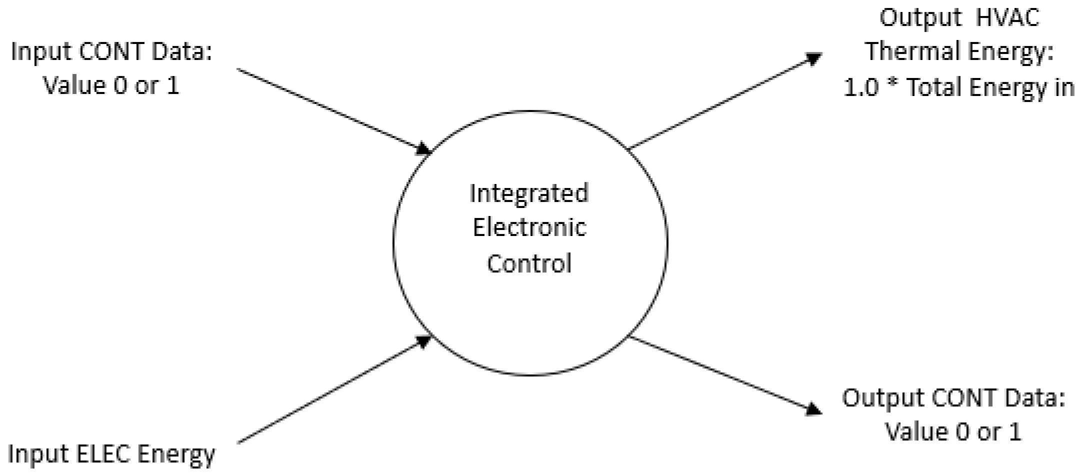


Figure 51 - Nodal Continuity for Integrated Electronic Control Node

3.6 Mathematical Formulation

To expand upon Trapp's model, new plexus and new architecture framework definitions were developed and applied to a new Architecture Flow Optimization (AFO) model. This model incorporates not only physical definitions of how a commodity could move through the logical architecture, but also how the commodity flowing through the network could affect the other components and plexus within the larger network.

The logical architecture provides a framework to relate the components' connectivity while physical constraints were imposed after nodes were assigned to a SDB in the preliminary arrangement. Operational constraints placed on the network require adequate redundancy and reserve capacity to ensure network feasibility through a series of scenarios.

These new nodal equations and optimization constraints can accurately model nodal continuity, energy allocation and dispersion into arcs of various commodities, and determine the electrical load required to transport these commodities. Furthermore, calculations of commodity flows are postponed until after component sizing by considering energy as the only commodity in the AFO.

$$\boldsymbol{Minimize}:$$

$$\sum_{(i,j)\in E} \Pi_{i,j}\, X_{i,j} + \pi_{i,j}\, x_{i,j} \qquad (i,j) \in E \qquad \text{(3-1)}$$

$$\boldsymbol{Subject\ To}:$$

$$\sum_{(i,j)\in E}^{k} x_{i,a}^{k} - \sum_{(i,j)\in E}^{k} x_{a,j}^{k} = s_{a}^{k} \qquad (i,j) \in E,\ (a \in N), (k \in K) \qquad \text{(3-2)}$$

$$\sum_{(i,j)\in E}^{k} x_{source,j}^{k} \leq s_{a}^{k} \qquad (i,j) \in E,\ (a \in N), (k \in K) \qquad \text{(3-3)}$$

$$\sum_{(i,j)\in E}^{k} x_{i,sink}^{k}\ ,\ \geq s_{a}^{k} \qquad (i,j) \in E,\ (a \in N), (k \in K) \qquad \text{(3-4)}$$

$$C_{j,a_{MEL}} \sum_{(i,j)\in E}^{k} x_{i,a}^{k} - x_{a,j}^{k} = 0 \qquad (i,j) \in E,\ (a \in N), (k \in K) \qquad \text{(3-5)}$$

$$C_{a,e_{MEL}}\, x_{i,a}^{k,p} - x_{e,,a}^{ELEC} = 0 \qquad (i,j) \in E,\ (e \in N), (k \in K), (p \in P) \qquad \text{(3-6)}$$

$$x_{i,j}^{k} = s_{a}^{k} \qquad (i,j) \in E,\ (a \in N), (k \in K) \qquad \text{(3-7)}$$

$$x_{i,j}^{k,m} = 0 \qquad (i,j) \in E,\ (m \in M), (k \in K) \qquad \text{(3-8)}$$

$$x_{i,prop\_SYS}^{k} - x_{j,prop\_SYS}^{k} = 0 \qquad (i,j) \in E,\ (prop\_sys \in N), (k \in \{1,2,3\}) \qquad \text{(3-9)}$$

$$x_{PGM/SPGM,j}^{k} \leq MCR_{engine} \qquad (i,j) \in E, (k \in K) \qquad \text{(3-10)}$$

$$x_{i,j}^{k} \geq 0 \qquad (i,j) \in E, (k \in K) \qquad \text{(3-11)}$$

$$x_{ij}^{k} \leq x_{ij} \qquad (i,j) \in E, (k \in K) \qquad \text{(3-12)}$$

$$X_{i,j} \in \{0,1\} \qquad \text{(3-13)}$$

3.6.1 Description of Variables

A description of variables for Equations (3-1) to (3-13) is listed below:

- Sets of indices of the equations
    - $(i,j) \in E$ is an arc from node i to node j located within the system as a member of the set of arcs E
    - $(a \in N)$ where a is a node within the set of nodes N
    - $(n \in N)$ where n is a node within the set of nodes N
    - $(k \in K)$ where k is the specified scenario within the set of scenarios K
    - $(m \in M)$ where m is the specified damage scenario within the set of damaged scenarios M
    - $(p \in P)$ Where p is a plex within the set of plexus P being evaluated within the network.
- Within Equation 3-1, the Objective Function:

  $\Pi_{i,j}$ represents the fixed cost associated with the engineering and installation costs associated with the arc. Fixed costs vary by type of arc and what commodity is being carried as well as the physical location of the arc, as an arc traveling through bulkheads and between SDB's can be considered costlier to engineer and install than one which remains within its own SDB.

  $X_{i,j} \in \{0,1\}$ is the binary value of the fixed cost of installation. The inclusion of the fixed cost equation in the objective function encourages the optimizer to minimize the number of arcs/edges /nodes within the system.

  $\boldsymbol{\pi_{i,j}}$ is the cost per unit flow associated with both the type of arc *(i,j)* and the total length of the arc as based upon Trapp's calculations. (Trapp 2015).

  $\boldsymbol{x_{i,j}}$ is the decision variable indicating the quantity of energy flow through arc *(i,j)*
- $x_{i,j}^{k}$ indicates the quantity of energy flow moving through arc *(i,j)* in scenario *k*
- s_{a}^{k} indicates the quantity of energy demanded by node *a* in scenario *k*.
- $\boldsymbol{C_{j,a_{MEL}}}$represents the coefficient associated with the plex of outgoing arc *j* from the MEL coefficient matrix of node type *a*.
- $\boldsymbol{C_{a,e_{MEL}}}$ represents the electrical energy coefficient associated with the plex *p* of the arc incoming to node *a*.
- $x_{i,a}^{k,p}$ represents the energy flow of plex *p* entering node *a* in scenario *k*.
- $x_{e,,a}^{ELEC}$ represents the quantity of electrical energy required for pumps whose flow is dependent upon the quantity of energy incoming from another plex. This represents the electrical energy required for the node to function properly and the network to remain feasible.
- $x_{i,j}^{k,m}$ represents when the flow through arc *(i,j)* should be set to zero for either damage or flow control circumstances.
- $x_{j,prop\_SYS}^{k}$ represents the MECH energy leaving the propeller at node *j* to the collection point of zonal propulsion node *Prop_SYS.*
- MCR_{engine} is the Maximum Continuous Rating from the engines and is the only upper bound in the network.

3.6.2 Objective Function

As in all linear programming, the objective function states the goals of the optimization for the representative design. Like the previous Trapp examples, the goal of the objective function is to minimize the aggregate flow capacity and fixed costs associated with supporting this network. The objective function as previously defined is comprised of four components, variable costs, variable flows (decision variables), fixed costs and binary variables in the form shown below:

$$\boldsymbol{Minimize}:$$

$$\sum_{(i,j)\in E} \Pi_{i,j}\, X_{i,j} + \pi_{i,j}\, x_{i,j} \qquad (i,j) \in E \qquad \textbf{(3-1)}$$

3.6.3 Constraint Equations

Equation (3-2) specifies the continuity of energy entering and leaving a generic node in the system. s_a^k is dependent on both the specific node a and the scenario k being evaluated, with a necessary value of zero, indicating that all the energy that enters the node must leave the node. It also acts as a numerical slack variable for the CPLEX optimization.

$$\sum_{(i,j)\in E}^{k} x_{i,a}^{k} - \sum_{(i,j)\in E}^{k} x_{a,j}^{k} = s_a^k \qquad (i,j) \in E,\ (a \in N), (k \in K) \qquad \textbf{(3-2)}$$

Equations (3-3) and (3-4) describe the relationships at terminal nodes in the system where energy is either added or removed from the system. At specified nodes such as the Propulsion_SYS collection node, s_a^k is assigned a specified value that the sum of energy entering the node must equal or exceed. In other system nodes, such as at calculated non-AFO thermal source nodes or non-AFO electrical sink nodes, the value of s_a^k is specified as having a particular value. The value of s_a^k at all other terminal nodes (FO Source, SW Sink, External Air Source & Sink) are set to zero, allowing the network to scale energy flowing in and out as required by the nodal constraints.

$$\sum_{(i,j)\in E}^{k} x_{source,j}^{k} \leq s_a^k \qquad (i,j) \in E,\ (a \in N), (k \in K) \qquad \textbf{(3-3)}$$

$$\sum_{(i,j)\in E}^{k} x_{i,sink}^{k}\ , \geq s_a^k \qquad (i,j) \in E,\ (a \in N), (k \in K) \qquad \textbf{(3-4)}$$

At nodes where more than one output is required to model the component, coefficients stored in the MEL coefficient matrix are applied in the constraints. Equation (3-5) is utilized for all outgoing arcs from node a. The energy entering node a is summed and then based on the coefficient matrix values, the outgoing arcs receive the proportion of energy specified by the coefficients.

$$C_{j,a_{MEL}} \sum_{(i,j)\in E}^{k} x_{i,a}^{k} - x_{a,j}^{k} = 0 \qquad (i,j) \in E,\ (a \in N), (k \in K) \qquad \textbf{(3-5)}$$

The equation for flow-dependent nodes, (3-6), calculates the ELEC energy demanded by a pump based on the energy flow that must be pumped through it as illustrated in Figure 50.

$$\boldsymbol{C_{a,e_{MEL}}\, x^{k,p}_{i,a} - x^{ELEC}_{e,,a} = 0 \qquad (i,j) \in E,\ (e \in N), (k \in K), (p \in P)} \qquad \textbf{(3-6)}$$

Fundamentally, Equations (3-5) and (3-6) are a key new feature in the AFO mathematical formulation. These equations allow the user to adjust how energy flows through the network based on the component models as specified in their coefficient vector. This also postpones the calculation of the commodity flow through the architecture until the AFO is complete

In cases where, the electrical load for node "a" is known for the given condition k, and not based upon the flow through a given node, the load is static. This operational requirement is achieved by setting the incoming ELEC arc to the specified energy flow value. In future cases, the incoming arcs may become a summation to allow for alternative power sources such as stored energy or a pulse forming network in addition to the zonal electrical distribution nodes.

$$\boldsymbol{x^{k}_{i,j} = s^{k}_{a} \qquad (i,j) \in E,\ (a \in N), (k \in K)} \qquad \textbf{(3-7)}$$

To accomplish the simulation of damaging nodes, the energy flow for each arc entering and exiting the damaged node is set to zero as shown in (3-8). Within the physical architecture, if a set of nodes are to be damaged, this method is repeated for all related arcs. The AFO examines M-1 survivability conditions where if an arc originates or terminates in a selected SDB (or all nodes in a SDB), the energy flowing in these arcs is set to zero. Each SDB is selected to be "damaged" one at a time over a series of scenarios evaluated by the AFO. Each scenario k is associated with a set of arcs m which are either available or not available based on their location in the set of SDBs M.

$$\boldsymbol{x^{k,m}_{i,j} = 0 \qquad (i,j) \in E,\ (m \in M), (k \in K)} \qquad \textbf{(3-8)}$$

In addition to M-1 damage scenarios, other scenarios shutting down specific components identified by the designer can be evaluated by specifying a set of arcs as unavailable. For the purposes of the AFO, an endurance cruising condition is evaluated where the PGMs are listed as unavailable and thus, all energy produced and used by the system must originate from the SPGMs. This scenario represents the ability of the ship to meet all electrical loads while transiting over large distances where speed is not the primary objective and provides a template for future specified scenario development.

Similarly, in areas where there is a physical connection between nodes, but logically there is no means for energy to flow through that arc, the arc is set to zero in the same manor an arc is damaged. An example of this is where the HFC system meets the CW system. If left un constrained, the optimizer could direct energy to flow "upstream" and from the HFC plex into the CW which is not how the system is designed to operated.

In some cases, an additional operational constraint is placed on the system beyond the nodal electric load requirements. In the standard operating conditions of sustained speed, endurance speed and battle condition, the propulsion delivered to each propeller is required to be equal. This forces the optimizer to produce a result with a balanced mechanical system to propel the ship while operating in normal conditions. Without this requirement, the optimizer will identify an unbalanced propulsion system where one shaft is capable of providing enough power to meet the sustained speed requirement and with a redundant shaft capable of meeting the propulsive load required under damaged conditions where the first shaft is not available.

$$\boldsymbol{x^{k}_{i,prop\_SYS} - x^{k}_{j,prop\_SYS} = 0 \qquad (i,j) \in E,\ (prop\_sys \in N), (k \in \{1,2,3\})} \qquad \textbf{(3-9)}$$

This operational constraint also provides another potential use for the AFO. By requiring arcs to be of equal size, a designer can program in an analysis of various maintenance and logistic strategies to be analyzed.

The only set of arcs subject to an upper bound, are the primary output arcs of the engines as described in Equation (3-10). This upper bound is determined by the designer as part of the design process.

$$\boldsymbol{x^{k}_{PGM/SPGM,j} \leq MCR_{engine} \qquad (i,j) \in E, (k \in K)} \tag{3-10}$$

All arcs are subject to a lower bound where the flow of energy is not permitted to go in reverse from head to tail. This prevents any back flow of energy through the network.

$$\boldsymbol{x^{k}_{i,j} \geq 0 \qquad (i,j) \in E, (k \in K)} \tag{3-11}$$

As discussed in Section 2.4, an aggregate flow is the flow through an arc representing the scenario in which the arc required the greatest capacity. The Aggregate is calculated as shown in Equation (3-12) where the objective decision variable $\boldsymbol{x_{ij}}$ is always greater than or equal to the flow encountered through that arc in any scenario examined.

$$\boldsymbol{x^{k}_{ij} \leq x_{ij} \qquad (i,j) \in E, (k \in K)} \tag{3-12}$$

As described in Section 3.6.1 the binary constraint encourages the optimizer to minimize the number of arcs required within the system while maintaining its prescribed functionality. Equation (3-13) describes how the Binary variable works within the objective function.

$$\boldsymbol{X_{i,j} \in \{0, 1\}} \tag{3-13}$$

3.7 Operational Architecture and Standard Scenarios

Within each scenario imposed on the network, certain outcomes must be attained for the network to be considered feasible. In a US Navy ship, it is expected that propulsion will always be available for the ship and that a minimum speed in each scenario is attainable. Using the process described in Chapter 1, the representative hull design is associated with a speed-power curve where the power required for a particular ship speed is calculated and can be specified as an energy output from the two propellers at the Propulsion _SYS node.

In addition to propulsion power, electric (ELEC) energy requirements are specified for each scenario *k* for the Combat System and PSYS nodes. Combat System loads vary depending on the scenario. These nodes require a baseline level of electric energy when operating in a cruising condition, and additional energy when operating in various other battle conditions and scenarios. Specific standard operating conditions are described in the following paragraphs.

The first scenario evaluated by the AFO is the “Cruise Condition” where the propulsive energy required is set to the calculated maximum speed attainable by the hull form given the propulsive power available onboard. This threshold value is imported from the SSM and was calculated during the initial representative design set up.

The Combat System requirements for scenario 1 include supporting the cruising energy requirements for the installed nodes as indicated in the CSEL and CS physical architecture. As these CS bring in ELEC energy to function, their nodal continuity requires them to output thermal energy which must be processed by one of the PSYS thermal energy plexus (HVAC, CW, Glycol, EC). The scenario and design are considered feasible if both the propulsive power requirement is met and all the other PSYS/CS stated loads are satisfied.

The second scenario evaluated by the AFO is considered the “Endurance Condition” where the propulsive energy required is chosen from the location along speed power curve which corresponds to the user defined transient speed. Transient speeds are slower than the maximum sustained speeds and due to the exponential relations hip between increased speed and increased power required, the power required in endurance condition can be considerably less than the cruising condition.

The Combat System load requirements for endurance condition mirror those of the cruising condition, and likewise, all the thermal energy produced by those systems must also be removed in the same manner.

Endurance Condition would be utilized by the US Navy when fuel efficiency and other factors take precedence of speed and timeliness of transit. Because of this desire for a fuel efficient transient condition, the energy entering and exiting a ship’s PGMs or MPEs is set to zero. This forces the entire propulsive and combat system requirements to be achieved using only the SPGM’s and SSDGs.

The third and final operational scenario evaluated is described as the “Battle Condition” where the propulsive loads are increased and the Combat System ELEC energy requirements change from their cruising electric draw to their battle electric draw as dictated by the CSEL. In a traditional mechanical drive ship, the propulsive energy for battle condition will match the propulsive energy required at cruising condition as all MPE’s are brought online.

In an IPS ship, it is not possible to dedicate all the energy produced by a PGM to propulsion, as the energy produced is a resource which must be shared with the Combat Systems ELEC requirements. Due to the limited quantity of energy available to the system because of the engines' MCR, the combat system nodes will receive their energy requirements first and the propulsive energy requirement is calculated as the residual energy available after all other operational requirements are satisfied. This sharing of resources is what makes the IPS ship an ideal candidate for the AFO.

3.8 Survivability and Operability in M-1 Scenarios

The scenarios following the standard intact operational conditions in the AFO incorporate damage and survivability into the network. Similar to how Trapp defined an M-1 network survivability as the ability of the system to sustain the loss of any single arc, one at a time while still meeting the overall system requirements; the AFO uses its own M-1 scenario based on SDB’s. The AFO’s M-1 condition shows the system can meet its operational requirements if any single SDB is removed from consideration by the AFO. In addition to the standard three scenarios previously discussed the AFO creates as many M-1 scenarios as there are SDB’s where each SDB is systematically “damaged” one at a time and that scenario is then added to the total set of scenarios to be optimized by the AFO.

The SDB is figurately removed from consideration by the network by setting the energy flow for all arcs originating or terminating in that SDB to zero. The goal is for the network to adapt and work around the “damaged” SDB to support the rest of the network through the existing logical architecture.

The operational conditions for the M-1 scenario include meeting all battle condition combat system loads as stated in the CSEL for all nodes outside of the damaged SDB. To account for the potential loss of power generation, the propulsive power required for each M-1 scenario is equal to that of the endurance condition.

These operational requirements ensure survivability is designed into the ship at the early stages of ship design and demonstrate its ability to “fight through” basic damage conditions.

Within the M-1 scenarios, the ship should can defend itself both through both its maneuverability and combat system capabilities.

3.8.1 Redundancy and Reserve Capacity

Considering the series of scenarios as one network architecture to be optimized does create a potential conflict when reviewing the results. As each scenario is taken into consideration, the aggregate scenario will likely not result in a combination of energy flows which matches exactly the optimal solution in any single scenario. This is due to reserve capacity and redundancy which must be built into the network to support all the scenarios but may not be required to support each individual scenario.

Reserve capacity in each arc refers to the excess capacity which is available to the specified arc in one scenario because the arc is required to support a greater energy flow in another. Because of this, it could be expected that while it may be optimal to route energy through one section of the architecture, if the optimizer has already "bought and paid for" the fixed cost and variable capacity elsewhere in the network, the optimizer will seek out that path to satisfy the requirements before exploring new paths.

Redundancy in the architecture is similar to reserve capacity. While examining the loss of all SDB's in the M-1 scenarios, arcs of the same plex connecting two locations may be required to remain in the network architecture. For example, if a string of electrical cables is traveling in parallel down both the port and starboard side of the ship, and one SDB is lost on the port side, the electrical capacity would be picked up by the starboard side cable. Likewise, if the starboard side SDB was lost, the electrical capacity required would be incorporated into the port side electrical cable. Thus, the optimizer may provide two redundant arcs carrying of same media in the aggregate solution.

3.9 Conclusions

Modeling the representative design in steady state, as a system of systems or a network, contains tremendous potential. In this method, energy flows between various commodities can be modeled and quantified and will allow the designer to ensure the appropriate machinery is in the optimal location to support the higher-level energy systems incorporated on a future Navy ship.

Leveraging the LP optimizers and NSMCF methodology discussed in Chapter 2, the energy flow and nodal requirements for each component modeled can be identified for any operational or damaged scenario desired (Trapp 2015). Quantifying flow through an arc as a variable cost based off the arcs capacity and the fixed costs associated with binary variables ensure the optimizer seeks the minimal network required to support the operational requirements of the ship as a whole (Trapp 2015).

Permitting the components to scale up and down to meet the operational demands based upon the output potential from each engine, ensures a wholistic design is considered throughout the optimization process. Constitutive relationships between components based upon efficiencies defined for each component type within the MEL and CSEL highlights the interconnectedness of each component, each plex/commodity and the ship as a whole.

3.10 Problem Pre and Post Processing

The process for extracting information contained within the SSM and developing a representative set of linear programming equations through MATLAB is shown in Figure 52.

The DV tab of the SSM defines which logical architectures are extracted from the SSM and containing the specified information.

Within the pre processing step of the AFO, the linear programming architecture is defined. Initially a list of all the logical node connections are compiled beginning with the explicit arcs from the PSYS, AAW, ASUW and ASW tabs. Each arc is assigned a specific number to be tracked through CPLEX and the associated nodal information is compiled. Nodal information is collected for both the arc head ("to") and tail ("from") including the node number, node name, compartment assigned, assigned SDB, equipment list number, distance between nodes, as well as fixed cost, variable cost and the MEL coefficient associated with the tail. This process is then repeated for every implicit (interplex) arc.

Once the entire architecture is compiled, the scenario matrix is organized. The matrix contains as many rows as there are arcs within the system and as many scenarios as there are SDB's plus the 3 standard conditions of Sustained speed, Endurance speed and Battle condition. Initially every arc is available to the system as designated by a 1 in each cell of the matrix. For endurance condition, the primary power/propulsion engines are turned off and all the arcs coming to or leaving these nodes will have their associated flow set to zero. After this, the writing file sequentially goes through the number of SDBs and if an arc's heat or tail resides with the SDB the flow through that arc is set to zero. This does not take into account arc routing, only the starting and ending points for the arcs.

MATLAB can begin writing the network in a LP format understood by CPLEX after this point. For each scenario being evaluated, MATLAB will look through the series of equations discussed in Section 3.6. Each node within the architecture will be evaluated for continuity. If the node is a terminal sink such as the Propulsion_SYS, it will be required to receive at least as much energy as was calculated by the SSM for the given Sustained, Endurance or Battle Condition. If the scenario being evaluated is a damaged scenario, the propulsion system requirement will be equal to the propulsion required to achieve endurance speed. After each node has been evaluated for continuity, the coefficient matrix parses out the sum of energy entering a node to the outgoing arcs by the coefficient assigned to each of the arcs.

To ensure fixed costs are incorporated into the objective function, binary variables are introduced. Binary variables indicate if any flow is required by the optimizer to travel through a certain arc, the fixed costs associated with that arc exist regardless of the flow capacity. Because of this the optimizer will seek to minimize the number of new arcs added to the architecture.

The final phase of writing the representative design architecture as a LP problem is the aggregate or "roll up" function. The aggregate arc is the are in the objective function and represents the maximum capacity required by the network to support the system in all of the defined scenarios.

Once the optimization is complete the resulting flows may be extracted from a text file. To extract the flows the unique arc number scenario matrix is created where the quantity of energy flowing through each arc in each scenario can be documented.

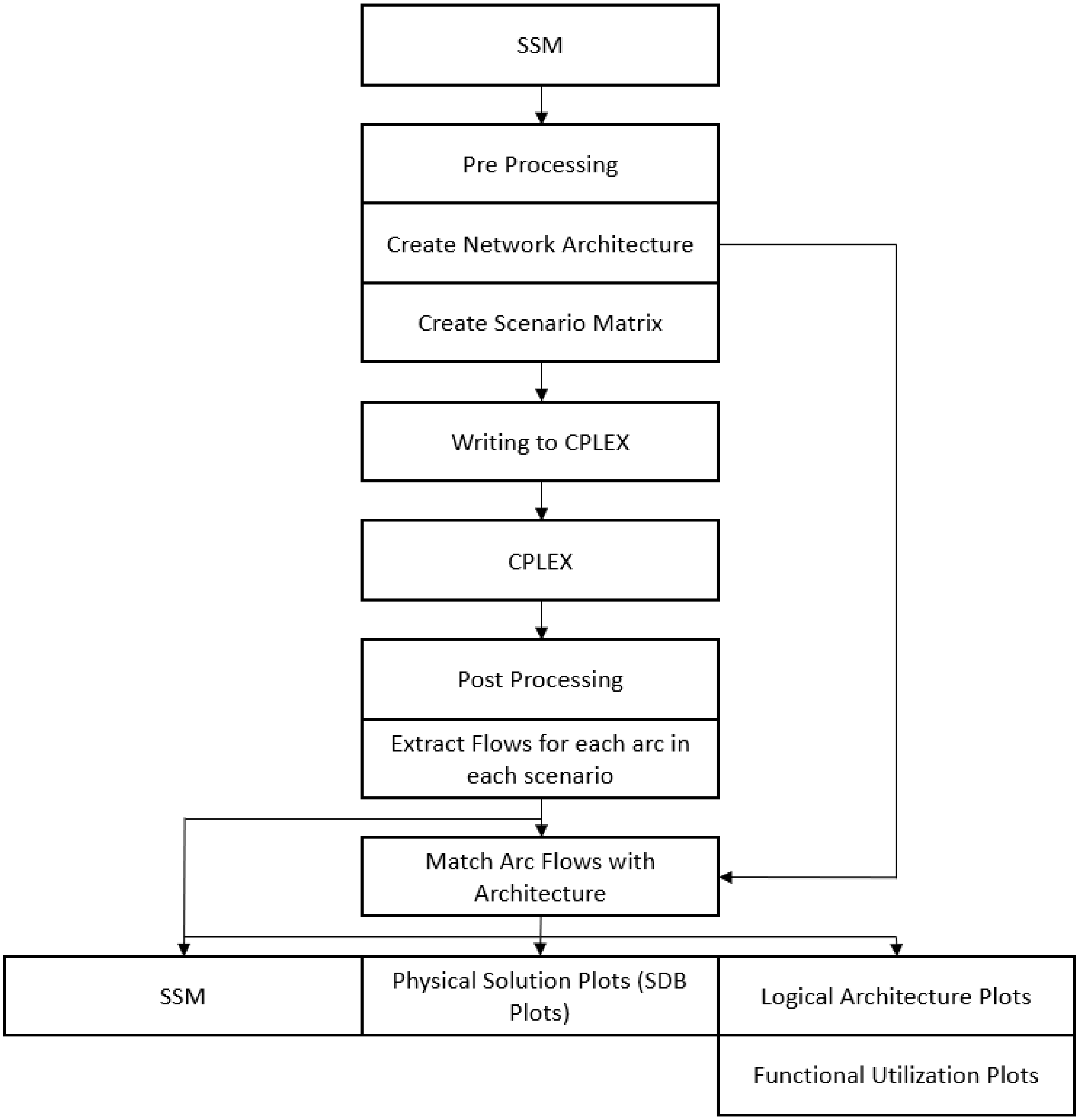


Figure 52 - AFO Process Flow

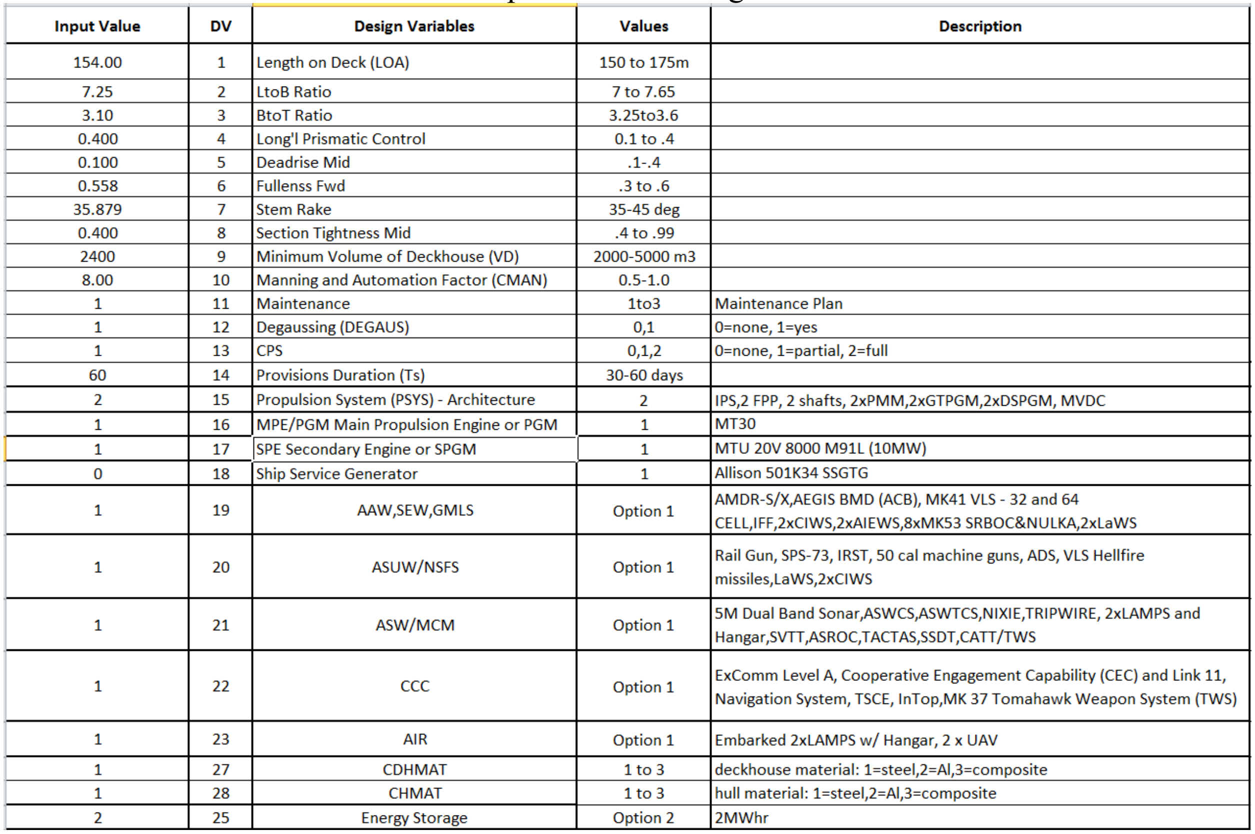
4 Architecture Flow Optimization Case Study and Results

4.1 Case Study Representative Design and Physical Architecture

To demonstrate the AFO tool and use its visualization tools for troubleshooting and understanding, a case study was performed following the CPES design process shown in Figure 22. This section will follow and in this CPES process through the AFO Exploration.

The mission need is for a future (large) surface combatant having capabilities to employ high energy weapons and sensors. The seven most demanding technologies considered in the concept and requirements exploration (C&RE) are rail gun, ASMD Radar, Active Denial System (ADS), Dual-Band Sonar, Laser Weapon System (LaWS) and a Medium Voltage DC Integrated Power System with Energy Storage. These technologies are included in CPES system option DVs: AAW=1, ASW=1, ASUW=1, CCC=1, PSYS=2 and ENER=2. The full set of design variable values for this representative design is listed in Table 4.

Table 4 – Representative Design DV Values



Input Value	DV	Design Variables	Values	Description
154.00	1	Length on Deck (LOA)	150 to 175m	
7.25	2	LtoB Ratio	7 to 7.65	
3.10	3	BtoT Ratio	3.25to3.6	
0.400	4	Long'l Prismatic Control	0.1 to .4	
0.100	5	Deadrise Mid	.1-.4	
0.558	6	Fullenss Fwd	.3 to .6	
35.879	7	Stem Rake	35-45 deg	
0.400	8	Section Tightness Mid	.4 to .99	
2400	9	Minimum Volume of Deckhouse (VD)	2000-5000 m3	
8.00	10	Manning and Automation Factor (CMAN)	0.5-1.0	
1	11	Maintenance	1to3	Maintenance Plan
1	12	Degaussing (DEGAUS)	0,1	0=none, 1=yes
1	13	CPS	0,1,2	0=none, 1=partial, 2=full
60	14	Provisions Duration (Ts)	30-60 days	
2	15	Propulsion System (PSYS) - Architecture	2	IPS,2 FPP, 2 shafts, 2xPMM,2xGTPGM,2xDSPGM, MVDC
1	16	MPE/PGM Main Propulsion Engine or PGM	1	MT30
1	17	SPE Secondary Engine or SPGM	1	MTU 20V 8000 M91L (10MW)
0	18	Ship Service Generator	1	Allison 501K34 SSGTG
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
1	20	ASUW/NSFS	Option 1	Rail Gun, SPS-73, IRST, 50 cal machine guns, ADS, VLS Hellfire missiles,LaWS,2xCIWS
1	21	ASW/MCM	Option 1	5M Dual Band Sonar,ASWCS,ASWTCS,NIXIE,TRIPWIRE, 2xLAMPS and Hangar,SVTT,ASROC,TACTAS,SSDT,CATT/TWS
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)
1	23	AIR	Option 1	Embarked 2xLAMPS w/ Hangar, 2 x UAV
1	27	CDHMAT	1 to 3	deckhouse material: 1=steel,2=Al,3=composite
1	28	CHMAT	1 to 3	hull material: 1=steel,2=Al,3=composite
2	25	Energy Storage	Option 2	2MWhr

After completing hullform exploration and refining the hullform design space, a representative design (hullform and deckhouse) is created, shown in Figure 53, consistent with this selection of hullform DV options. System option logical architectures are those shown previously in Figure 5 through Figure 16. VC data for weight, space and power are as listed in the MEL and CSEL, examples shown previously in Section 1.2.1.

Next, subdivision blocks (SDBs) are created for the representative hullform and deckhouse as shown in Figure 54. Compartments are assigned to the SDBs as shown previously in Figure 18 and nodes are placed at the center of the SDBs as shown in Figure 19 (3D) and Figure 55 (Profile). This is the initial design physical architecture.

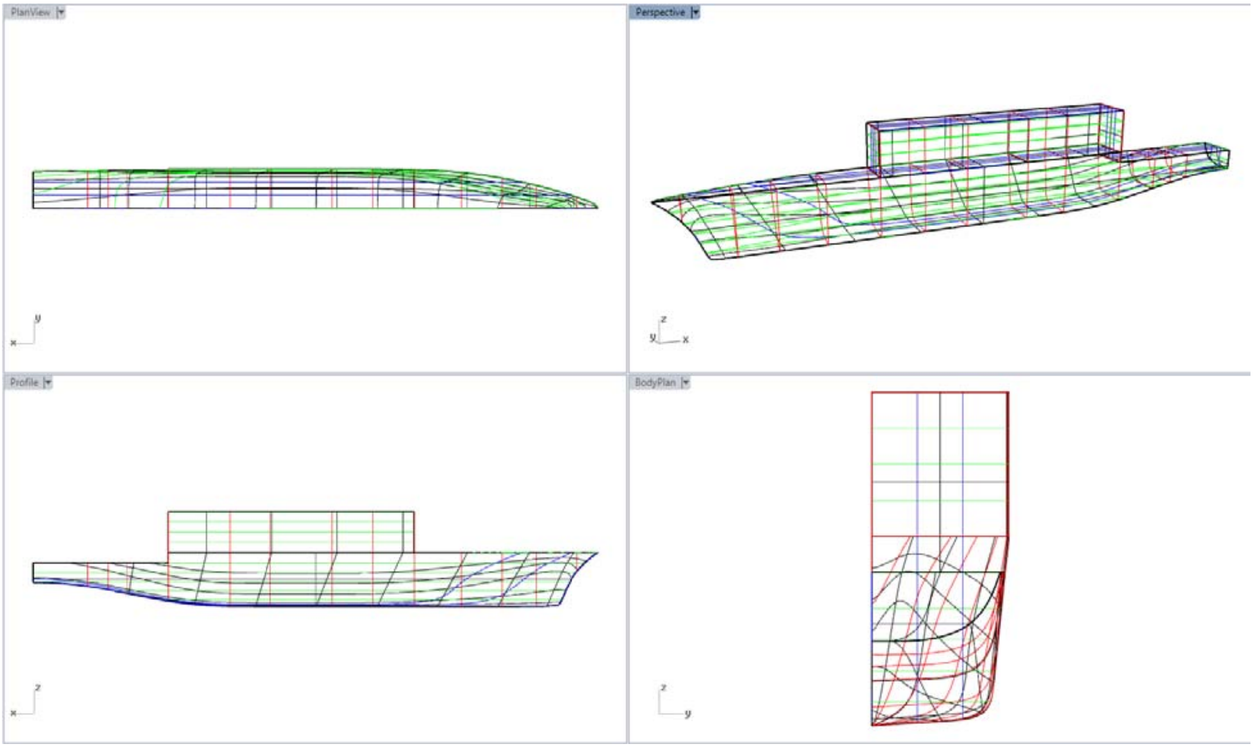


Figure 53 - Representative Hullform and Deckhouse Envelope

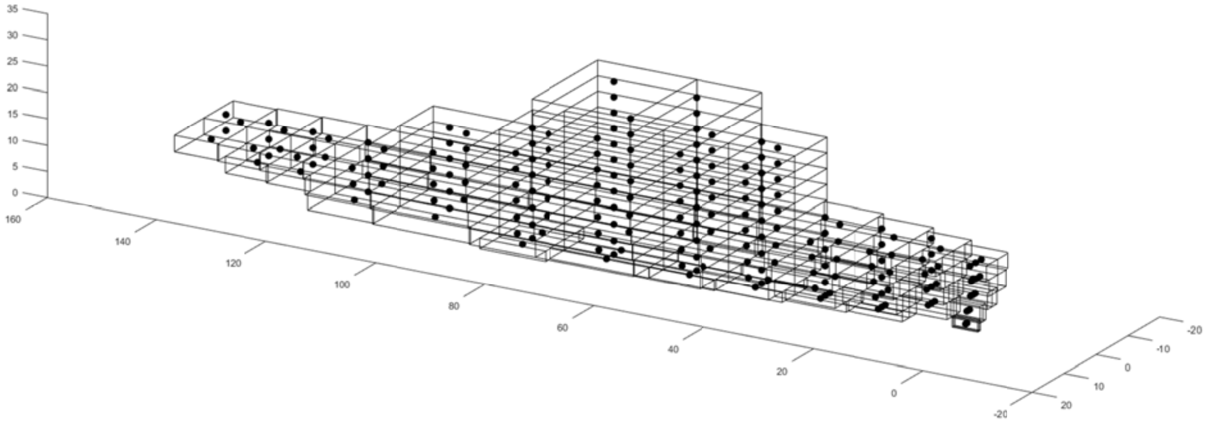


Figure 54 - Representative Hullform and Deckhouse Subdivision Block (SDBs) and Nodes

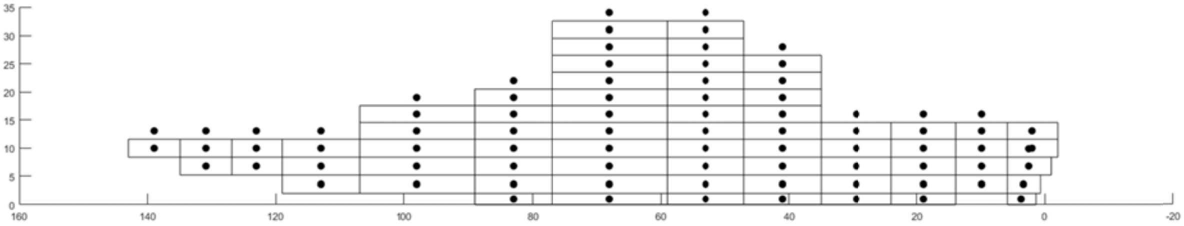


Figure 55 - Profile View with SDB Nodes

The PSYS worksheet data includes the assignment of VCs to compartments and since compartments are assigned to SDBs, VCs are assigned to SDBs, and this represents the first intersection of logical and physical architecture, part of the physical solution. This enables a good estimate for the distance between logical nodes which is used in the AFO to specify the length of piping, cable and shafting, part of the cost estimate.

The Operational architecture associated with this representative design include being able to produce 51MW of propulsion power at sustained speed resulting in an estimated top speed of 29.59 knots. In the endurance condition, the propulsive power required is 4.2MW to attain a speed of 16 knots. In the Battle condition, only 19MW is available for propulsion power of sufficient for an estimated 26.6 knots while supporting high level energy systems including the 32MJ railgun, two 3.3 MW X/S band radars and 2.1MW Laser Weapons System.

Once all of these steps in Figure 22 have been completed, the actual AFO can begin. System and ship data is extracted from the SSM and the CPLEX input file is created using our pre-AFO MATLAB code. CPLEX is run and its output data is process using our post-AFO MATLAB code as described in Section 3.10. Results can then be visualized and assessed.

4.2 Flow Visualization Results

Scenario visualizations presented in this chapter begin with the baseline connectivity of Scenario 0 (Figure 56 and Figure 57), where only the basic connection between components is shown in the Pre-AFO condition. This visualization is difficult to display as a profile or 3D image in the physical domain as nodes are all placed in the center of the SDB's and all arcs travel in a delta y, delta z, delta x path. Thus, only MECH (grey), ELEC (red), CW (blue) and SW (green) plexus are displayed to reduce clutter in the image and avoid overlapping visual arcs to the maximum extent possible.

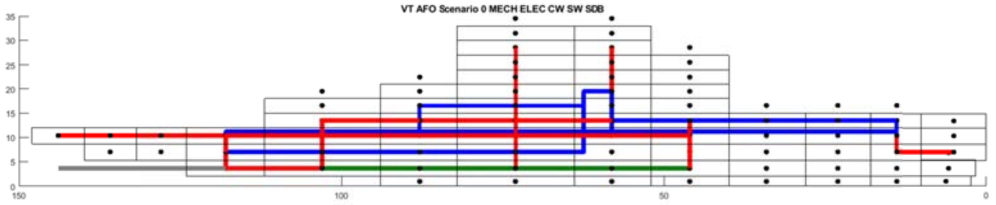


Figure 56 - Pre AFO Profile View

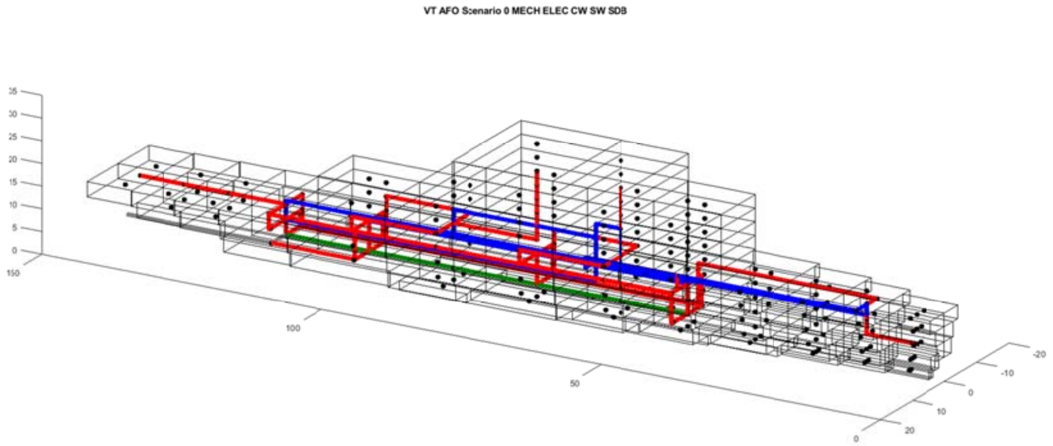


Figure 57 - Pre AFO 3D View

The same plexus are shown for Scenario 1, Sustained speed condition (Figure 58 and Figure 59), Scenario 2, Endurance speed condition (Figure 60 and Figure 61) , and Battle Condition (Figure 62 and Figure 63).

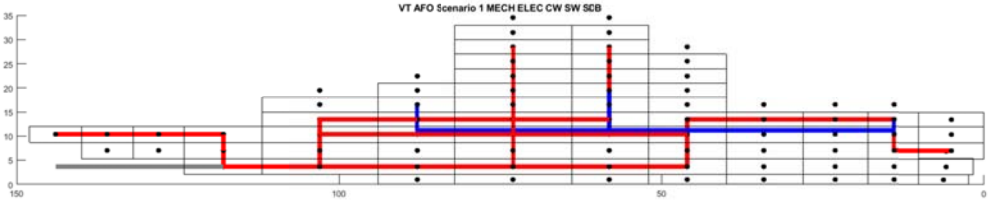


Figure 58 - Sustained Speed Profile View

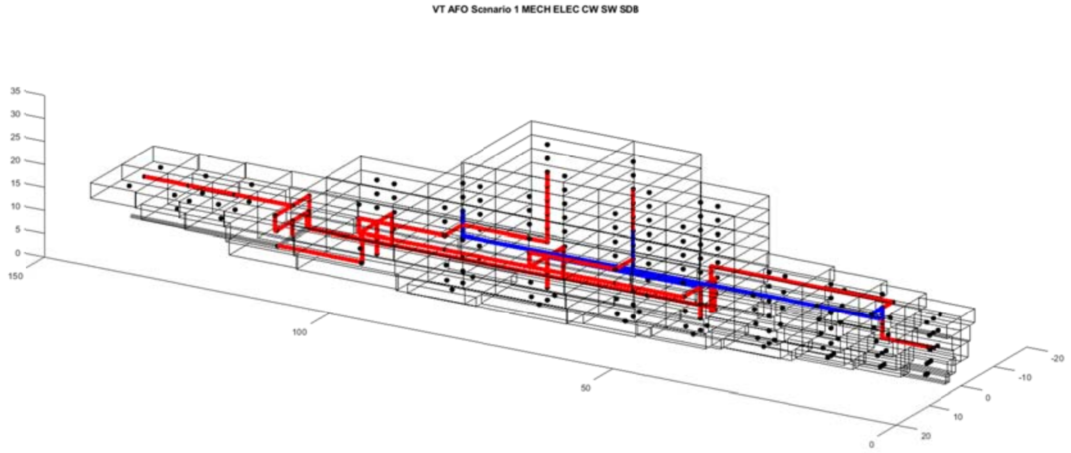


Figure 59 - Sustained Speed 3D View

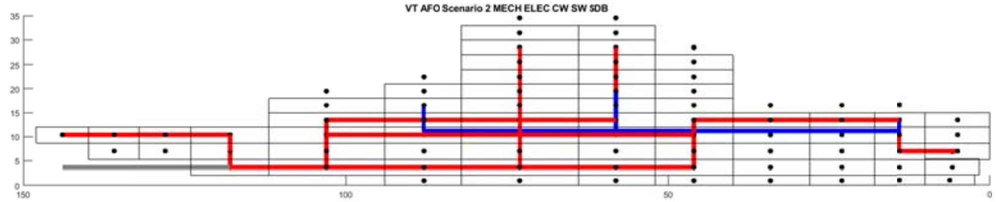


Figure 60 - Endurance Speed Profile View

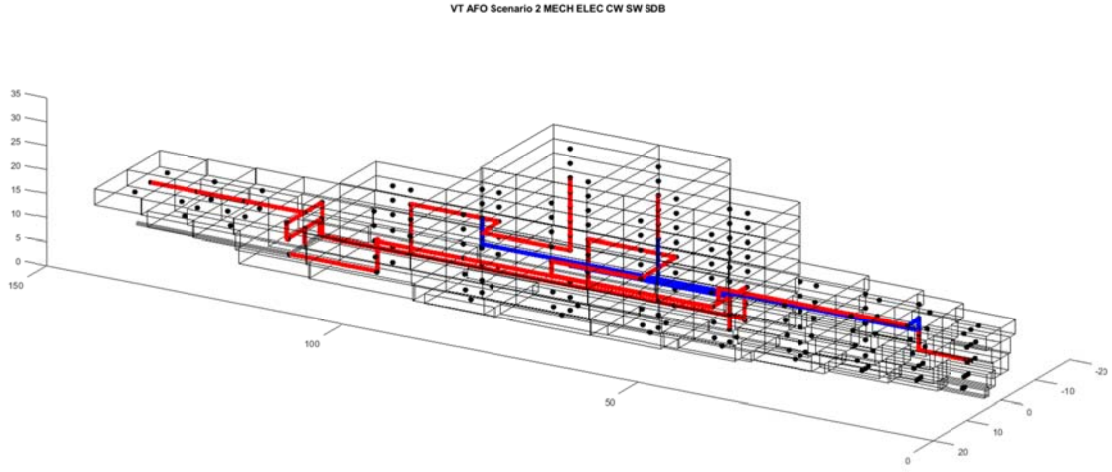


Figure 61 - Endurance Speed 3D View

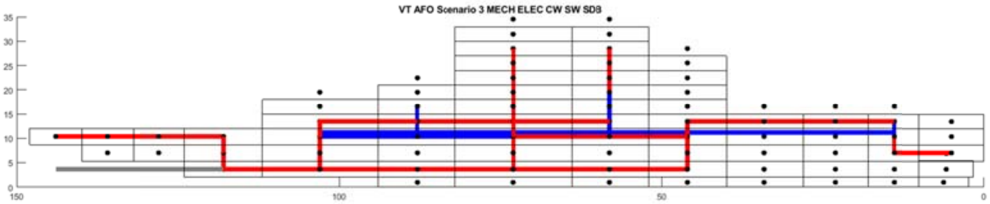


Figure 62 - Battle Condition Profile View

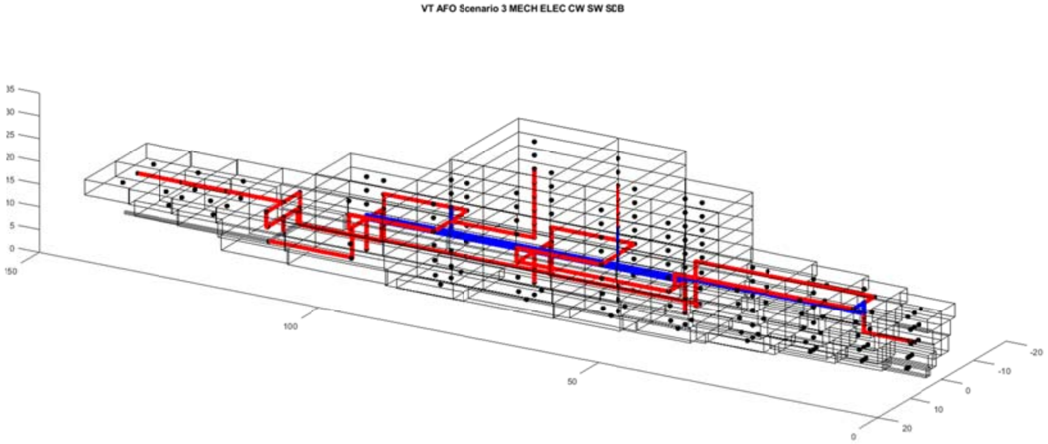


Figure 63 - Battle Condition 3D View

Scenario 91 representing the loss of MMR1 Lower SDB Figure 64), Scenario 130 representing the loss of AMR2 Lower, Scenario 166 showing loss of CIC, and Scenario 190 showing loss of Combat Systems Equipment Room #2 are shown below.

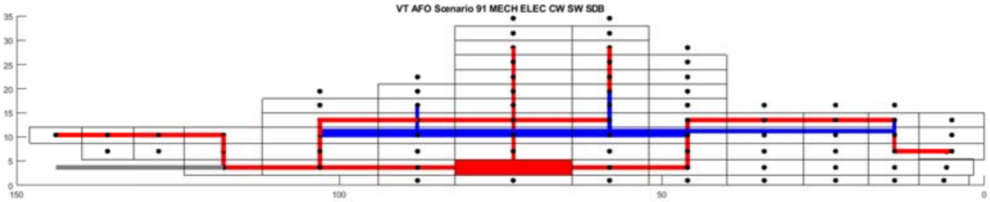


Figure 64 - Damaged MMR1 Lower Profile View

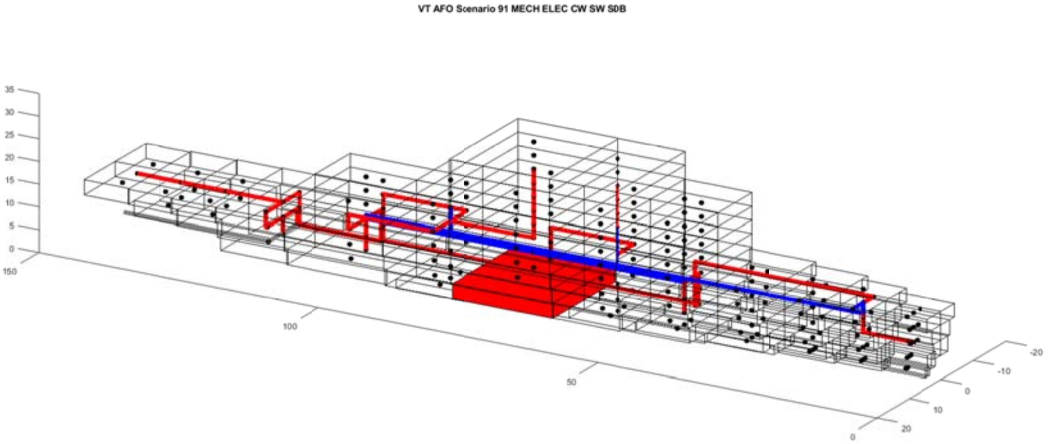


Figure 65 - Damaged MMR1 Lower 3D View

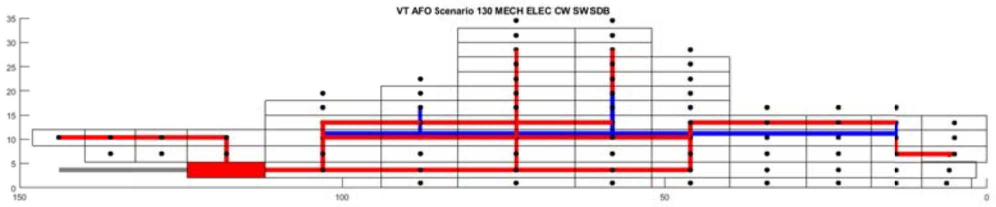


Figure 66 - Damaged AMR2 Lower Profile View

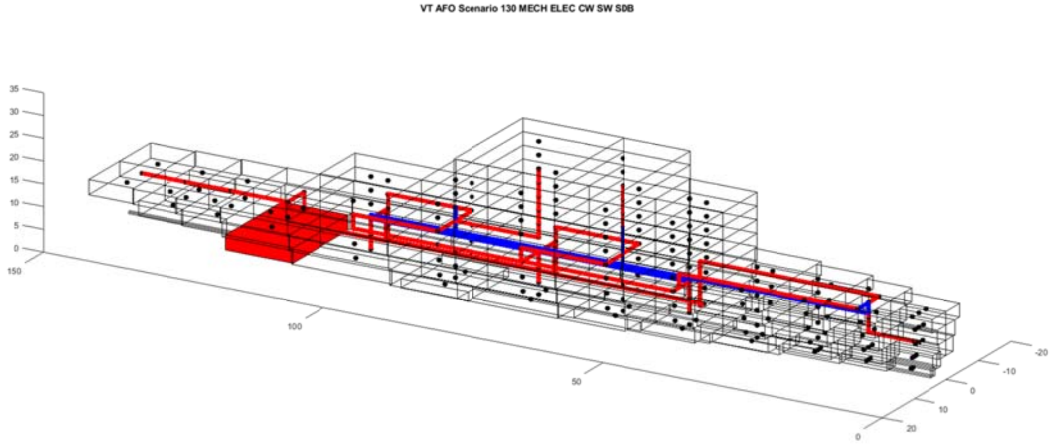


Figure 67 - Damaged AMR2 Lower 3D View

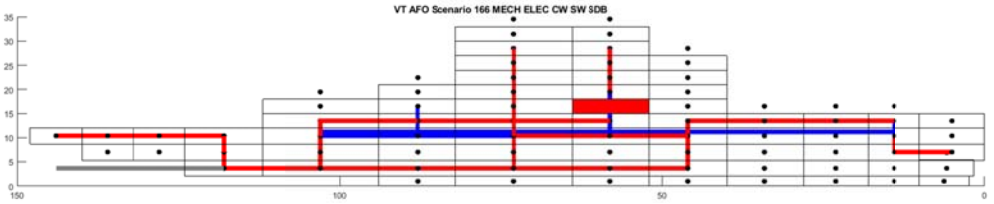


Figure 68 - Damaged CIC Profile View

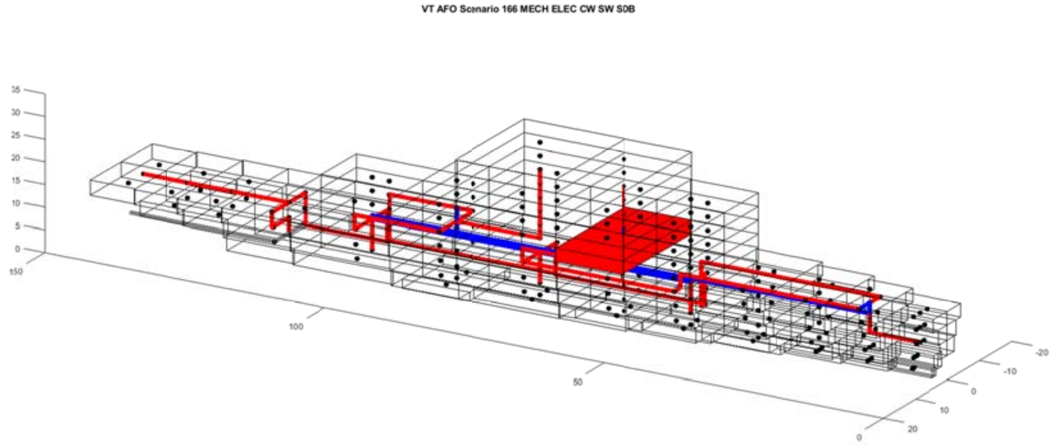


Figure 69 - Damaged CIC 3D View

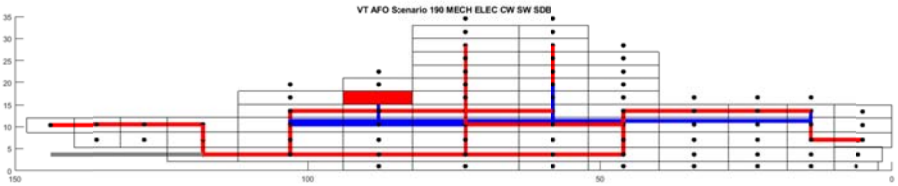


Figure 70 - Damaged CSER2 Profile View

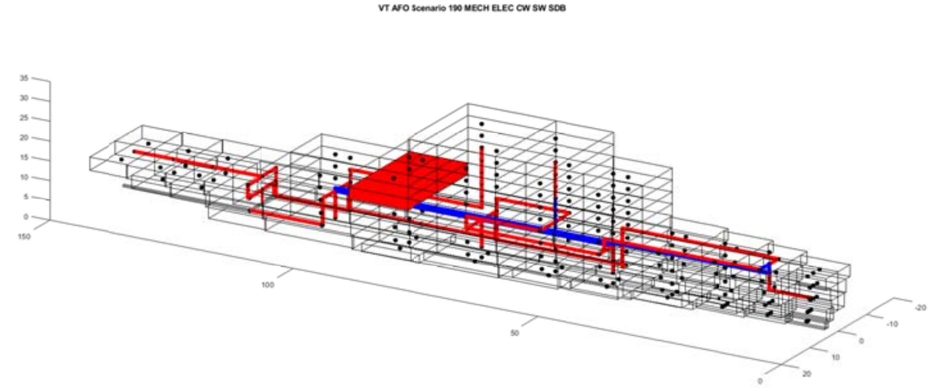


Figure 71 - Damaged CSER2 3D View

In the damage scenarios (Figure 64 through Figure 71) arcs appear to transit through damaged SDBs. The arcs shown display the path along which the arcs distance was calculated, purely based on the delta x, delta, y and delta z distances. The actual routing may or may not be through these SDBs. Some of these SDBs are also split port and starboard to allow P&S separation to be effective in reducing vulnerability. This cannot be seen in the physical views, but is much more apparent in the logical views.

Scenario 218 (Figure 72 and Figure 73) represents the aggregate scenario showing the aggregate flows for each of the arcs displayed. If an arc or node must be used in any of the operational or damage scenarios they appear in the aggregate view, also indicating their maximum flow. These aggregate views are very similar to the battle operational condition.

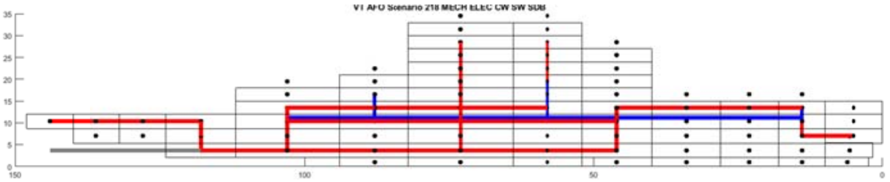


Figure 72 - Aggregate Flow Profile View

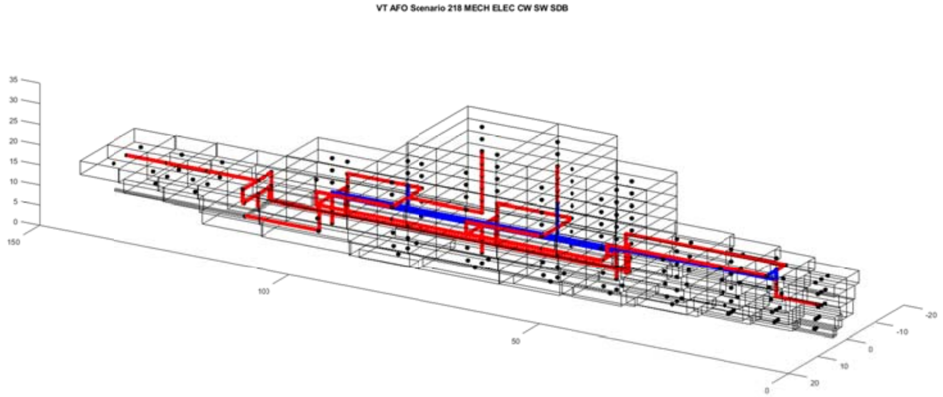


Figure 73 - Aggregate Flow 3D View

Illustrating this case is scenario 91 in which the MMR1 Lower has been damaged as seen in Figure 64 and Figure 65. Within the SDB plots, the lower SDB of MMR1 has been shaded out, representing the loss of all arcs entering and exiting this location. This is verified in Figure 78 as it can be seen, the electrical energy leaving PGM#1 in Electric zone 2 has no flow through it. When Figure 78 is compared with Figure 79 (loss of AMR2 Lower) it is striking how the paths through the logical architecture differ with a simple change in the location of electrical energy production .

Within the logical architecture plots for individual plexus, greater detail is available to analyze the results of the optimization. The four zone electrical plex is shown in Figure 74, Pre-AFO, through Figure 82, Aggregate Flow. Figure 75 Sustained Speed, Figure 76, Endurance Speed, and Figure 77, Battle Condition show the standard undamaged conditions for the network. Within the electrical plex, we can visualize how the energy produced by the PGMs/SPGMs is comparable, but the distribution of energy is quite different. In sustained speed, significantly more energy is used in Zone 3 which is reasonable as the PMM's providing propulsion are located within this zone. In the Battle condition, additional ELEC energy is required in Zone 1 where high energy weapons systems such as the railgun are utilized, where they were not required to be energized in the sustained speed scenario. The endurance scenario displays how ELEC energy is dispersed throughout the ship when no PGMs are available. This results in no ELEC energy originating from Zones 2 and 3.

The standalone node to the right of the ELEC logical plex represents stored energy within the ship. Stored Energy is not used in either sustained or endurance speed scenarios, however, beginning in Figure 77, Battle Condition and continuing through the damaged scenarios the node for stored energy changes color from black to red, indicating it is used in the scenario. The stored energy node is implicitly connected directly to the combat system nodes which require pulse power, thus no arcs appear in the network. This creates an alternative path from the zonal electrical distribution nodes for these pulse power combat system nodes to receive energy from the fully charged 20MW of stored energy onboard. The energy delivered is assumed to be the correct voltage and frequency required by the individual nodes and sufficient for their operation in normal conditions.

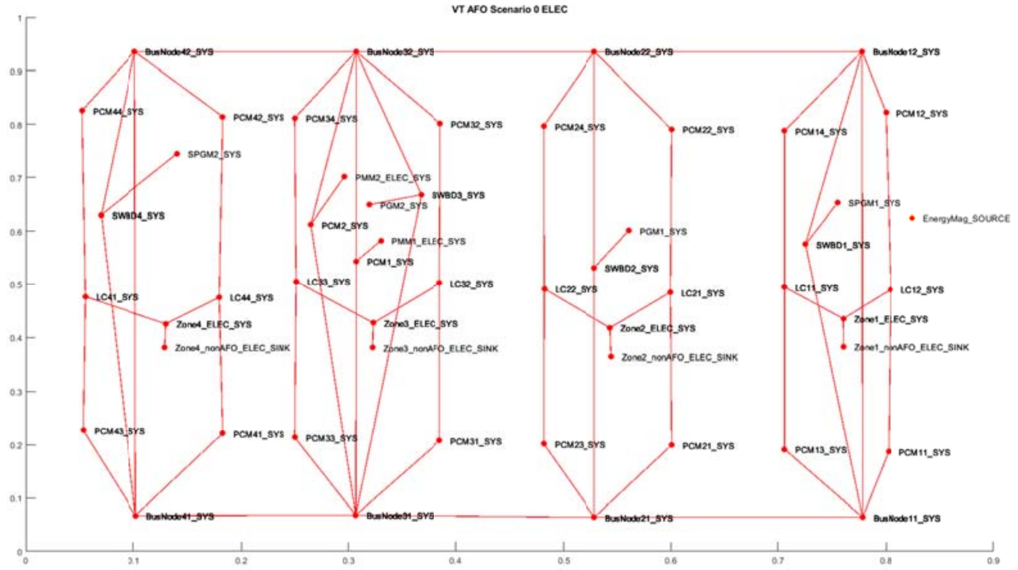


Figure 74- Pre AFO Connectivty ELEC

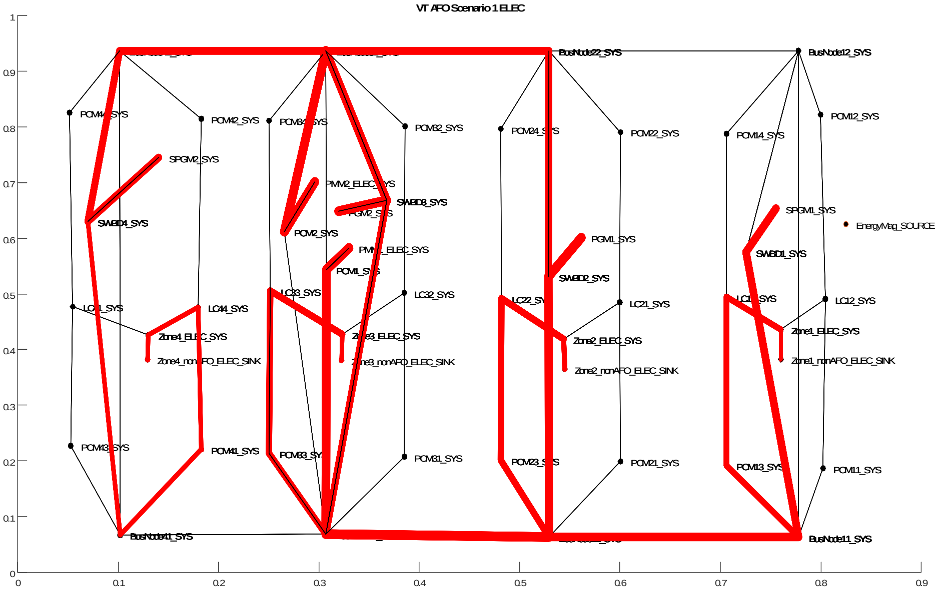


Figure 75 - Sustained Speed ELEC

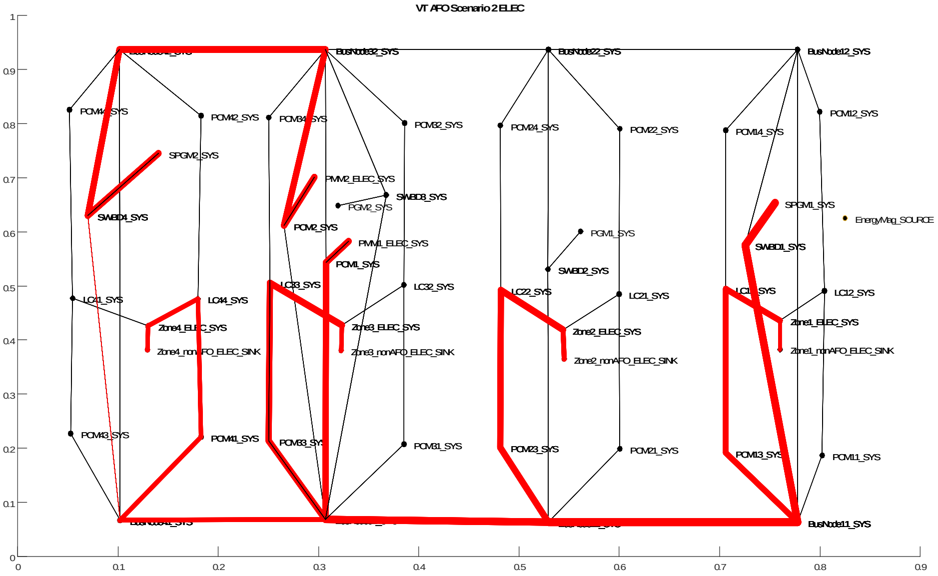


Figure 76 - Endurance Speed ELEC

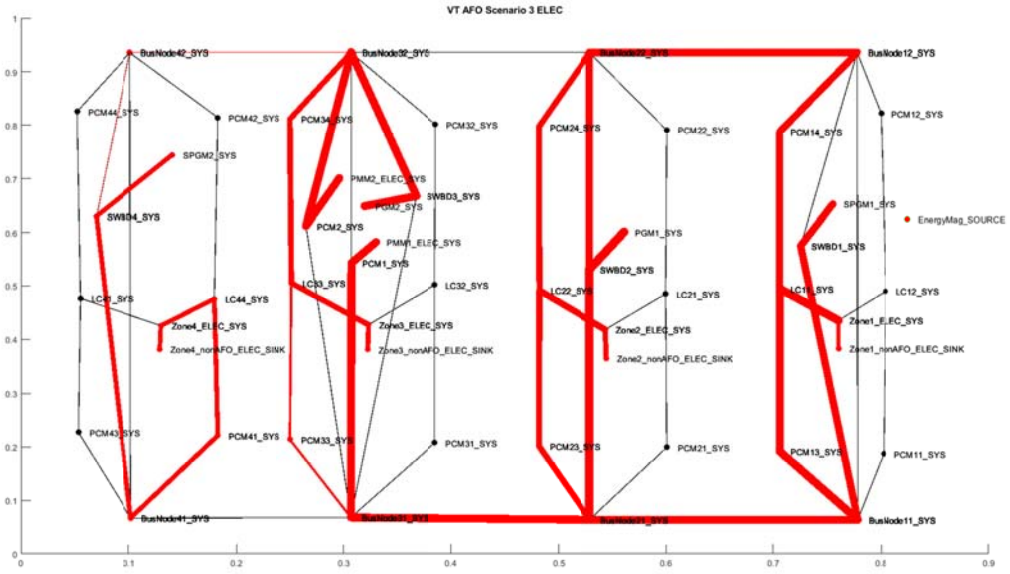


Figure 77- Battle Condition ELEC

The logical architectures for the ELEC plex in damaged conditions are shown in Figure 78, damage to MMR1 Lower, Figure 79, damage to AMR2 Lower, Figure 80, damage to CIC and Figure 81, damage to Combat Systems Equipment Room 2. In these scenarios, the battle electric loads must be maintained for each component located outside of the damaged SDB and power to sustain at least endurance speed must be provided to the MECH plex. Damage to MMR1 lower and AMR2 Lower provide similar impacts to the network in that each of these scenarios eliminate a PGM or SPGM from contributing to the total electrical energy in the plex. However, the loss of AMR2 Lower drives an important concept in ship design. The requirement is that both PMMs and the PCMs that supply them cannot be located in the same SDB and provide propulsive power to the ship in all damaged scenarios. This requires these systems to be separated in the physical architecture to ensure sufficient redundancy in the Operational Architecture.

Damage to CIC and CSER does not dramatically impact the flow of energy in the ELEC plex. The slight variations are seen in the shifting of energy used between zones as less energy is required in the zone with the damaged SDB.

The Aggregate Flow for the ELEC plex is shown in Figure 82. This shows the arcs of the ELEC plex with the greatest capacity required to support the network in all conditions. Interestingly, the optimizer elected not to use 8 of the 18 PCMs. This is likely due to each zone having 4 PCMs, with two co located on both the port and starboard side. Rather than force the objective function to "pay" for a second PCM in each SDB, CPLEX eliminated the node from consideration as it didn't add any additional redundancy in the M-1 scenarios.

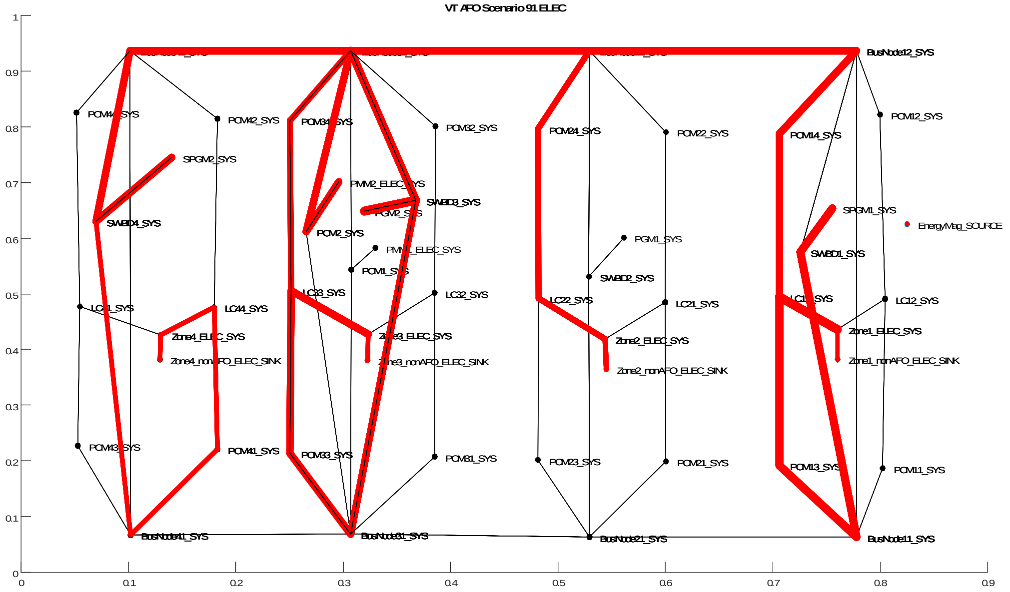


Figure 78 - MMR1 Lower Damaged ELEC

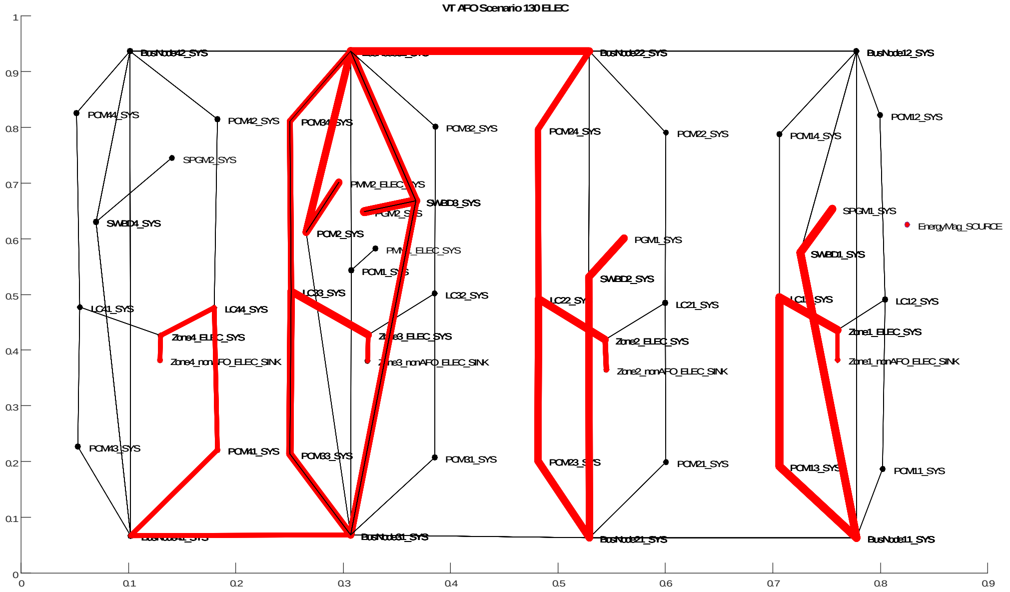


Figure 79 - AMR2 Lower Damaged ELEC

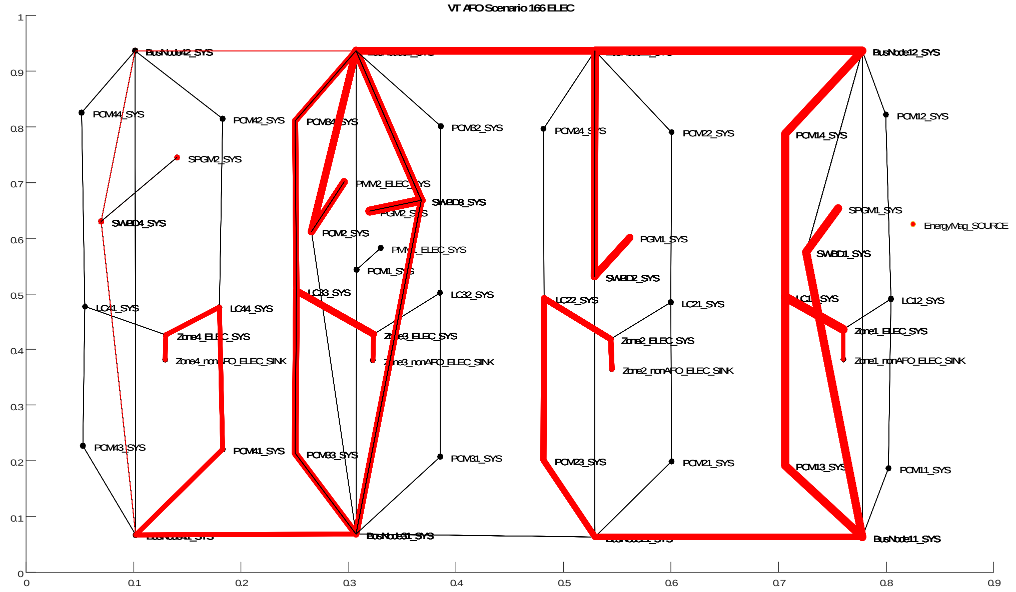


Figure 80 - CIC Damaged ELEC

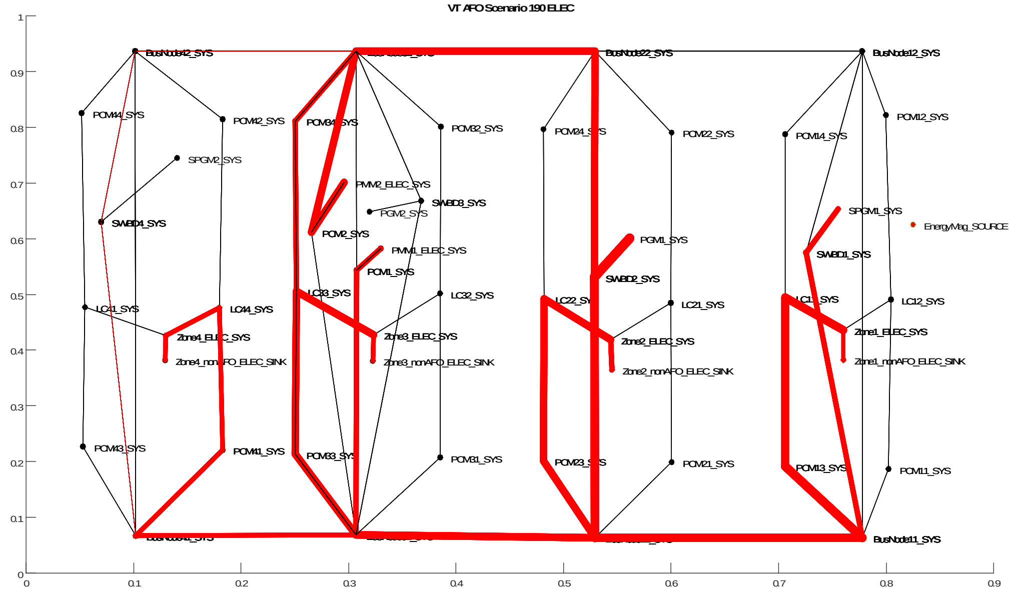


Figure 81 - CSER2 Damaged ELEC

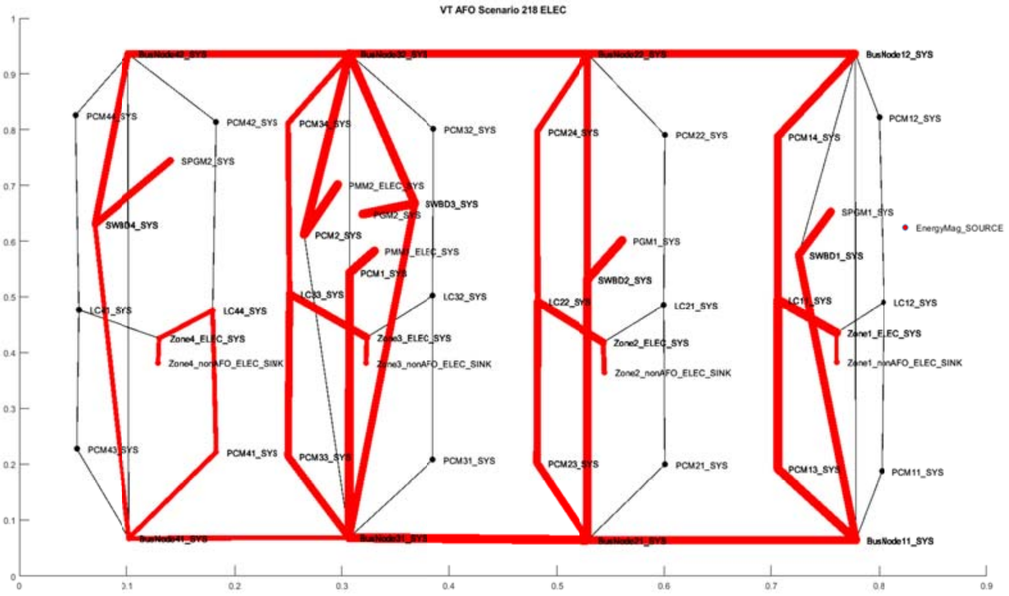


Figure 82 - Aggregate Flow ELEC

The logical plots for the CW plex are shown in Figure 83, Pre-AFO through Figure 91, Aggregate Flow. Figure 84, Sustained Speed, Figure 85, Endurance Speed, and Figure 86, Battle Condition show the undamaged conditions for the network. Comparing the energy within the CW plex at Sustained and Endurance speed which require cruising condition electric loads is quite different than the energy contained within the CW plex at Battle Condition. This difference is caused by the additional equipment online and increased electrical loads, and thus thermal energy generation, at Battle Condition. In Zones 2 and 3, this additional energy entering the CW plex can be observed as coming from the heat exchanger connecting the CW plex to the EC, Glycol and HVAC plexus.

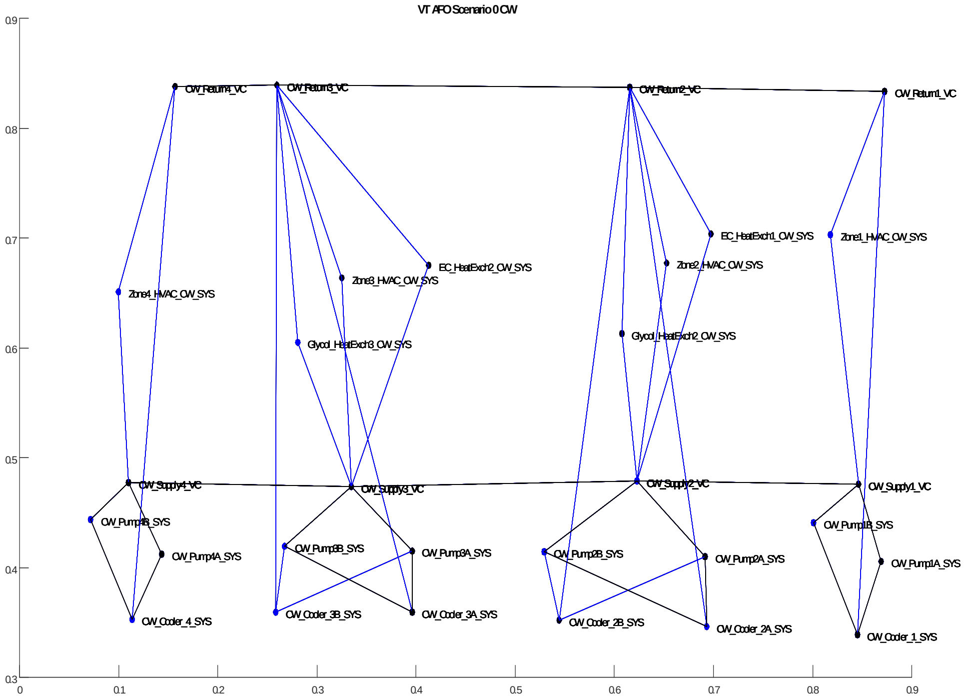


Figure 83 - Pre AFO Connectivity CW

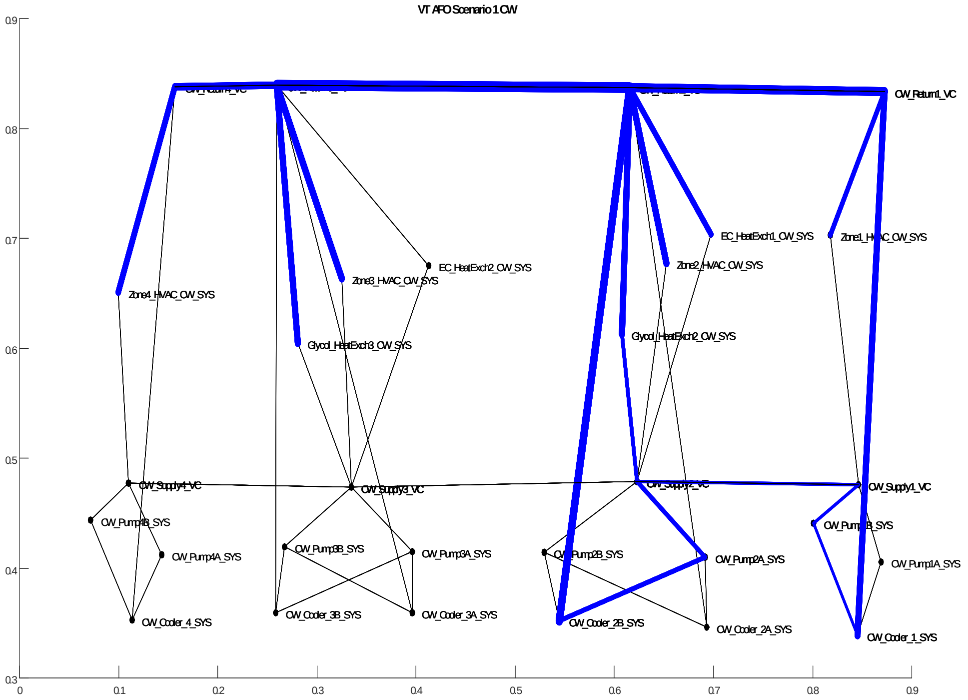


Figure 84 - Sustained Speed CW

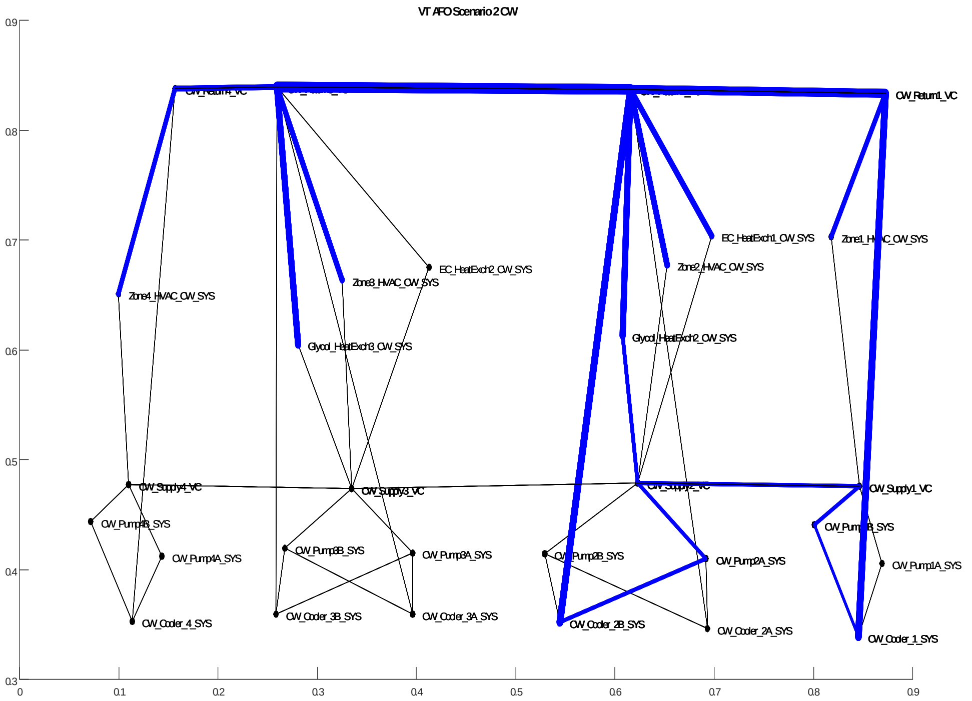


Figure 85 - Endurance Speed CW

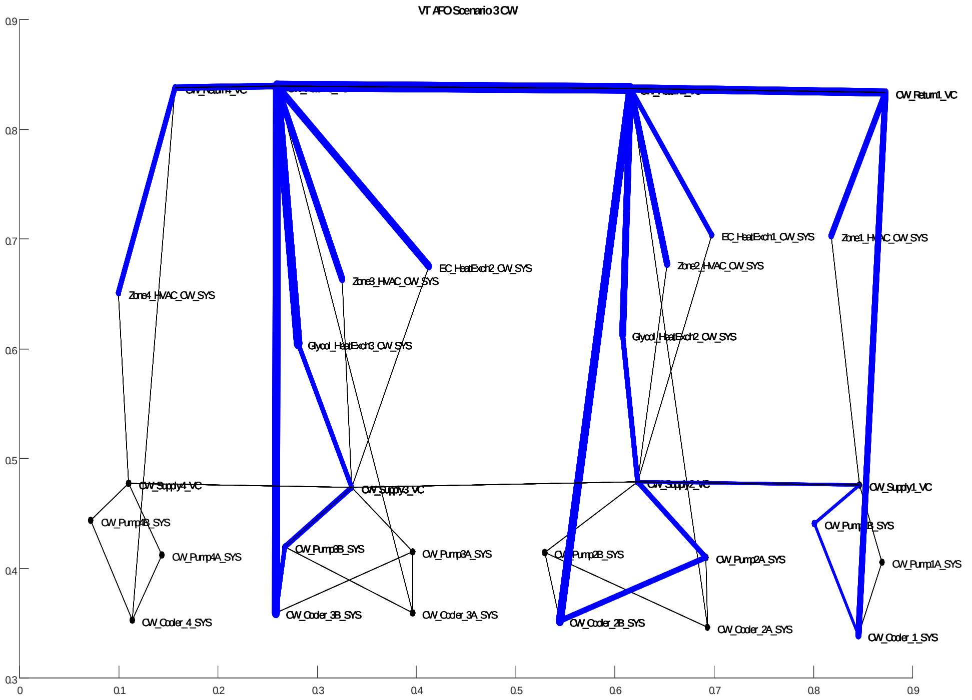


Figure 86 - Battle Condition CW

The CW plex in damaged conditions are shown in Figure 87 through Figure 90. There do not appear to be significant differences in the energy flow within the CW plex with the loss of MMR1 Lower and AMR2 lower. Differences are apparent when comparing the loss of CIC and CSER2. When CIC is damaged, the energy coming from the EC plex is transferred solely via EC heat exchanger 2 while when CSER2 is damaged, the energy from the EC plex is transferred to the CW plex via EC heat exchanger 1.

The Aggregate Flow for the CW plex is shown in Figure 91. This shows the arcs of the CW plex with the greatest capacity required to support the network in all conditions. Interestingly, the optimizer shows that with the exception of HVAC, there is no need for the fourth CW loop. The aggregate plex shows that through proper cross-connections, the thermal energy required to be carried by the CW system could be accomplished using only three loops in the stated M-1 scenario of redundancy.

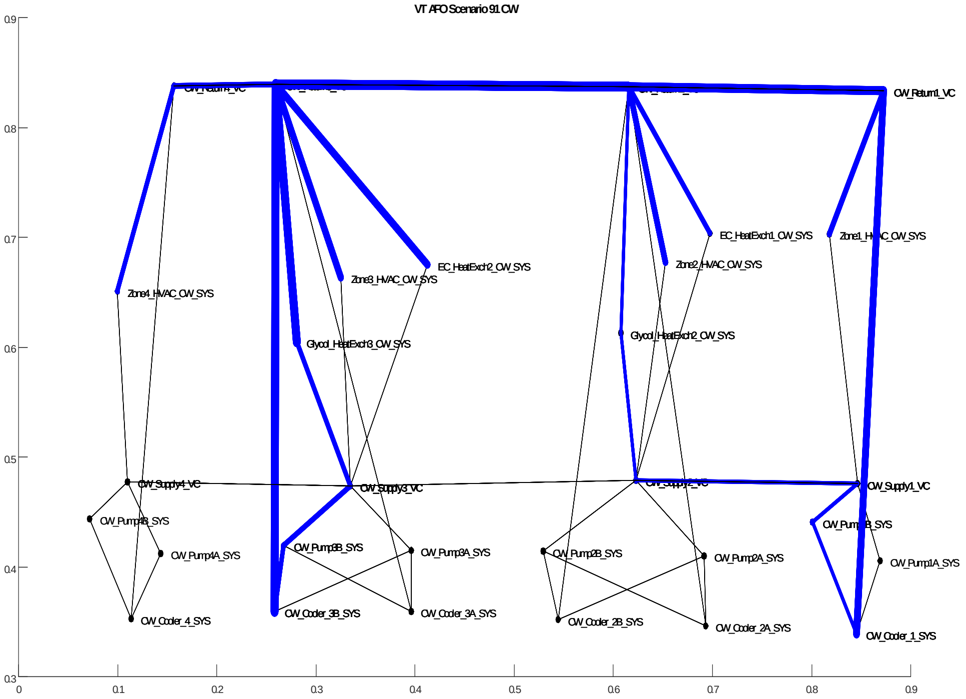


Figure 87 - MMR1 Lower Damaged CW

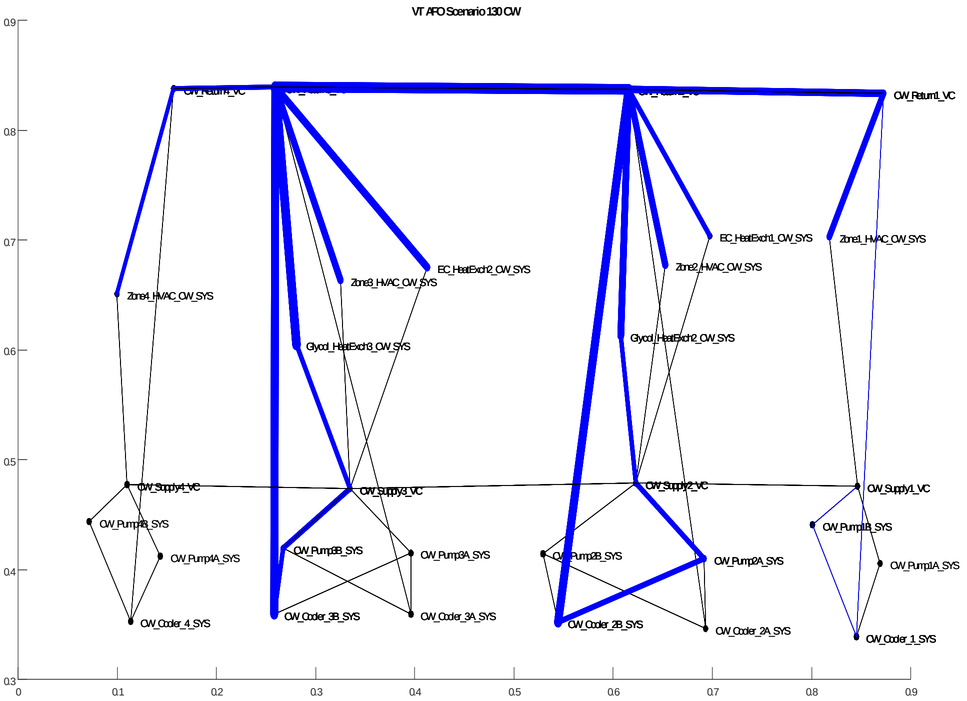


Figure 88 - AMR2 Lower Damaged CW

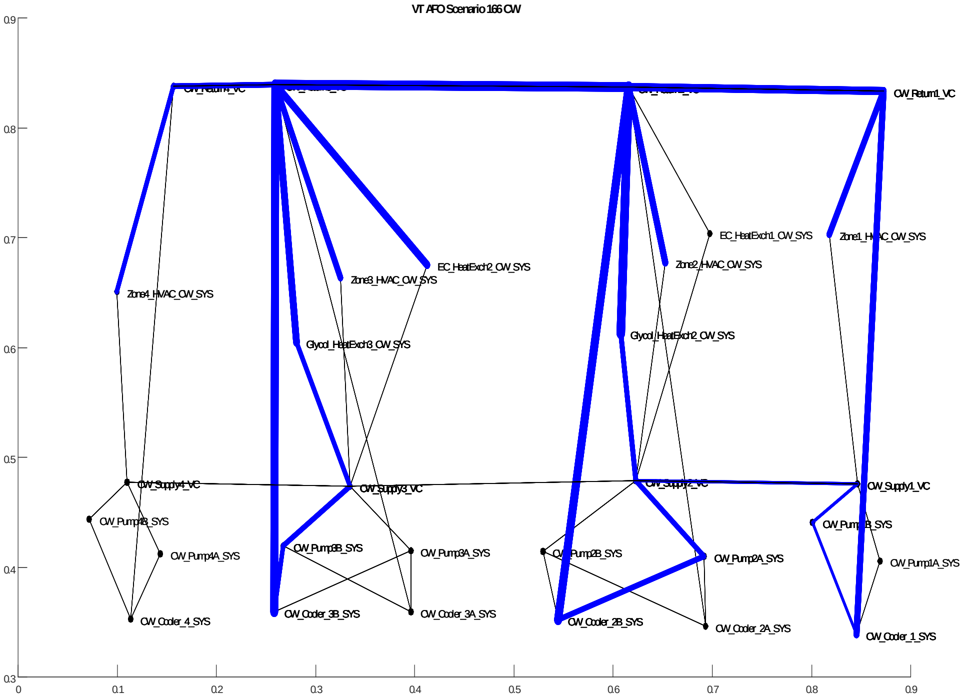


Figure 89 - CIC Damaged CW

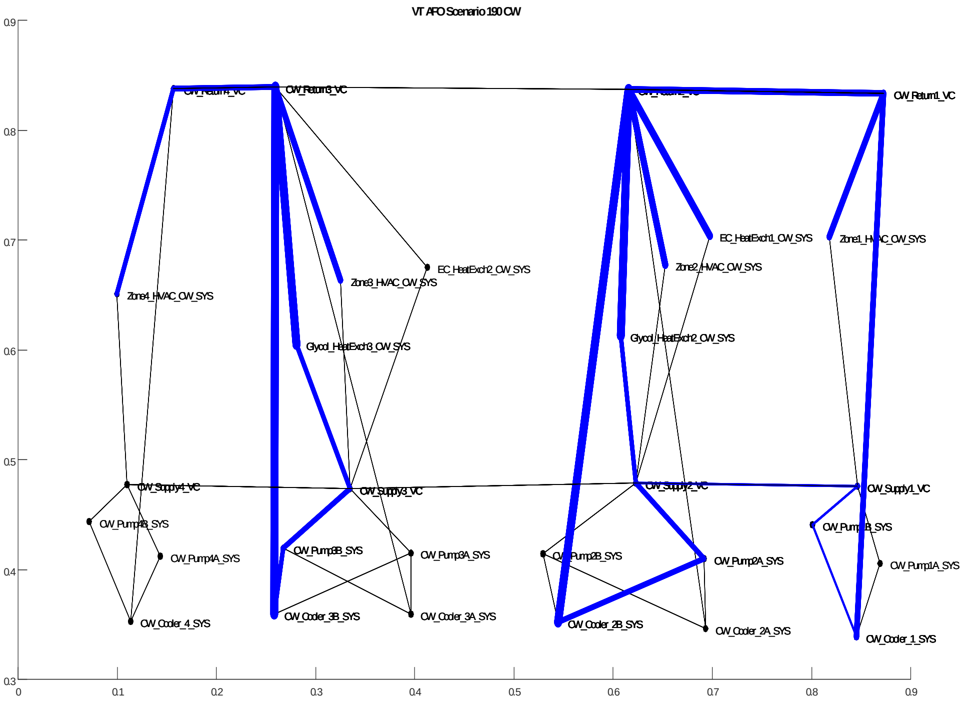


Figure 90 - CSER2 Damaged CW

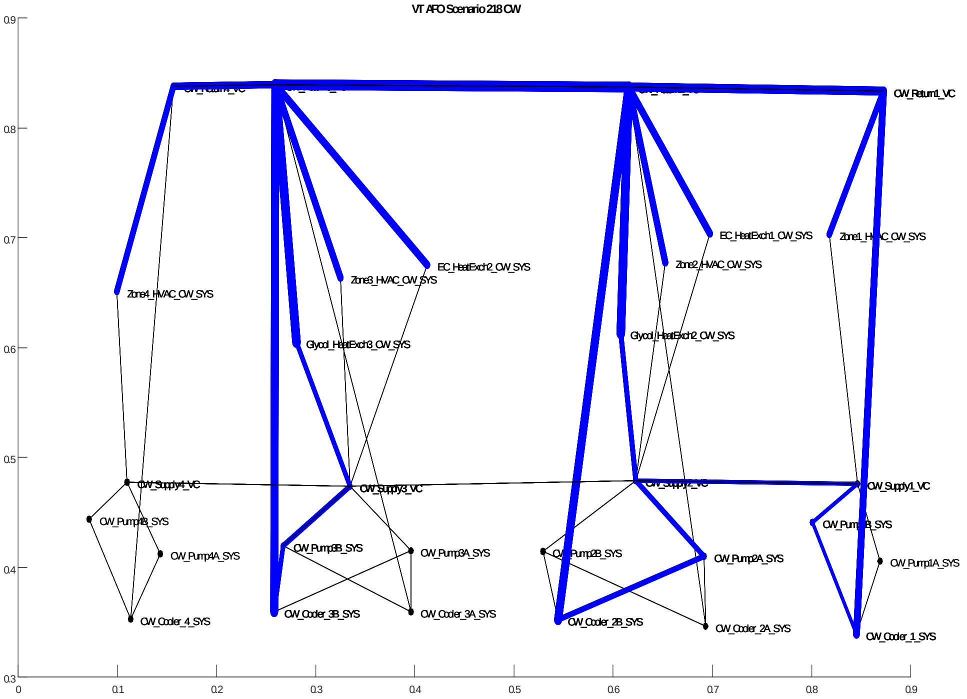


Figure 91 - Aggregate Flow CW

The logical plots for the FO plex are shown in Figure 92, Pre AFO through Figure 100, Aggregate Flow. Figure 93, Sustained Speed, Figure 94, Endurance Speed and Figure 95, Battle Condition show the undamaged conditions for the network. With an IPS it is expected the energy flows through the FO plex will be highly correlated to the energy flows of the ELEC plex. Sustained Speed and Battle Conditions like the ELEC plex are very similar as each engine is required to produce at or near its MCR. Endurance condition shows the FO delivered to both PGMs is zero, as neither of them are considered online in the Endurance condition.

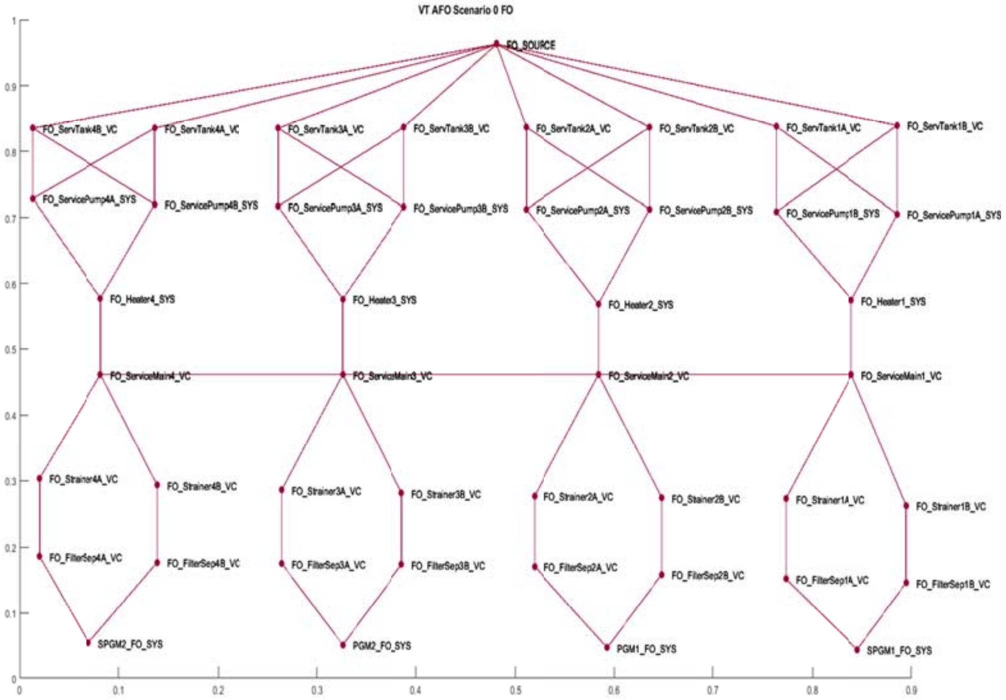


Figure 92 - Pre AFO Connectivity FO

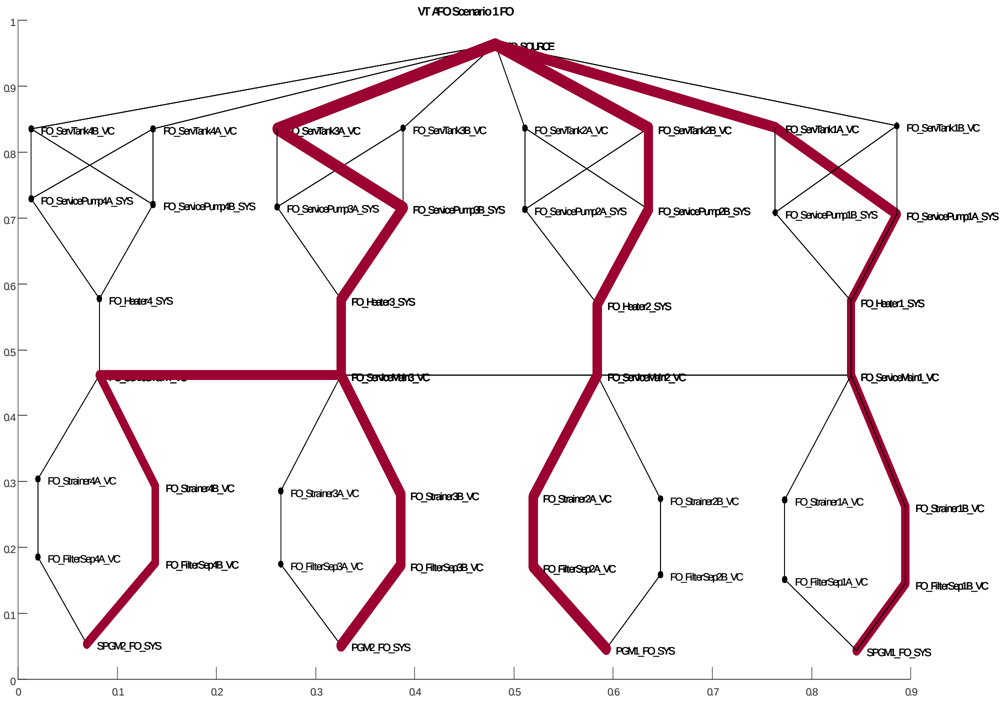


Figure 93 - Sustained Speed FO

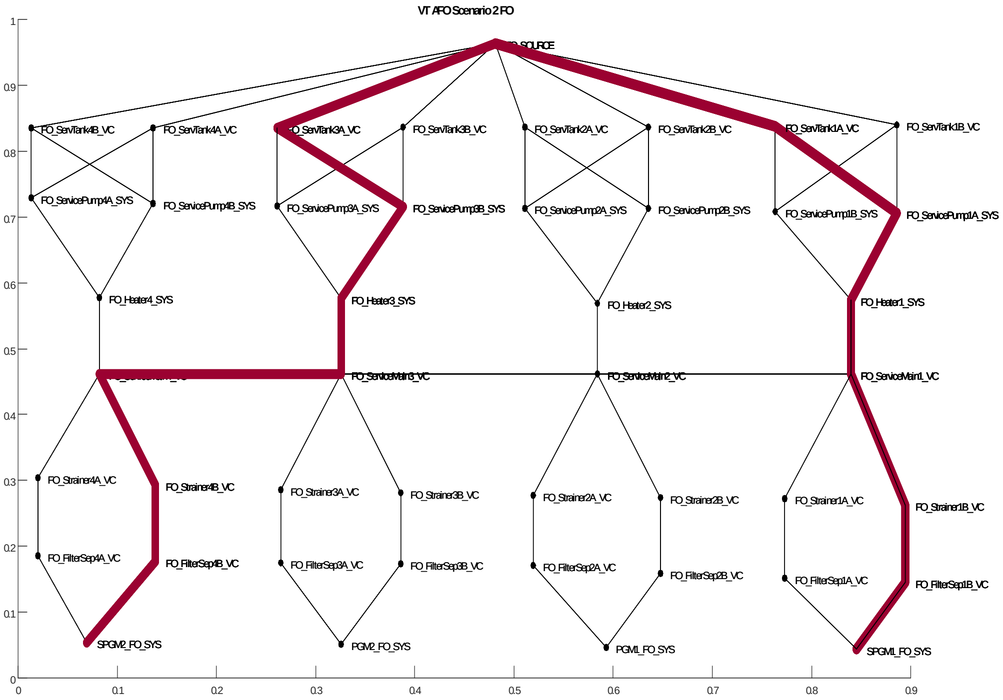


Figure 94 - Endurance Speed FO

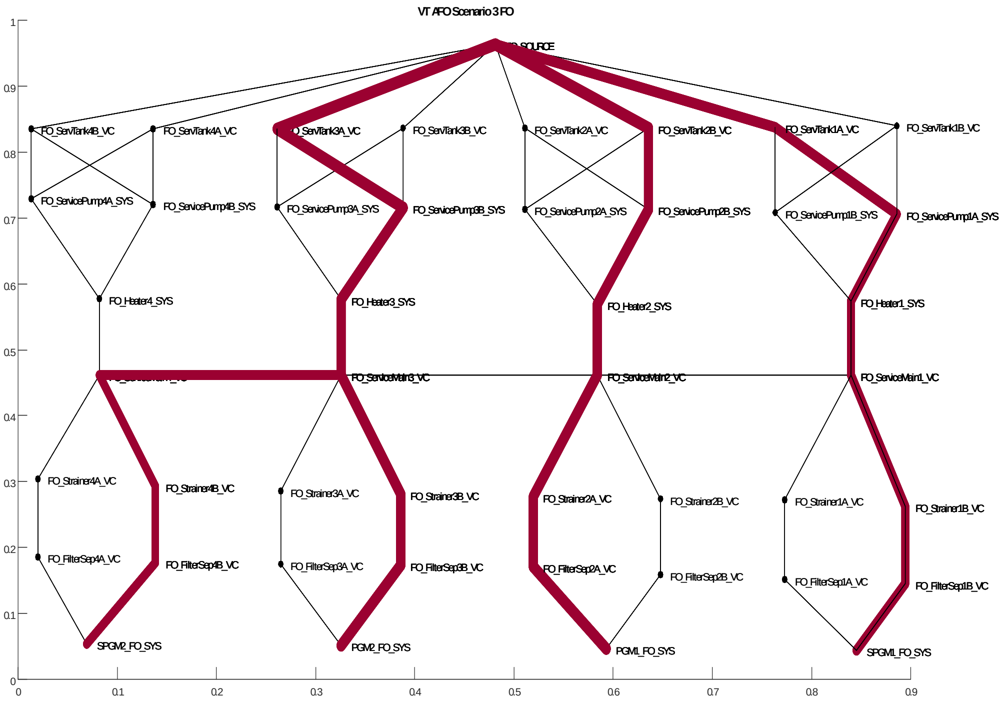


Figure 95 - Battle Condition FO

The logical architectures for the FO plex in damaged conditions are shown in Figure 96, damage to MMR1 Lower, Figure 97, damage to AMR2 Lower, Figure 80, damage to CIC and Figure 99, damage to Combat Systems Equipment Room 2. In these scenarios Battle Condition electric loads must be maintained, but only endurance propulsive power must be provided. Damage to MMR1 Lower produces a result where no FO is provided to PGM1 as it is not considered to be online in this damage condition. Likewise, when AMR2 Lower is damaged, SPGM2 is considered damaged and unavailable, thus, no FO is provided.

Damage to CIC and CSER appears to have minimal impact on the FO plex except that less FO energy is required to be delivered to the PGMs in these damaged scenarios.

The Aggregate Flow for the FO plex is shown in Figure 100. Similar to the ELEC plex, CPLEX elected not to utilize one of the A or B sets of filters, strainers or pumps associated with the FO going to each PGM/SPGM. This was caused by the both sets of pumps, filters and strainers being co located in the same SDB. Therefore, in the M-1 scenario, if one of them were damaged, they both were and thus from an M-1 survivability standpoint, the extra set of filters, strainers and pumps, provided no additional redundancy for the plex.

Another interesting result in the Aggregate Flow of the FO plex is the zone 4 service tanks and pumps were eliminated from the plex, indicating if the FO Main cross connect between zones 3 and 4 was always open and available, the ship would be able to meet all its requirements through only 3 sets of FO service tanks and pumps.

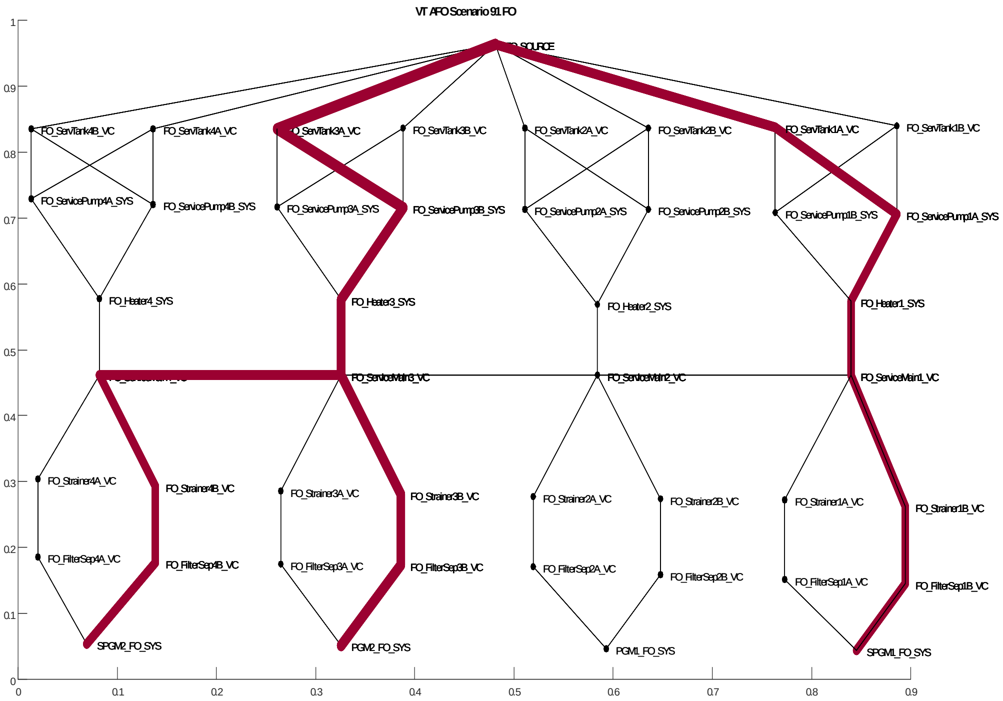


Figure 96 - MMR1 Lower Damaged FO

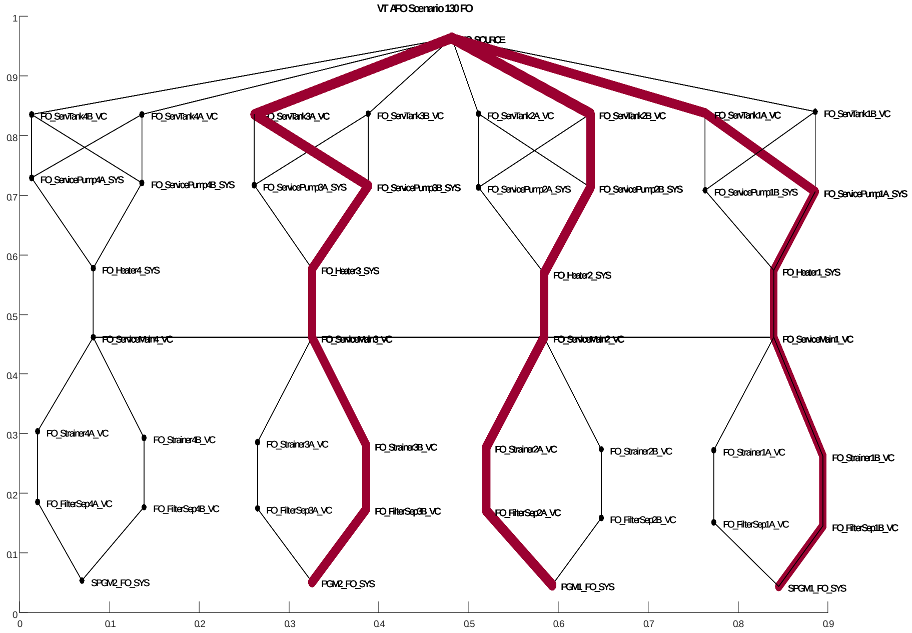


Figure 97 - AMR2 Lower Damaged FO

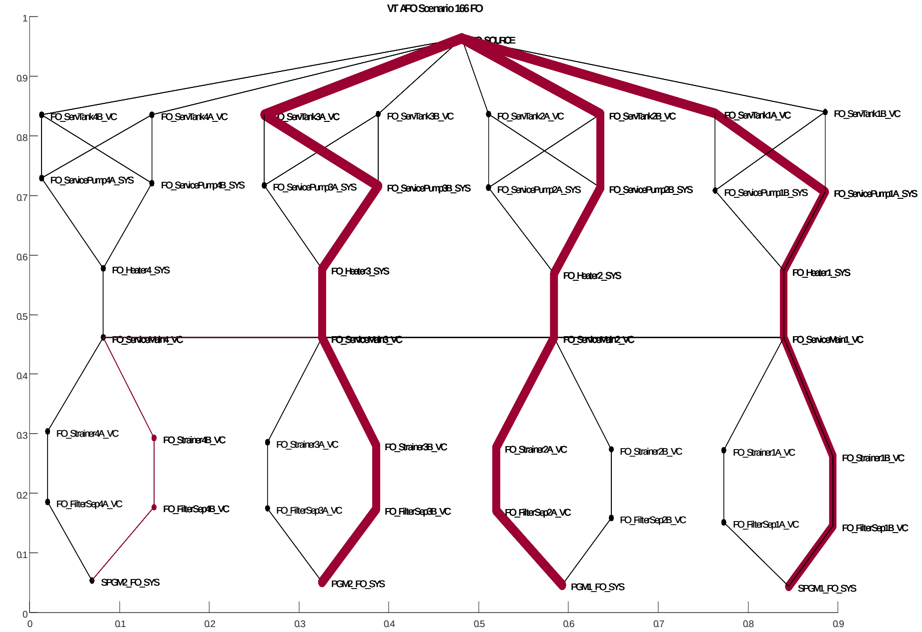


Figure 98 - CIC Damaged FO

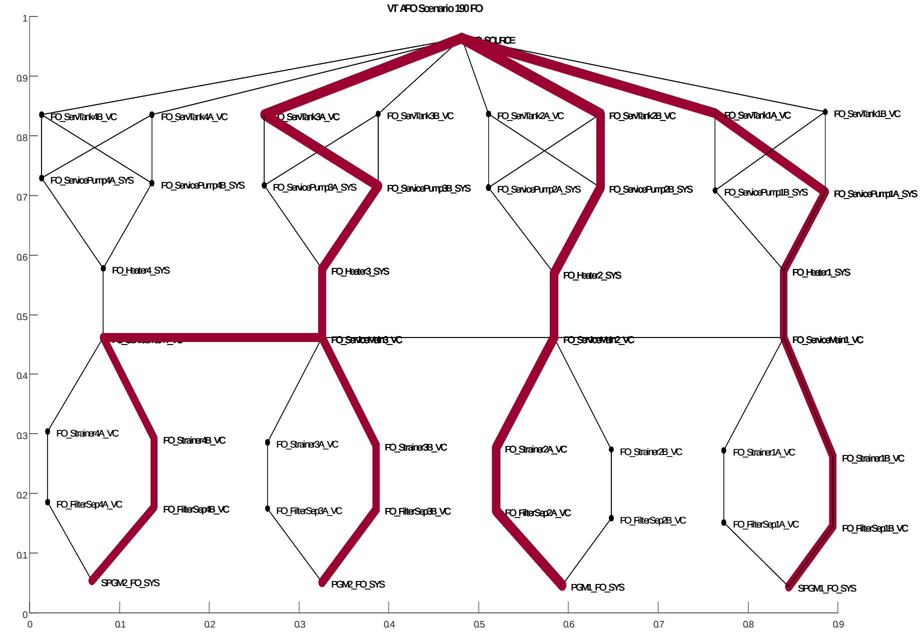


Figure 99 - CSER2 Damaged FO

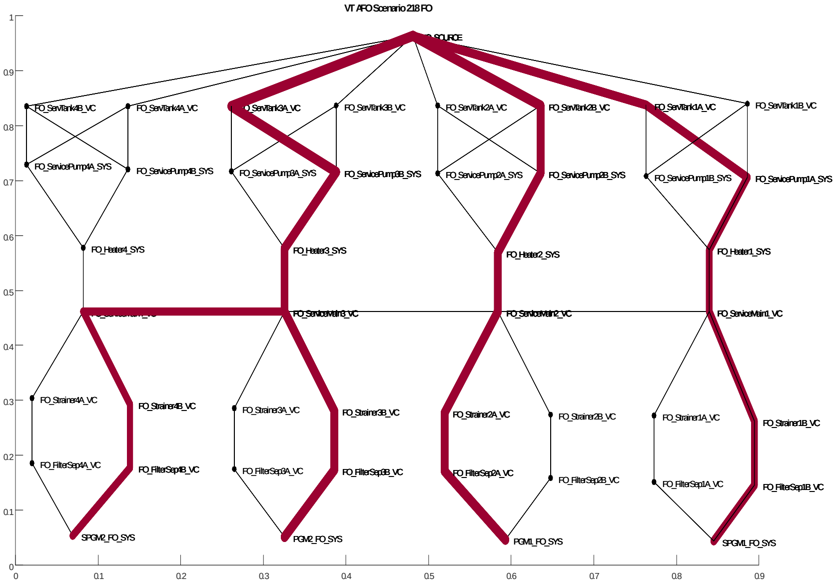


Figure 100 - Aggregate Flow FO

A consolidated set of logical architecture energy flows for the Battle Condition are shown in Figure 101 through Figure 110 to illustrate the flow of energy between the logical plexus represented in the AFO. Chemical energy is carried from the terminal node, FO Source, through the FO plex as shown previously. The energy leaves the FO plex once the chemical energy reaches the PGMs where it is converted into electrical and thermal energy between Figure 101, Figure 102, Figure 104 and Figure 109. The electrical energy is distributed through Figure 102 to the electrical components required by the operational condition which produce thermal heat in the HVAC, Electronic Cooling and Glycol plexus. The thermal energy in these plexus' is deposited into the CW plex through the zonal chill water system nodes. The thermal energy within the chill water system heat is then deposited into the HFC plex through CW coolers 3B, 2B and 1 which can be seen in both plexus in Figure 107 and Figure 108. The HFC and LO plexus then deposit their thermal energy into the SW system through their respective coolers. The SW plex then directs the accumulated thermal energy overboard and out of the network through the terminal node, SW Sink.

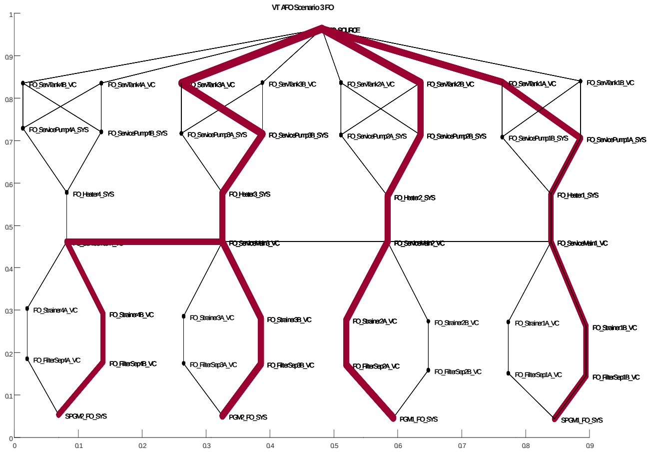


Figure 101 - Battle Condition FO

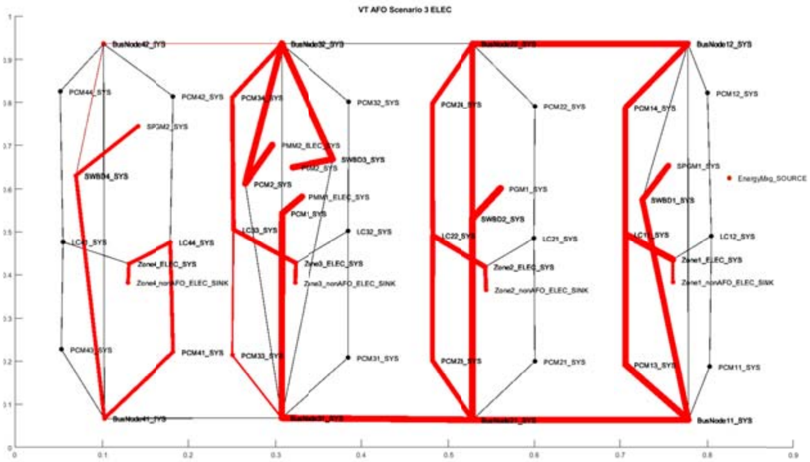


Figure 102 - Battle Condition ELEC

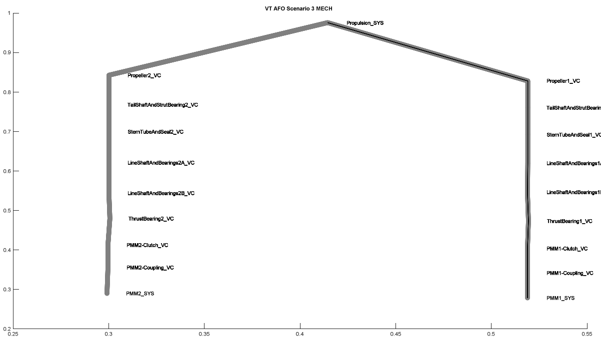


Figure 103 - Battle Condition MECH

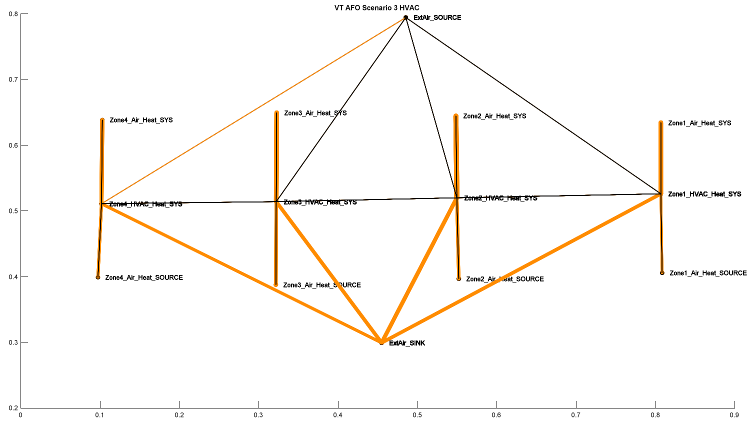


Figure 104 - Battle Condition HVAC

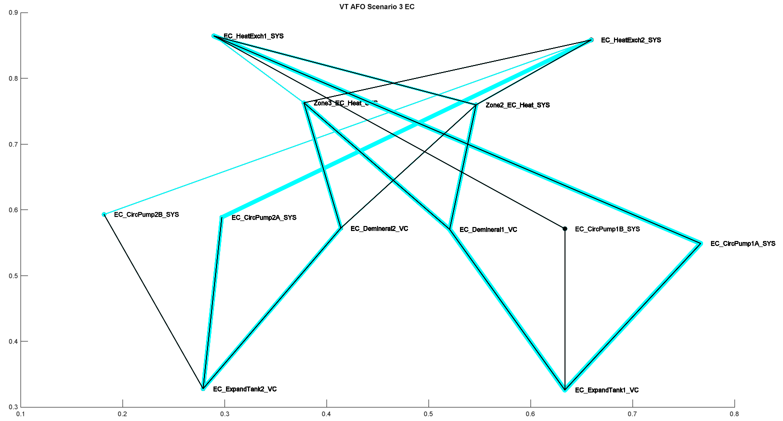


Figure 105 - Battle Condition EC

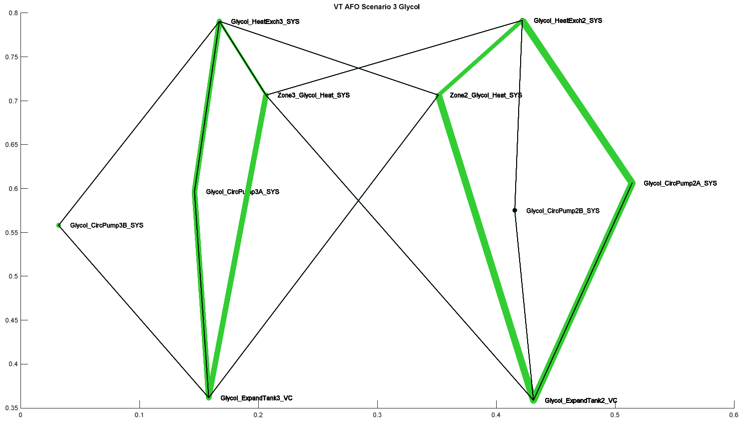


Figure 106 - Battle Condition Glycol

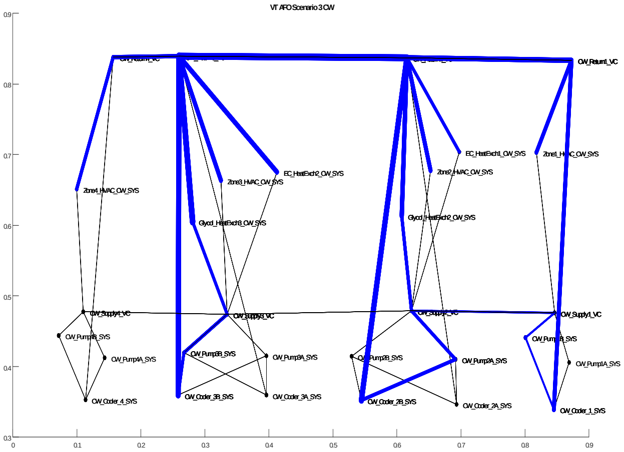


Figure 107 - Battle Condition CW

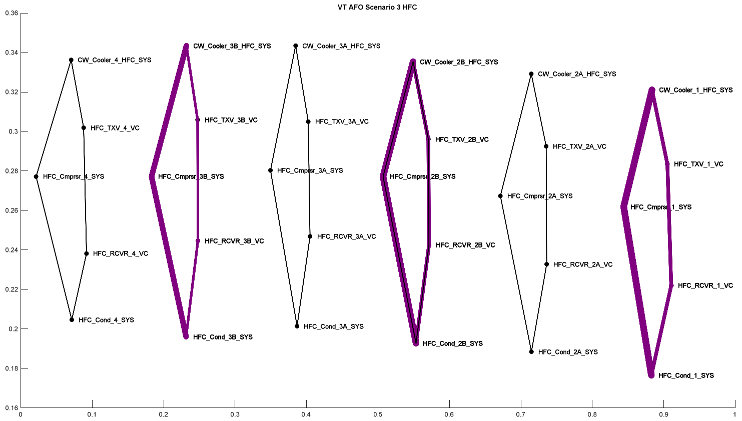


Figure 108 - Battle Condition HFC

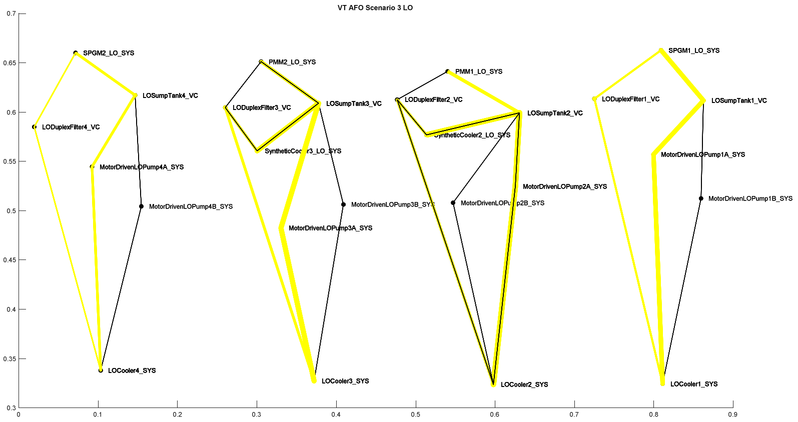


Figure 109 - Battle Condition LO

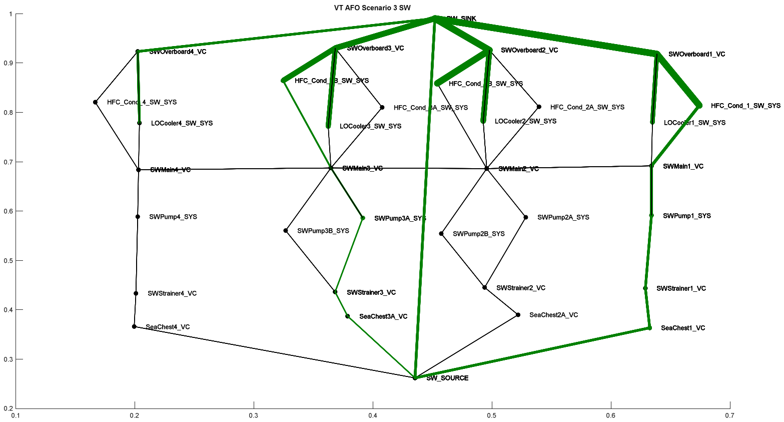


Figure 110 - Battle Condition SW

4.3 Elimination of redundant Arcs and Nodes

The physical architecture shown previously provides an overview of the energy flows through the ship but fails to provide sufficient detail for decisions to be made regarding the optimality of each plex individually. The architecture flows for each individual plex do provide significant insight into how the energy flows through the plex and how the system architecture could be further refined.

The individual scenario logical architectures validate energy is flowing through the plex in a logical way while the aggregate arcs provide greater understanding about how certain arcs or nodes are completely unused. Within the Electrical Aggregate Flow shown in Figure 82 there are some portions of the network plex which are unused. Because the aggregate arc flows represent the case where the greatest capacity was required from all the scenarios evaluated, these nodes can be considered as candidates for elimination from the network and ultimately reduce the cost of producing the plex and ship.

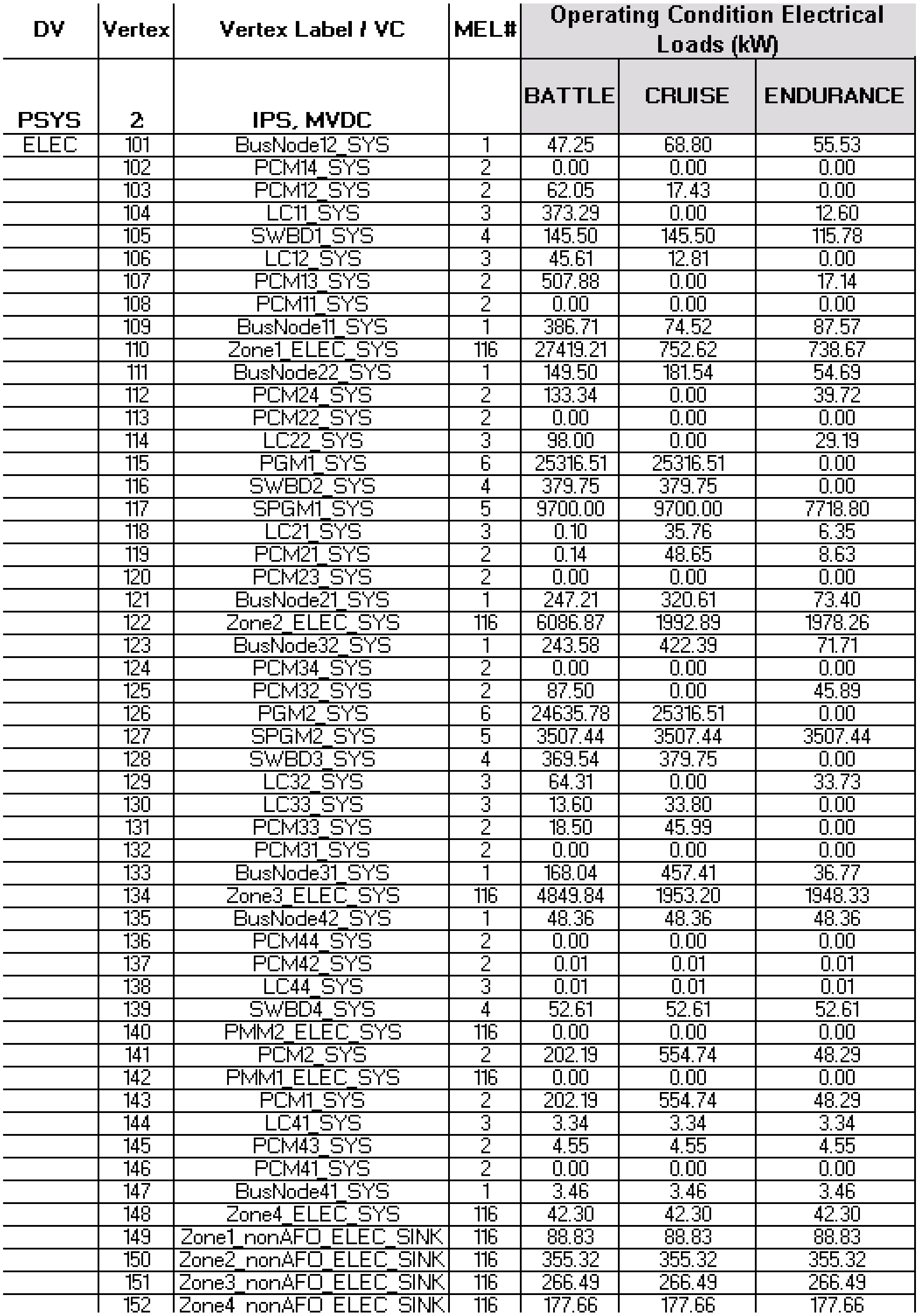
The elimination of these nodes would be based upon the scenarios implemented and the constraints applied to the problem. In this case, we can see that nodes co located with redundant nodes in the same compartment (PCM 11_SYS and PCM_13_SYS in the bottom right corner of the figure for example) are not necessary. Intuitively this makes sense from a survivability stand point in the M-1 scenario example. If a SDB is damaged and no energy is permitted to flow through, then both nodes are eliminated from consideration in that scenario. However, due to the fixed cost associated with the arcs and nodes, the optimizer sought ways to reduce cost where possible, and was able to meet the electrical energy demands of the ship while using only 1 PCM in this SDB. In total through all of the scenarios evaluated, the optimizer recommended 8 PCMs as targets for potential elimination.

While additional study is required to ensure the system remains maintainable, this result indicates standard maintenance alone should not be the reason these PCMs remain in the final network. Assuming maintenance of components only takes place while in normal operating conditions where SDBs are not damaged, one PCM at a time would be able to be taken out of the network for maintenance and sufficient capacity would exist elsewhere in the system to provide all the electrical energy requirements to sustain the system in any of the three standard operating conditions of cruising, endurance and battle. This also assumes each component is capable of scaling up and down as necessary to meet the capacity demands with no imposed upper bounds.

4.4 Calculated Electrical Loads

Using the flow results of the AFO, the electrical loads required at each node/VC can be determined at any scenario evaluated. Table 5 shows the resulting ELEC nodal loads from the optimization for Battle, Sustained and Endurance conditions. This information represents the difference of electrical energy entering the node and the electrical energy leaving the node, resulting in the draw of the component in the desired scenario. This process can also provide the electrical power required at the flow dependent pumps allowing a designer to either allow the pumps to scale as required by the optimal network or apply an additional supply chain constraint where each pump of a similar node type must have the same capacity and electric draw to decrease the number of unique pumps installed onboard.

Table 5 - Calculated Electrical Loads



DV	Vertex	Vertex Label / VC	MEL#	Operating Condition Electrical Loads (kW)		
PSYS	2	IPS, MVDC		BATTLE	CRUISE	ENDURANCE
ELEC	101	BusNode12_SYS	1	47.25	68.80	55.53
	102	PCM14_SYS	2	0.00	0.00	0.00
	103	PCM12_SYS	2	62.05	17.43	0.00
	104	LC11_SYS	3	373.29	0.00	12.60
	105	SWBD1_SYS	4	145.50	145.50	115.78
	106	LC12_SYS	3	45.61	12.81	0.00
	107	PCM13_SYS	2	507.88	0.00	17.14
	108	PCM11_SYS	2	0.00	0.00	0.00
	109	BusNode11_SYS	1	386.71	74.52	87.57
	110	Zone1_ELEC_SYS	116	27419.21	752.62	738.67
	111	BusNode22_SYS	1	149.50	181.54	54.69
	112	PCM24_SYS	2	133.34	0.00	39.72
	113	PCM22_SYS	2	0.00	0.00	0.00
	114	LC22_SYS	3	98.00	0.00	29.19
	115	PGM1_SYS	6	25316.51	25316.51	0.00
	116	SWBD2_SYS	4	379.75	379.75	0.00
	117	SPGM1_SYS	5	9700.00	9700.00	7718.80
	118	LC21_SYS	3	0.10	35.76	6.35
	119	PCM21_SYS	2	0.14	48.65	8.63
	120	PCM23_SYS	2	0.00	0.00	0.00
	121	BusNode21_SYS	1	247.21	320.61	73.40
	122	Zone2_ELEC_SYS	116	6086.87	1992.89	1978.26
	123	BusNode32_SYS	1	243.58	422.39	71.71
	124	PCM34_SYS	2	0.00	0.00	0.00
	125	PCM32_SYS	2	87.50	0.00	45.89
	126	PGM2_SYS	6	24635.78	25316.51	0.00
	127	SPGM2_SYS	5	3507.44	3507.44	3507.44
	128	SWBD3_SYS	4	369.54	379.75	0.00
	129	LC32_SYS	3	64.31	0.00	33.73
	130	LC33_SYS	3	13.60	33.80	0.00
	131	PCM33_SYS	2	18.50	45.99	0.00
	132	PCM31_SYS	2	0.00	0.00	0.00
	133	BusNode31_SYS	1	168.04	457.41	36.77
	134	Zone3_ELEC_SYS	116	4849.84	1953.20	1948.33
	135	BusNode42_SYS	1	48.36	48.36	48.36
	136	PCM44_SYS	2	0.00	0.00	0.00
	137	PCM42_SYS	2	0.01	0.01	0.01
	138	LC44_SYS	3	0.01	0.01	0.01
	139	SWBD4_SYS	4	52.61	52.61	52.61
	140	PMM2_ELEC_SYS	116	0.00	0.00	0.00
	141	PCM2_SYS	2	202.19	554.74	48.29
	142	PMM1_ELEC_SYS	116	0.00	0.00	0.00
	143	PCM1_SYS	2	202.19	554.74	48.29
	144	LC41_SYS	3	3.34	3.34	3.34
	145	PCM43_SYS	2	4.55	4.55	4.55
	146	PCM41_SYS	2	0.00	0.00	0.00
	147	BusNode41_SYS	1	3.46	3.46	3.46
	148	Zone4_ELEC_SYS	116	42.30	42.30	42.30
	149	Zone1_nonAFO_ELEC_SINK	116	88.83	88.83	88.83
	150	Zone2_nonAFO_ELEC_SINK	116	355.32	355.32	355.32
	151	Zone3_nonAFO_ELEC_SINK	116	266.49	266.49	266.49
	152	Zone4 nonAFO ELEC SINK	116	177.66	177.66	177.66

5 Conclusions and Future Work

This thesis presents a unique method and tool to optimize naval ship system logical and physical architecture considering necessary operational conditions and possible damage scenarios. The particular and unique contributions of this thesis are: 1) initially only energy flow is considered without explicit consideration of commodity flow (electric, mechanical, lube oil, chilled water, etc.), which is calculated in a post-processing step; 2) AFO is applied to a large and complex naval surface combatant system of systems, demonstrating its scalability beyond simple applications; 3) data necessary for the AFO is extracted directly from a naval ship synthesis model at a concept exploration level of detail demonstrating its value in early stage design; and 4) it uses network-based format and methods which make it adaptable to future knowledge-based network analysis methods and approaches.

The AFO provides an optimized and feasible physical solution to the physical and logical architectures of a notional ship design. This physical solution ensures sufficient reserve capacity and redundancy is incorporated in the design much earlier in the design process than previously thought possible. In addition to the sizing of components, the AFO has the potential for incorporation into a full system response in the time domain in conjunction with naval operational effectiveness models, design reference mission and full operational architecture.

5.1 Future Work

5.1.1 Energy Storage

Energy storage may be the key to the affordability and effectiveness of future naval surface combatants using high energy weapons and sensors. AFO and the associated tools and processes in development provide the right approach at the right resolution/level of detail to implement energy storage in early stage design where the important decisions about using it must be made. It requires that AFO be extended to the time domain, but this seems very doable.

5.1.2 Deactivation Diagrams

Currently, the AFO is programed to provide power to every component which is available outside of the damaged SDB. Navy operational doctrine would shut down all system components in systems disabled by damaged components. A deactivation diagram network approach is being developed that may be used to quickly determine the minimum combination of components in functional systems which must continue be powered for a design to be considered feasible in damage scenarios.

5.1.3 Routing of arcs

Currently arcs are only considered damaged if they originate or terminate in damaged SDBs. Arcs are not considered damaged if they just pass through a SDB which has been damaged. It is anticipated that some arcs transiting through a damaged SDB would also be damaged. In the AFO, arcs are routed in purely 90-degree increments towards centerline, in the y direction, then vertically, in the z, and finally longitudinally, in the x direction. Additionally, the expansion of the M-1 damaged scenario to include the impacts of a damage ellipsoid, will also yield impactful information.

5.1.4 Dynamic Operating Environments (External temperatures)

As was shown in the case of Brittan's latest Type 45 Destroyer, operational environments can severely impact the ability of a ship to perform its mission. The AFO ensures the thermal energy generated by components in operation onboard the ship is removed but does not address the impacts of varying external conditions. How the system of systems operates in the North Atlantic maybe quite different from how it operates on the equator (Britton 2016).

5.1.5 Transient Operating Scenarios and Recoverability

The AFO models how components operate in a steady state scenario. It does not consider pulse loads or varying electrical load requirements. Modeling the ship's energy distribution while generators and various combat systems are brought on and off line is critical in transient scenarios. Furthermore, determining a ship's recoverability, ability to restore mission capabilities after damage, cannot be done without transient models

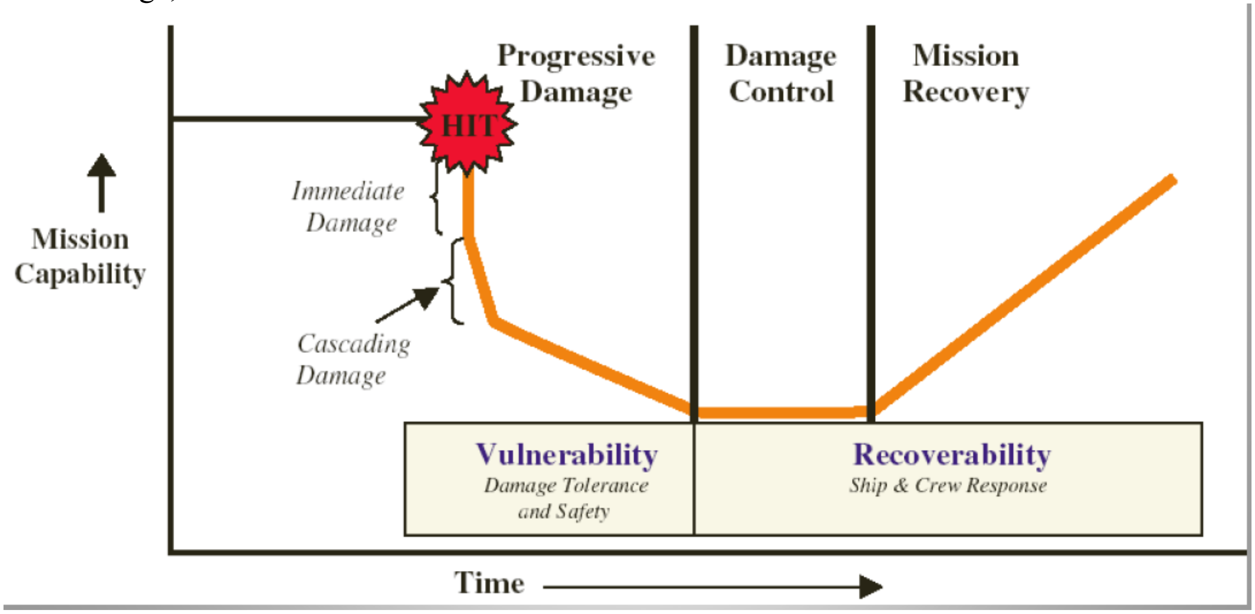


Figure 111 - (D. A. Brown, NE18A: Naval Engineering Lecture Series n.d.)

As combat systems continue to become more and more dependent upon high energy power sources, the incorporation of stored energy may become advantageous. How stored energy devices can act as a dampener of pulse loads on the rest of the system and how it can transition from being an energy sink (charging) to an energy source (producing) will be critical.

5.1.6 Pulse Power

A stand-alone pulse power node or zonal pulse power nodes in the ELEC plex could serve this purpose as a means of drawing electrical energy while charging and discharging it to pulse power components via implicit arcs as needed in Battle or Damaged conditions. This method alleviates the burden of pulse power loads on the ELEC network. Alternatively, a new pulse power plex could be added to study its interactions with the ELEC network and evaluate future system architectures.

5.1.7 Impacts of Part Load Efficiencies

Along with introduction of campaign planning, partial load efficiencies and the loss of those efficiencies should be incorporated. While the system should can maintain operations at the full capability of the network, the ship's ability to sustain operations on sight could be severely compromised by inefficiencies in the nodes.

5.1.8 Constraints for Maintenance

An area for potential examination is the incorporation of maintenance, life cycle cost and modularity constraints. The arcs to and from each component were allowed to scale up and down as needed without consideration for life cycle supportability or the logistics supply chain. This was done intentionally to allow the solver to produce the optimum solution and provide a baseline for further examination.

However, future designers may wish to incorporate life cycle costs and supportability of parts into the optimization which may produce greater life cycle cost savings if for example each CW pump was required to operate at the same capacity, and decrease the number of unique parts required to be kept in stock to support the ship.

When extrapolating the AFO into a time domain and campaign style planning, the incorporation of maintenance should be considered. Much like in the endurance condition, when the PGMs were intentionally deactivated, users may choose certain configurations in which only the "A" side or "B" side of a component is working. Additionally, in other transiting scenarios, the designer may with to reduce wear on machinery by opening all the cross connects and forcing one of the zonal cooling networks to process heat produced by the entire ship, which would allow maintenance to be performed on the off line components.

5.1.9 Integration of VT_AFO into VT Ship Design Process

The AFO offers tremendous potential to improve the insight obtained in the stages of concept exploration and early stage ship design. This tool should be implemented to better articulate a cost/benefit analysis of affordable readiness for the Navy and to understand how varying operational conditions can impact the components and sailors on the ship. VT AFO can be used to evaluate the tradeoffs of different ship system architectures in an Analysis of Alternatives. As the AFO is refined and additional network configurations are optimized, this information could be incorporated into machine learning to quickly optimize not only the current state of a ship, but also the best way to transition from steady state scenario to steady state scenario.

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References

Andrews, D.J. 2003. "Marine Design - Requirement elucidation rather than requiremnt engineering." *International marine Design Conference.* Athens, Greece.

Ashish, Goel. 2008. *Chapter 3: Linear Programs.* Prod. Stanford University. Stanford, CA. Accessed 04 15, 2018. https://web.stanford.edu/~ashishg/msande111/notes/chapter3.pdf.

Ashish, Goel. 2008. *Chapter 5 Network Flows.* Stanford University. Stanford, CA, Fall. Accessed 04 15, 2018. http://web.stanford.edu/~ashishg/msande111/notes/chapter5.pdf.

Brefort, Dorian, Colin Shields, Agnieta Jansen, Etienne Duchateau, Rachel Pawling, Koen Droste, Ted Jasper, et al. 2017. *Ocean Engineering.* 10 28. Accessed 04 15, 2018. http://doi.org/10.1016/j.oceaneng.2017.10.028.

Britton, Bianca. 2016. *Britain's Royal Navy warships are breaking down because sea is too hot.* 06 10. Accessed 04 16, 2018. https://www.cnn.com/2016/06/09/europe/britain-royal-navy-warships/index.html.

Brown, Alan. 2018. "Marine Engineering." In *Marine Engineering*, by Unknown, 13. Blacksburg, VA: Unknow.

Brown, Alan, interview by Kevin Robinson. 2018. *Webex meeting* (04 20).

Brown, Dr Alan. n.d. *Naval Engineering Lecture Series 57A.* Blacksburg, VA.

Brown, Dr Alan. 2016. *NE1_02C: Naval Engineering Lecture Series.* Blacksburg, VA.

Brown, Dr Alan. n.d. *NE18A: Naval Engineering Lecture Series.* Blacksburg, VA.

Brown, Dr. Alan, interview by Kevin Robinson. 2018. *Research Meeting 25APR2018* (April 25).

Chinneck, John W. 2017. *Practical Optimization: A Gentle Introduction.* Ottawa, Ontario, Canada, 10 12.

Doerry, Norbert and Amy, John. 2016. "Design Considerations for a Reference MVDC Power System." *Presented at SNAME Maritime Convention 2016.* Bellevue, WA, November 1-5.

Goodfriend, David. 2015. *Exploration of System Vulnerability in Naval Ship Concept Design.* Masters Thesis, Blacksburg, VA: Virginia Tech.

IBM. 2014. *IBM ILOG CPLEX Optimization Studio CPLEX User's Manual Version 12 Release 6.* USA: International Business machines Corp.

Konak, Abdullah, Smith, Alice E. 2006. "Network Reliability Optimization." In *Handbook of Optimization in Telecommunications*, by M.G.C, Pardalos, P Resende, 735-760. Springer Verlag, USA. Accessed 04 15, 2018. http://www.eng.auburn.edu/sites/personal/aesmith/files/bookchapter.pdf.

Leon, Steven J. 2006. *Linear Algebra with Applications.* Upper Saddle River, NJ: Pearson Prentence Hall.

Man Diesel. 2014. *Thermo Efficiency System for Reduction of Fuel Consumption and CO2 Emission.* 10. Accessed 04 23, 2018. https://marine.mandieselturbo.com/docs/librariesprovider6/technical-papers/thermo-efficiency-system.pdf?sfvrsn=24.

Markle, Stephen P, PE. 2018. "Motivation – Survivability, System Interdependence and Affordability." *Naval Engineering Education Consortium.* Bethesda, MD: Virginia Tech. 1-5.

McCallum, Michael. 2001. *EMAT6690: An Introduction to Linear Programming.* Accessed 04 15, 2018. http://jwilson.coe.uga.edu/EMT668/EMAT6680.F99/McCallum/emat6690/Linear%20Programming/Linear%20Programming.html.

MIT. 2016. *Network Models.* Massachusetts Institute of Technology. Cambridge, MA. Accessed 04 15, 2018. http://web.mit.edu/15.053/www/AMP-Chapter-08.pdf.

Sierksma, Gerard. 2001. *Linear and Integer Programming: Theory and Practice.* CRC Press.

Trapp, Thomas A. 2015. "Shipboard Integrated Engineering Plant Survivable Network Optimization." Cambridge: Massachusetts Institute of Technology, June.

Zivi, Edwin, Scott Sudhoff, and Aaron Cramer. 2011. "Performance Metrics for Electric Warship Integrated Engineering Plate Battle Damage Response." IEEE Transactions on Aerospace and Electronic Systems, January.