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SYSTEMS ENGINEERING ANALYSIS CAPSTONE PROJECT REPORT

SET-BASED DESIGN: FLEET ARCHITECTURE AND DESIGN 2030–2035

by

David Alessandria, Isa Al-Jawder, Eric Clow, Carlos Maldonado, Jeremiah Medina, Brandon Nichols, and Timothy Uchida

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Project Advisors: Fotis Papoulias
Robert Dell

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This report outlines a design methodology and provides a recommendation for an alternative fleet architecture to the United States naval force for 2030–2035. While there are many methods and techniques to generate future fleet alternatives, Set-Based Design (SBD) is used in this report to generate a future fleet architecture. SBD principles maintain multiple requirements and leave design options open late into the development cycle without committing to any specific designs. The purpose of leaving multiple design options open until the very end is to reduce the amount of rework and cost overruns if requirements change. As the design timeline concludes, SBD uses empirical data to collapse focus to the final design solution.

To implement SBD in this report, the team developed a computer model to optimize ship and platform choices simultaneously across eight critical warfare areas based on multiple user defined inputs. This theoretical "optimized fleet" is measured against unique measures of effectiveness to verify its validity for future operations. This method of analysis proposes a future fleet architecture consisting of 297 fighting ships, 88 Military Sealift Command ships, and 566 unmanned vehicles.

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SET-BASED DESIGN: FLEET ARCHITECTURE AND DESIGN 2030–2035

LT David Alessandria, USN	LT Isa Al-Jawder, USN	LT Eric Clow, USN
LT Carlos Maldonado, USN	LT Jeremiah Medina, USN	LT Brandon Nichols, USN
	LT Timothy Uchida, USN	

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Reviewed by:
Dr. Fotis Papoulias, Project Advisor
Dr. Robert Dell, Project Advisor

Accepted by:
Ronald Giachetti, Chair, Systems Engineering Department
Patricia Jacobs, Chair, Operations Research Department

Jeffrey Kline
Chair, Systems Engineering Analysis Department

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This report outlines a design methodology and provides a recommendation for an alternative fleet architecture to the United States naval force for 2030–2035. While there are many methods and techniques to generate future fleet alternatives, Set-Based Design (SBD) is used in this report to generate a future fleet architecture. SBD principles maintain multiple requirements and leave design options open late into the development cycle without committing to any specific designs. The purpose of leaving multiple design options open until the very end is to reduce the amount of rework and cost overruns if requirements change. As the design timeline concludes, SBD uses empirical data to collapse focus to the final design solution.

To implement SBD in this report, the team developed a computer model to optimize ship and platform choices simultaneously across eight critical warfare areas based on multiple user defined inputs. This theoretical "optimized fleet" is measured against unique measures of effectiveness to verify its validity for future operations. This method of analysis proposes a future fleet architecture consisting of 297 fighting ships, 88 Military Sealift Command ships, and 566 unmanned vehicles.

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LIST OF ACRONYMS AND ABBREVIATIONS

A2AD	anti-access area denial
AAA	anti-aircraft artillery
AAW	anti-air warfare
ACTUV	anti-submarine warfare continuous trail unmanned vessel
AF	amphibious force
AFSB	afloat forward staging base
AGER	technical research and spy ship
AOR	area of operation
AMW	amphibious warfare
ARG	amphibious ready group
ASCM	anti-ship cruise missile
ASROC	anti-submarine rockets
AS	submarine tender
ASW	anti-submarine warfare
ATS	towing salvage and rescue ship
B	billion
BBG	battleship battle group
BMD	ballistic missile defense
C5I	command computers communications control and collaborations intelligence
C&D	command and decision
CAP	capability
CLG	light carrier group
CG	guided missile cruiser
COCOM	combatant commander
COTS	commercial off-the-shelf
CRUDES	cruiser-destroyer
CSBA	Center for Strategic and Budgetary Assessments
CSG	carrier strike group
CVL	aircraft carrier, light

CVN	aircraft carrier, nuclear
CVW	carrier air wing
DDG	guided missile destroyer
DDG-1000	Zumwalt class guided missile destroyer
DOD	Department of Defense
DON	Department of the Navy
EEZ	exclusive economic zone
ER	extended range
EPF	expeditionary fast transport
ESB	expeditionary sea base
ESD	expeditionary sea dock
ESG	expeditionary strike group
EW	electronic warfare
FAC	fast attack craft
FIAC	fast inshore attack craft
FDNF	forward deployed naval force
FRP	fleet response plan
FY	fiscal year
HCU	helicopter combat squadron
HP	horsepower
HSC	helicopter sea combat squadron
HSM	helicopter maritime strike squadron
HSU	unmanned helicopter combat squadron
IAMD	integrated air missile defense
ICAV	inspections, certifications, assessments, and visits
ICBM	inter-continental ballistic missile
IJN	Imperial Japanese Navy
IOFRP	improved optimal fleet response plan
IRIN	Islamic Republic of Iran, Navy
ISIS	Islamic State of Iraq and Syria
ISR	intelligence, surveillance, and reconnaissance
KPN	People's Republic of North Korea Navy

LCAC	landing craft air cushion
LCS	littoral combat ship
LCU	landing craft, utility
LHA	landing helicopter amphibious assault ship
LHD	landing helicopter deck amphibious assault ship
LSD	dock landing ship
LPD	amphibious transport dock
MCM	mine countermeasure ship
MDUSV	medium displacement unmanned surface vessel
MEU	marine expeditionary unit
MIW	mine warfare
M	million
MM	mission modules
MOE	measures of effectiveness
MOP	measure of performance
MP	mission package
MSC	Military Sealift-Command
NM	nautical mile
NPS	Naval Postgraduate School
NSFS	naval surface fire support
NWDC	Navy Warfare Development Command
OFRP	optimized fleet response plan
OPNAV	Office of the Chief of Naval Operations
PC	patrol boat
PBD	point-based design
PLAN	People's Liberation Army Navy (Chinese Navy)
SCN	shipbuilding and conversion, Navy
SEA	Systems Engineering and Analysis
SBD	set-based design
SSC	ship-to-shore connector
SSBN	ballistic missile submarine, nuclear
SSGN	conventional missile submarine, nuclear

SSN	fast attack submarine, nuclear
STW	strike warfare
SUW	surface warfare
T-AO	fleet replenishment oiler
T-AOE	fast combat support ship
TERN	tactically exploited reconnaissance node
THAAD	terminal high-altitude area defense
TLAM	tomahawk land attack cruise missile
TY	then year
UAS	unmanned aerial system
UAV	unmanned aerial vehicle
USFF	United State Fleet Forces
USPACFLT	United States Pacific Fleet
USV	unmanned surface vessel
UUV	unmanned underwater vessel
UxV	unmanned systems
VAQ	electronic attack squadron
VAW	airborne early warning squadron
VCU	unmanned communications relay squadron
VFA	strike fighter squadron
VFU	unmanned strike fighter squadron
VQU	unmanned electronic attack squadron
VRC	fleet logistics support squadron
VTOL	vertical takeoff and landing
VWU	unmanned airborne early warning squadron
WWI	World War One
XLDUUV	extra-large displacement unmanned underwater vehicle

EXECUTIVE SUMMARY

This report describes the application of set-based-design (SBD) to develop a U.S. Navy fleet architecture for the 2030–2035 timeframe. Quantifying the effectiveness of a navy's fleet is no easy task. Metrics to quantify the fleet were derived from the following two documents: *A Design for Maintaining Maritime Superiority* and *A Cooperative Strategy for 21st Century Seapower.* Along with the two major source documents, other Congress-mandated studies on future fleet architectures add to the dynamic and depth of analysis in the Systems Engineering and Analysis Cohort 26 (SEA-26) capstone project.

While the majority of the previous studies on this topic highlight specific points of concern for the U.S. Navy's future, this capstone focuses on a flexible fleet that can withstand multiple possible adversaries while reaching, and hopefully exceeding, a minimum level of warfare capabilities across eight naval warfare areas (strike warfare [STW], anti-air warfare [AAW], surface warfare [SUW], anti-submarine warfare [ASW], ballistic missile defense [BMD], electronic warfare [EW], mine warfare [MIW], and amphibious warfare [AMW]).

The team derived quantitative requirements from guiding principles articulated in the source documents to generate different emphases on the future of the U.S. Navy to include, but are not limited to, geographical, adversarial, and warfare-focused emphases. These different emphases define the "sets" in this study's SBD. Specific examples of sets include a sea-control focused navy, a sea-control focused navy with unmanned systems, a BMD along with STW-focused navy, and a non–blue water navy emphasis. Using measures of performance (MOP), the sets contribute bounds to a feasibility region for each of the Navy's eight primary warfare areas. Each feasible region bounds possible data points quantifying the MOP for each warfare area given an associated monetary value. An optimization model developed for this study serves as a tool that selects a specific list of platforms by keeping the data points within their respective feasibility regions across all eight warfare areas. This tool comprises a spreadsheet consisting of quantitative assumptions, stakeholder-based input, set-defined constraints, and equations calculating the various measures for this study. Given our assumptions and constraints, the optimization model generates a future fleet architecture consisting of 297 fighting ships and 586 unmanned systems as outlined in Table 5 of the full report. This solution yields 9 carrier strike groups (CSGs), 4 DDG-1000 battle groups, 9 light carrier groups (CLGs), 12 amphibious ready groups (ARGs), 4 mine countermeasure (MCM) squadrons, and 6 littoral surface action groups (SAGs).

The main budget constraint for this study is a $257B (FY2035) shipbuilding and conversion Navy (SCN) budget. However, only fighting platforms are considered for this study; outfitting, overhaul, refueling, support ships, and port facilities ships all contribute to the reduction in budget, yielding a $164B (FY2035) budget constraint for the optimization model. Other fleet accounts supporting aircraft procurement, manpower, and maintenance may be added as future constraints.

The implementation of unmanned systems in the 2035 fleet increases the MOPs by 19% at a cost of $5.7B. This $5.7 billion cost is not considered an SCN expense, and does not result in an additional monetary expense within our model. This, too, is an additional constraint for future research.

Principles from the source documents guide the development of five measures of effectiveness (MOE) to assess the capabilities of the generated fleet architecture, and allocation of platforms across the numbered fleets allows for maximization of MOEs. The current-day (2017) platform allocation serves as a basis for 2035 platform distribution, as we use the current force as the starting point. Manual distribution of the platforms allows users of the tool to keep human decision-makers involved in maximizing MOEs.

SBD is an effective and unique tool upfront in the design process, however cumbersome and difficult when considering complex problems such as designing a future naval fleet architecture. SBD pairs well with optimization methods by restricting the multidimensional feasible region. The use of SBD in this study lead the results that shift the fleet focus away from undersea warfare platforms and the idea of a high value unit-centric battlegroup. SBD provides guidance to the development of a future fleet architecture, but it cannot possibly consider all factors that must be addressed in the final fleet solution. A factor that must be considered in any future addition to this research is platform vulnerability to specific threats and scenarios.

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I. INTRODUCTION

A. BACKGROUND

The construction of something as vast and complex as the United States Navy is an endeavor not undertaken lightly. Much planning and preparation is invested to assure the systems, weapons, and capabilities developed will be effective not only at the time of inception, but well into the future. With long development, testing and construction cycles modern ships take decades to field, and serve for decades following Initial Operational Capability introduction. Therefore, it is imperative that we construct the best fleet possible, as the fleet we design today will continue to serve for decades to come.

The United States has traditionally equipped, and its leaders have promised to continue to equip, its people with the best and most technologically advanced equipment ever developed. From the tiny black box hidden inside a console to the enormity of a Carrier Strike Group, the United States relies on equipment to carry out missions. This capstone research project optimizes the fleet composition at the level of individual ships and platforms while developing analytical tools to inform the construction of the future Navy of 2030–2035.

The measure of naval strength has evolved from simply counting the number and size of guns into a multi-dimensional spectrum of warfare where capabilities and capacities are much harder to measure. Traditional methods developing the future fleet architecture revolved around the concept known today as point-based design (PBD). For example, in the dreadnought era of the early 20th century, tonnage and gun caliber were the metrics of a successful fleet. Fleet design and architecture were focused on designing large ships with multiple turrets and large guns to encounter an adversarial force with similar metrics of fleet quantification.

Today's fleets must contend in a far more dangerous, complex, and dynamic world of tactics and weapons. They must be prepared to fight subsurface, surface, aerial, and space systems in the kinetic, electromagnetic, and cyber domains. Information regarding the enemy is equally, if not more important, than the maximum raw firepower one's fleet is capable of employing. In an age of over-the-horizon targeting, net-centric fires, hypersonic anti-ship cruise missile threats, and the proliferation of sub-surface capabilities, fleets must be sufficiently flexible to counter, or at least mitigate a multidimensional threat axis.

Utilizing a new project management technique referred to as "Set-Based Design," (for example, see Singer, Doerry, and Buckley 2009) the Naval Postgraduate School Systems Engineering Analysis Cohort 26 (SEA-26) developed tools and designed an alternative fleet architecture for the 2030–2035 timeframe.

B. TASKING STATEMENT

A tasking letter submitted to the team by CAPT (ret) Jeff Kline USN under the direction of the Office of the Chief of Naval Operations (OPNAV) code N9I guides the efforts of the SEA-26 Capstone research project. The original tasking statement outlines the techniques to be used, as well as the desired products of the future fleet architecture plan.

> Design an alternative fleet architecture (platforms, support) and design (concept of strategic employment) to the programmed force for the 2030–2035 timeframe. Consider the anticipated dynamics of future naval combat, emerging technologies, and potential adversaries' trends in systems which threaten U.S. sea control. To the maximum extent possible, use set-based design to meet capability, capacity, and mission set requirements articulated in *A Design for Maintaining Maritime Superiority* and *A Cooperative Strategy for 21st Century Seapower*. The fleet architecture should include the numbers, kinds, and sizes of vessels, numbers and types of associated manned and unmanned vessels, and the basic capabilities of each of those platforms. Assess your fleet architecture and design against the programmed force costs, technical risk, and their ability to satisfy national and military strategy. (Kline 2017)

C. PROBLEM STATEMENT

The naval fleet of 2035 is currently under construction. In order for the fleet the United States is building now to address the future needs of the Navy, the United States must consider platform and fleet architectures that will be as flexible and agile as possible. By direction of the sponsor, set-based design (SBD) is used in this study to attempt to solve the problem of deciding what will best suit our future needs. The tasking statement above provided by OPNAV N9I provides the context below for which this research project is based upon:

> Emerging technologies in unmanned systems; autonomy; missile systems; undersea systems; long-range, netted and multi-domain sensors; and networks create a new environment for operations on and over the sea. This changing technology environment both challenges traditional fleet operations and provides opportunities for innovative tactics, techniques, and procedures to achieve naval objectives in sea control, power projection and counter anti-access area denial (A2AD) strategies. The Naval Postgraduate School Warfare Innovation Continuum is a series of independent, but coordinated cross-campus educational and research activities to provide insight into the opportunities for warfighting in the complex and electromagnetically contested environment at sea and near the sea-land interface. It will address opportunities in unmanned systems technologies to support web fires and tactically offensive operations, and further develop the concept of electromagnetic maneuver warfare as an asymmetric advantage. The larger research question is, "Will emergent technologies innovatively employed strengthen naval capabilities in contested environments?" (Kline 2017).

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II. FLEET ARCHITECTURE AND FLEET DESIGN

A. DEFINITION OF FLEET DESIGN

"A fleet design is how the fleet, the Navy's highest warfighting tactical echelon, fights, and wins in any environment, as expressed through concepts, doctrine, and tactics, techniques, and procedures" (Kline 2017). For the purpose of this team's report, the fleet consists of surface vessels, submarines, manned and unmanned aircraft, and ship-based aircraft to conduct naval operations. United States Navy's fleet is divided into smaller numbered and geographically distributed fleets. Given the current fleet design and assumption that assets will continue to be placed in the same geographic area of operations (AORs) as the 2017 fleet, the SEA-26 team focused our efforts on constructing a Fleet Architecture vice a Fleet Design.

B. DEFINITION OF FLEET ARCHITECTURE

In order to properly assess what a future United States naval force looks like, it is important to first understand what a Fleet Architecture is and how it is defined by leading fleet guidance. As defined by CAPT Jeff Kline, USN, Retired, a fleet architecture consists of those activities that support the fleet design, to include:

1. Presence, surge forces, and force packages.

2. How forces prepare and recover from deployment.

3. Bases and facilities that support or host the fleet.

4. Materiel components of the fleet, such as ships, aircraft, unmanned vehicles, personnel, weapons, and sensors (2017).

Based on the definition above, this study delivers a fleet architecture consisting of the following five elements:

1. Number of Vessels.

2. Number of Manned Vehicles.

3. Number of Unmanned Vehicles.

4. Activities of Ship Life Cycles.

5. Activities of Facilities for Support.

C. FLEET DESIGN DEFINITIONS

Although we are focusing on Fleet Architecture, throughout this report fleet design specific terms are used many times in order to assist in the defining and shaping of our trade space for the Fleet Architecture tool we are constructing. Below is a short list of said design terms, commonly referred to as "-ilities"

Flexibility: Ships built with the ability to conduct multiple missions or accept mission systems and equipment that can be removed and replaced pier-side, in a short period of time, to adapt a ship's capabilities to a specific mission.

Modularity: Ships built with common design interfaces and modular components that reduce the complexity of adding, adapting, and modernizing capabilities. Modularity is commonly paired with commercial off-the-shelf (COTS) tools parts and materials which assist in modularity and easy budget cost for the Fleet.

Commonality: Ability of hardware and software combinations to be easily installed and implemented across multiple ship platforms without sacrificing performance. Standardization is another term that can help define commonality, along with COTS as defined above.

Scalability: Capabilities developed independently of ships using standardized design specifications which allow the same systems, at various scales, to be applied across multiple ship platforms.

D. REQUIREMENTS DEVELOPMENT AND DECOMPOSITION

The development of requirements for our future fleet analysis is based on the source documents *A Design for Maintaining Maritime Superiority* and *A Cooperative*

Strategy for 21st Century Seapower. Based on our analysis of these documents, we define the four principle tenants of a fleet architecture below:

1. Force packages: Presence, surge forces, and force packages;

2. Preparation and recovery of forces: How forces prepare and recover from deployment;

3. Support Bases and Facilities: Bases and facilities that support or host the fleet; and

4. Material components of the fleet, such as ships, aircraft, unmanned vehicles, personnel, weapons, and sensors.

The measures of effectiveness used in this report's analytics are derived from these four principles, and traceability is provided in Tables 1 and 2.

Table 1. Requirement Traceability from *A Design for Maintaining Maritime Superiority*. Adapted from Department of the Navy (2016).

High Level Needs Statement Line Item	Fleet Architecture Traceability	Derived Fleet Architecture Requirements
Shipping traffic over traditional sea lanes is increasing, new trade routes are opening in the Arctic, and new technologies are making undersea resources more accessible.	3. Support Bases and Facilities 4. Material Components	Additional undersea resources, both manned and unmanned, for an additional geographic area in the Arctic.
Rise of the global information system – the information that rides on the servers, undersea cables, satellites, and wireless networks that increasingly envelop and connect the globe.	1. Force Packages 4. Material Components	Increase the capability of command computers communications control and collaborations intelligence (C5I) and "grid" centric warfare. Also consider warfare capabilities in a denied or degraded communications environment.
The increasing rate of technological creation and adoption: • Multi-layered integrated air missile defense (IAMD) environment	1. Force Packages 4. Material Components	Apply emerging technologies that are feasible in the 2030–2035 timeframe. Also consider that due to ship life cycle constraints, the fleet of 2030–

High Level Needs Statement Line Item	Fleet Architecture Traceability	Derived Fleet Architecture Requirements
• Long range power projection • Mark 45 5” extended-range • Advanced ASCM threats		2035 will consist of 60% of the fleet of 2017.
Both China and Russia are also engaging in coercion and competition below the traditional thresholds of high-end conflict, but nonetheless exploit the weakness of accepted norms in space, cyber and the electromagnetic spectrum. The Russian Navy is operating with a frequency and in areas not seen for almost two decades, and the Chinese People’s Liberation Army Navy PLA(N) is extending its reach around the world.	1. Force Packages 2. Preparation and Recovery of Forces 3. Support Bases and Facilities 4. Material Components	While the National Security Strategy of 2017 seems to focus on non-state actors and rogue nations, the rise of peer competitors will be a concern in 2030–2035. Consider the return of Symmetric Warfare.
Surge Ready	2. Preparation and Recovery of Forces	Defeat aggression in overlapping conflicts. Have an adequate number of platforms to have a robust fleet response plan (FRP).
Balanced force of submarines, aircraft carriers, amphibious ships and surface combatants designed for combat.	1. Force Packages 4. Material Components	Optimize capabilities of each platform in the U.S. Navy’s inventory.
Improve Joint Force interdependence, increase synergy with Air Force and Army. For example; intelligence surveillance and reconnaissance (ISR), terminal high altitude area defense (THAAD), Patriot Missile Batteries. Joint Special Forces embarked on Navy Ships.	1. Force Packages 4. Material Components	After optimization of capabilities, consider using Army and Air Force assets already present rather than using additional Navy asset.
Implement a predictable naval force employment model—the Navy’s optimized fleet response plan (O-FRP)—which structures pre-deployment maintenance, training, and inspection schedules.	1. Force Packages 2. Preparation and Recovery of Forces 3. Support Bases and Facilities 4. Material Components	Produce a percentage of available and deployable assets.
Modularity. Collaborate with our industry partners to design interoperable and adaptable platforms.	1. Force Packages 4. Material Components	Consider platforms with built-in versatility.
Develop networked, integrated, and multi-dimensional capabilities to defeat adversary air and missile	1. Force Packages 4. Material Components	Balance the force among all warfare areas. Do not rely on a single type of asset or platform

High Level Needs Statement Line Item	Fleet Architecture Traceability	Derived Fleet Architecture Requirements
threats.		for a single warfare area. Consider layered and distributed concepts.
Optimize the use of our platform payload volume by integrating kinetic and non-kinetic warfighting capabilities in cyberspace and the electromagnetic spectrum.	1. Force Packages 4. Material Components	Do not quantify the fleet architecture solely in terms of offensive capability.
Continue developing and integrating unmanned systems. This includes air, surface, undersea, and land-based applications.	1. Force Packages 2. Preparation and Recovery of Forces 4. Material Components	Optimize and distribute capabilities.
Prioritize development of long-range stand-off weapons based on air, underwater, and surface.	1. Force Packages 4. Material Components	Consider the development of the long range strike Tomahawk and Rail Gun combat systems.
Develop the capability to employ connectors, including combinations of landing craft, amphibious vehicles, small craft, and multi-mission aviation platforms in the littoral.	1. Force Packages 4. Material Components	Consider amphibious assets based upon their ability to embark and employ ship to shore connectors.

Table 2. Requirement Traceability from *A Cooperative Strategy for 21st Century Seapower*. Adapted from Department of the Navy (2015).

High Level Needs Statement Line Item	Fleet Architecture Traceability	Derived Fleet Architecture Requirements
Consider Potential Adversaries to Sea Control: • Consider China's naval expansion • Russian Military modernization • North Korea • Iran • ISIS and Non-State Affiliated Actors • Receding Arctic • Challenges in space and cyberspace • Coastal Defense Batteries with ranges of 700–800 miles at Mach 5 • Space sensing, The Navy cannot	1. Force Packages 2. Preparation and Recovery of Forces 3. Support Bases and Facilities 4. Material Components	Must consider the future dynamics of naval combat.

High Level Needs Statement Line Item	Fleet Architecture Traceability	Derived Fleet Architecture Requirements
rely on ships remaining hidden for extended periods in a 2030 environment.		
Increase forward deployed ships to reduce costly rotations and deployments, boost in theatre.	2. Preparation and Recovery of Forces 3. Support Bases and Facilities	After assets are determined, methodically and carefully place the assets worldwide to combat future potential adversaries and threats.
Employ modular designed platforms that allow mission modules and payloads to be swapped.	1. Force Packages 4. Material Components	Consider platforms with built-in versatility.
Expand the practice of employing adaptive force packages, tailored to specific regional environments.	1. Force Packages 2. Preparation and Recovery of Forces 3. Support Bases and Facilities 4. Material Components	Must consider the future dynamics of naval combat and how they apply to regional threats.
Increase the presence in the Gulf from 30 ships to 40 ships in 2020.	2. Preparation and Recovery of Forces 3. Support Bases and Facilities 4. Material Components	Consider additional forward deployed assets.
Develop and evolve our electromagnetic maneuver warfare, space, and cyber concepts	1. Force Packages 4. Material Components	Increase the capability of C5I and “grid” centric warfare. Also consider warfare capabilities in a denied or degraded communications environment.
Improve our capability to seize, establish, sustain, and protect austere expeditionary bases.	1. Force Packages 4. Material Components	Must consider the future dynamics of naval combat: long range standoff strike weapons and the future of ship-to-shore connectors.

III. SET-BASED DESIGN

A. EXPLANATION OF SET-BASED DESIGN

SBD is a design method that leaves requirements and/or design options open and unspecified for a longer period through the design process (for example see Singer, Doerry, and Buckley 2009). SBD provides the design team with flexibility from requirements analysis to establishment of the final system design. As the design deadline approaches, empirical data is used to collapse focus to the final design options. This could also be summarized as make all of the decisions as late as possible to not exclude any promising design options.

The "sets" in SBD can describe a set of design options that describe one possible permutation of the design of a system. Therefore, each set has a different description and consequently different requirements. The goal of SBD is to allow those different requirements from each set to remain candidates for the final design - in other words, keep the requirements feasible until the design team is ready to commit to a final design. Ideally, the final system design will satisfy requirements common to all sets in order to produce the most versatile system possible. In Figure 1, each colored elliptical region represents a set, each of which possess design options unique to the set. At the end of the SBD process, a selection of design options is drawn from the feasible region common to all sets.

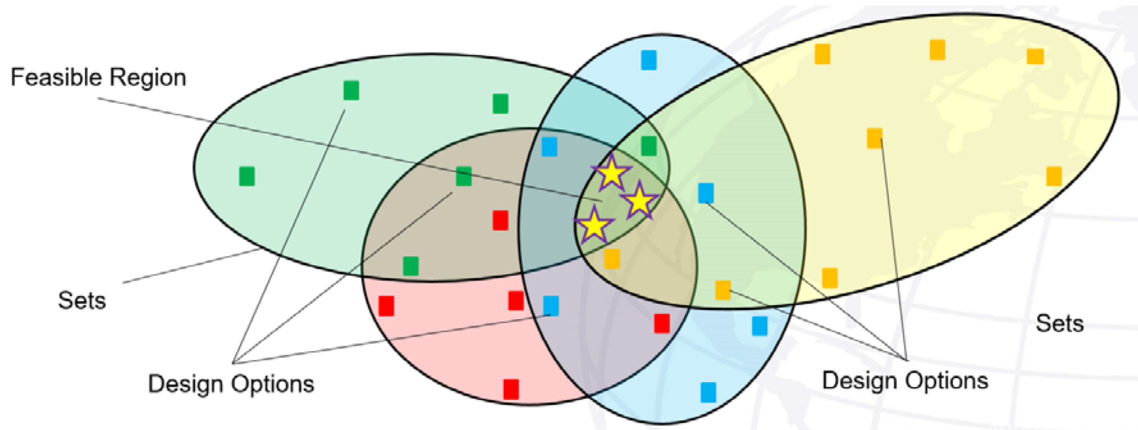

Figure 1. Concept of Set-Based Design

B. SET-BASED DESIGN VS. POINT BASED DESIGN

The traditional design process (point-based design) involves the commitment to a design option (requirement, specification, concept, etc.) as soon as the decision can be made. All further progress through the design process is then based on that chosen design option. As the system design matures, the design team continues to commit to design options to converge on a final system design. However, in the late stages of the design process, the potential for changes to design options exist. If the design team changes design options in later stages of the design process, then the design process incurs major penalties in terms of cost and time to rework the design at the point of the altered design option. For example, in PBD of an automobile, the team may commit to an engine specification of 285 horsepower (HP). Consequently, the components of the engine will be designed around producing 285 HP. If later in the project the design team decides to increase the power specification to 300 HP, the team will have to redesign the components to meet that new requirement.

SBD eliminates the major penalties of cost and time by replacing the commitment to a specific design option with a field of probable design options instead. In SBD of the automobile mentioned previously, the team will not commit to a particular specification, but rather an acceptable interval, such as 250–350 HP. In this way, engine components can be designed to be within a particular range to meet the acceptable interval for the specification, and the design team can choose any quantity between 250 - 350 HP for the final system design without suffering the same consequences in PBD. Figure 2 visually compares SBD and PBD. In SBD, potential permutations of a final system design are numerous early in the design process, but a particular design is realized over time through continual analyses of alternatives. However, in PBD, the design team may come close to converging on a final system design, but may change design options and face numerous new permutations of a final system design.

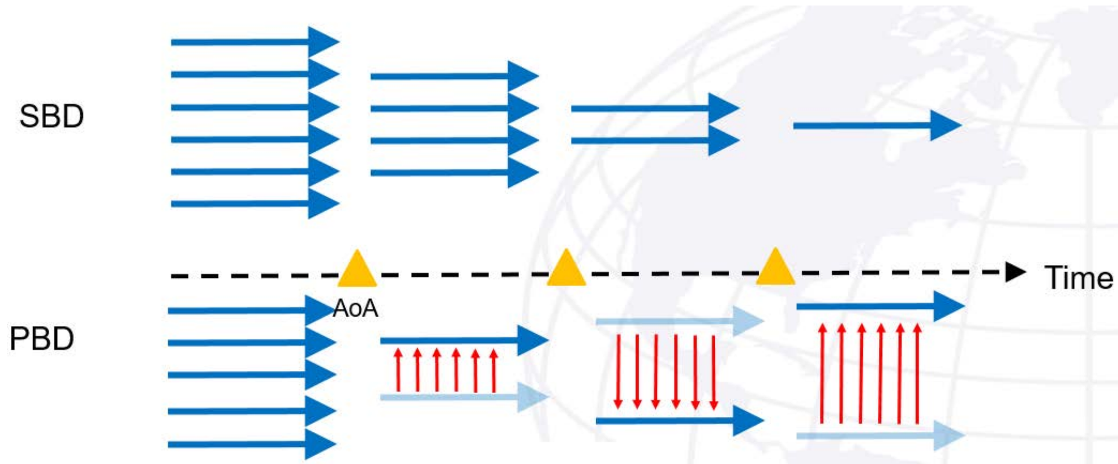

Figure 2. Comparison of Set-Based Design and Point-Based Design. Source: Singer, Doerry, and Buckley (2009).

C. SET-BASED DESIGN APPLIED TO THE FLEET ARCHITECTURE

The objective of this study is to produce a fleet architecture (as defined in Chapter II.B using SBD. For the purposes of this study, the definition of a "set" is as follows:

> *A set is a unique emphasis on warfighting capabilities of the fleet in the 2030–2035 timeframe that possesses a unique description and unique requirements for the warfare areas of Strike Warfare, Anti-Air Warfare, Surface Warfare, Anti-Submarine Warfare, Electronic Warfare, Mine Warfare, Amphibious Warfare, and Ballistic Missile Defense.*

Set descriptions are provided in Chapter III.D. The warfare areas are defined in Section IV.F. as MOPs for this study. The unique requirements specific to each set are provided as feasibility constraints in Chapter V.D.4 as they apply to SBD.

This study does not select a superior set; it enumerates the platforms required to meet the requirements based upon the intersecting contribution of multiple sets.

D. SET DESCRIPTIONS

(0) Set Zero (Baseline, Current Day)

a. This set is merely a reflection of current day (2017) fleet design. While there is some flex to be understood, with new ships being built and old ships being retrofitted in the yards, we assume that there is no unmanned (autonomous) systems in use and the littoral combat ship (LCS) is restricted to nine working platforms. This baseline is generally considered the "big ship, lots of capabilities and warfare areas, aircraft carrier" fleet design. With eleven nuclear powered carriers, this design relies on air power projection from sea to support Amphibious Warfare (AMW), and Anti-Air Warfare (AAW) operations. An important second primary mission area is strategic deterrence via Surface Warfare (SUW). Set Zero will be the baseline against which all other sets will be measured. (271 ships).

b. Requirements Derivation: Given the past wars that the U.S. Navy has fought, today's Navy (2017) mirrors the requirements set in the Cold War and WWII. As we plan to fight our naval battles primarily in Blue Water, today's fleet is centralized on the CSG and its ability to project over large areas at sea and over land. Specific information on the complement and utilization of a CSG is provided in Appendix B.

c. Fleet Quantification Assumptions: Please see Appendix A.

(1) Set One (Sea Control Focus)

a. This set leans heavily on Wayne Hughes "A New Navy Fighting Machine" fleet design (Hughes 2009). It focuses on SUW via a multitude of small single or dual mission areas. This architecture is comprised of 304 ships seeing an increase on the Baseline design via the small SUW craft such as LCS or missile boats. Although this navy will continue blue water operations, the primary focus of this fleet design will be on green water operation. This shift in focus helps deter and restrict growing foreign navies such as the PLAN (China), KPN (North Korea), IRIN (Iran) and other aggressive but fiscally constrained countries.

b. Requirements Derivation: This Set traces its roots from the rapidly growing threat posed by the PLAN. While its fleet has only an emerging robust blue water capacity, its capabilities operating inside China's exclusive economic zone (EEZ, inside 200 nm) are striking. Given that China's Fleet composition is heavily biased towards small, fast and somewhat disposable missile boats, its ability to accept losses while still being an effective counter ship naval force infers the U.S. Navy must change to counter their strengths, if the U.S. wishes to have a viable influence in the Chinese EEZ.

c. Fleet Quantification Assumptions: Littoral focus yields new designed U.S. missile boats or the reconfiguring of the LCS class. Further discussion of LCS capabilities and mission modules is included in Appendix H.

(2) Set Two (South China Sea / Pacific Theater, Surface and Unmanned Focus)

a. This fleet set is structured to fulfill both a blue and green water focus instead of a single objective as is the case in fleet design Zero and One. In order to meet the demand of both high sea operations and littorals, this fleet architecture calls for a drastic increase of ship numbers. In this design, we can expect the SSGN, Cruiser-Destroyer Forces, and light aircraft carrier (CVL) production numbers to increase. More information on the CVL and light carrier group (CLG) concepts are provided in Appendix D. Without additional ships, this fleet set will fail to cover both of the large domains it seeks to emphasize. Since this architecture follows the generic "big and little" of "high and low" navy concept, merely increasing ship numbers will not be enough to match the ever growing foreign navy presence in the Pacific, and specifically, the South China Sea. To fill these voids, this fleet architecture will include a large number and wide variety of unmanned systems. Specifically, unmanned aerial vehicles (UAVs) of group 3, 4, and 5 (Appendix G), unmanned surface vessels (USVs), (medium displacement unmanned surface vessel (MDUSV)), and unmanned underwater vehicles (UUVs) will be the center pieces for filling gaps in: comms nets and systems, surface or subsurface restricted mission sets, and reduced risk to human life reconnaissance and information gathering missions. Additional information on MDUSV and UUV can be found in Appendix I and K, respectively.

b. Requirements Derivation: There is a large push to increase the U.S. Navy's capabilities and assets in all water areas (blue, green, and brown). This push will demand a much higher mission flexibility of existing naval assets or a massive increase in platform numbers. In 2017 the Army covers brown water areas however in the future the Navy will likely have a larger role in this domain.

c. Fleet Quantification Assumptions: UxV technology will be mature enough to be tested and serviceable in the Fleet. They will provide real capabilities to the Fleet and reduce the burden on manpower and maintenance compared to existing manned systems.

(3) Set Three (Ballistic Missile Defense and Strike Warfare Focus)

a. This fleet set focuses on the ever present ballistic missile nuclear warfare threat. While there are relatively few countries that can "reach" the United States with nuclear missiles, the technology is growing and proliferating rapidly to smaller, less developed countries. To combat the growth in nuclear threats, this fleet architecture calls for a drastic increase in the SSBN numbers along with a UAV heavy comms net. Since detecting and destroying ICBMs in flight is only half the fight, this architecture will shift its main warfare focus to Ballistic Missile Defense (BMD) and Strike Warfare (STW) to both find and destroy ballistic missiles flight, and the facilities on the ground, further preventing adversary capabilities to conduct ballistic missile warfare. The UAV comms net will be a system of systems that employs the current day cooperative engagement capability to link both Navy BMD assets jointly with Army and Air Force assets; specifically THAAD, Patriot, ISR, and sea based x-band radar.

b. Requirements Derivation: as rising world powers continue to test and develop their own nuclear programs, the U.S. Navy and U.S. Air Force face a growing demand on their ballistic missile defense programs. Today's aging AEGIS system, although adapting and receiving upgrades, is a system that will not be able to face this rising demand for BMD worldwide with current construction rates.

c. Fleet Quantification Assumptions: over the next 20 years North Korea, Russia, China will continue to push their presence on the world stage via BM power. We are also assuming that there will be at least 2–3 more nations that rise up with nuclear programs of their own. The fleet quantification assumptions come from stakeholder responses from questions provided in Appendix M.

(4) Set Four (Green and Brown Water Focus)

a. This fleet architecture set embodies the idea that the future of the U.S. Navy Fleet lays in future platforms. To employ this mentality, this fleet design calls for ceasing the production of all Destroyer (DDG) 51 classes and nuclear aircraft carrier (CVN) classes. In their stead we focus the majority of our shipbuilding budget into the DDG 1000, SSGN, LCS, and

LPD 17 classes along with heavy unmanned systems involvement (UAV, UUV, and ACTUV). These unmanned systems will create Unmanned Underwater Groups (UUG)not on acronym list. More information on the UUG concept can be found in Appendix E. Each of these platforms brings some of the most modern developments in weaponry along with the ability to be flexible. This flexibility comes from the ability to be modular and employ technology that has the ability to learn and the physical room to develop and change throughout the life of the platform. This type of flexibility boosts the fleet's ability to become more reactive to whatever environments our nation calls for. This fleet architecture replaces the CVN battle group centric concept with a "small lineup" utilizing the DDG 1000 as the high value unit while focusing in on speed, tactics, and firepower to gain tactical advantage over adversaries mainly in the green and brown water areas, yet still being able to fight in blue water. The DDG 1000 is adopted as a High-Value Unit alongside the CVN and will be redesigned as a Battleship. The Battleship is at the center of a battleship battle group (BBG) and augments the CVN and their associated CSG. More information on the BBG concept can be found in Appendix F. By more units doing less, the fleet can accomplish more missions in smaller areas on a larger scale.

b. Requirements Derivation: Since the cost of building the traditional style naval fleet, CVNs specifically, is too expensive for congressional budgeting, the U.S. Navy is being forced to adapt and convert to a more cost effective fleet. Today the navy has one commissioned DDG1000. It is capable of absorbing the communications and command and decision C&D aspects brought to the fight traditionally by CVNs. Its AEGIS suite is the newest and most capable system in the fleet and it has the space to house a fleet-level staff making it the ideal new high value unit at a significantly lower cost than the CVN. The DDG-1000 is also much more capable of defending itself than the CVN and will require a smaller compliment of guard ships. With advanced technology in Anti-Submarine Warfare (ASW), AAW, BMD, and SUW (rail gun), the Zumwalt provides capabilities for tomorrow's fleet demands at cost.

c. Fleet Quantification Assumptions: budget for the U.S. fleet will only continue to decrease as political pressure forces cutbacks on Department of Defense (DOD) budget.

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IV. MEASURES OF EFFECTIVENESS

The measures of effectiveness (MOEs) for this study are used to measure the degree to which the resultant fleet architecture meets the essential functions of the Navy as described in Section III of *A Cooperative Strategy for 21st Century Seapower*. The essential functions of the Navy are: All Domain Access, Deterrence, Sea Control, Power Projection, and Maritime Security.

This study derives a MOE for each essential function, except Maritime Security. As stated in *A Cooperative Strategy for 21st Century Seapower*, "Maritime security protects U.S. sovereignty and maritime resources, supports free and open seaborne commerce, and counters weapons proliferation, terrorism, transnational crime, piracy, illegal exploitation of the maritime environment, and unlawful seaborne immigration." Through sanctions, U.S. Navy maritime interdiction operations, and U.S. Coast Guard operations, Maritime Security is assumed to be fulfilled with any of this study's fleet sets. The final MOE establishes "Fleet Flexibility," defined in this study as the average number of warfare areas (out of the eight previously listed) attained by the numbered fleets that possess platforms. In other words, Fleet Flexibility is a check to ensure that the numbered fleets can perform in the eight warfare areas required by the Navy.

This study adopts a total of five fleet level MOEs to measure the degree to which the fleet architecture accomplishes the essential functions and warfare areas of the Navy:

- MOE 1 – Domain Grid Factor (All Domain Access)
- MOE 2 – Cumulative Deterrence Coverage (Deterrence)
- MOE 3 – Weapon Density (Sea Control)
- MOE 4 – Cumulative Power Projection (Power Projection)
- MOE 5 – Fleet Flexibility

Each MOE and the associated variables and criteria is explained in the subsequent sections.

The main constraint in this study is the SCN budget for fiscal year (FY) 2035. The SCN budget constraint is $164,000,000,000 ($164B, FY2035$). Therefore, the *new ship construction* for the fleet architecture between 2017 and 2035 *must not exceed* $164B, FY2035$.

A. MOE 1 – DOMAIN GRID FACTOR

All Domain Access is defined in A *Cooperative Strategy for 21st Century Seapower* as the "ability to project military force in contested areas with sufficient freedom of action to operate effectively." "The ability to project military force in contested areas" involves presence in contested areas with weapons coverage and the appropriate sensors to establish fire control if necessary. The coverage applies to the air, surface, and subsurface physical domains. "Sufficient freedom of action" is assumed to be available through the establishment of rules of engagement and adherence to tactics, techniques, and procedures defined by doctrine and established procedures at the tactical unit level (e.g. Commanding Officer's Standing Orders). To achieve All Domain Access, weapons must cover all physical domains, but must have sensor coverage that encompasses at least the same magnitude of area as the weapons coverage. Therefore, a "Domain Grid Factor" is defined below as the MOE to measure All Domain Access:

$$\textbf{MOE 1: Domain Grid Factor, } \boldsymbol{\eta} = \frac{S_A}{W_A} + \frac{S_S}{W_S} + \frac{S_U}{W_U}$$

where

S_A = Air Sensor Coverage Ratio = $\frac{Area\ Covered\ by\ Air\ Sensors\ by\ All\ Platforms\ (nm^2)}{Total\ Air\ Area\ Required\ to\ Be\ Covered\ (nm^2)}$

S_S = Surface Sensor Coverage Ratio = $\frac{Area\ Covered\ by\ Surface\ Sensors\ by\ All\ Platforms\ (nm^2)}{Total\ Surface\ Area\ Required\ to\ Be\ Covered\ (nm^2)}$

S_U = Subsurface Sensor Coverage Ratio = $\frac{Area\ Covered\ by\ Subsurface\ Sensors\ by\ All\ Platforms\ (nm^2)}{Total\ Subsurface\ Area\ Required\ to\ Be\ Covered\ (nm^2)}$

W_A = Air Weapon Coverage Ratio = $\frac{Area\ Covered\ by\ Air\ Weapons\ by\ All\ Platforms\ (nm^2)}{Total\ Air\ Area\ Required\ to\ Be\ Covered\ (nm^2)}$

W_S = Surface Weapon Coverage Ratio = $\frac{Area\ Covered\ by\ Surface\ Weapons\ by\ All\ Platforms\ (nm^2)}{Total\ Surface\ Area\ Required\ to\ Be\ Covered\ (nm^2)}$

W_U = Subsurface Weapon Coverage Ratio = $\frac{Area\ Covered\ by\ Subsurface\ Weapons\ by\ All\ Platforms\ (nm^2)}{Total\ Subsurface\ Area\ Required\ to\ Be\ Covered\ (nm^2)}$

For each term of MOE 1, limits are imposed, subject to the input of stakeholders. For example:

- All ratios, S_A, S_S, S_U, W_A, W_S, and W_U, may be at least 0.8.

- All ratios, $\frac{S_A}{W_A}$, $\frac{S_S}{W_S}$, $\frac{S_U}{W_U}$, may be at least 0.8.

Any deviation from these limits would require additional analysis.

Each factor given above is a ratio of the amount of area covered by the global allocation of platforms to the amount of area required to be covered in the appropriate domain. Therefore, each ratio is unit-less and represents a relative degree to which the coverage is accomplished comparing the coverages in 2035 to those in 2017. This report does not advocate for a larger or smaller domain grid factor for overall fleet design, as this MOE only provides a reference point from which to compare the future fleets against one another.

Figure 3 provides a visual representation of the grid factor. A larger grid factor equates to more sensor coverage compared to weapon coverage.

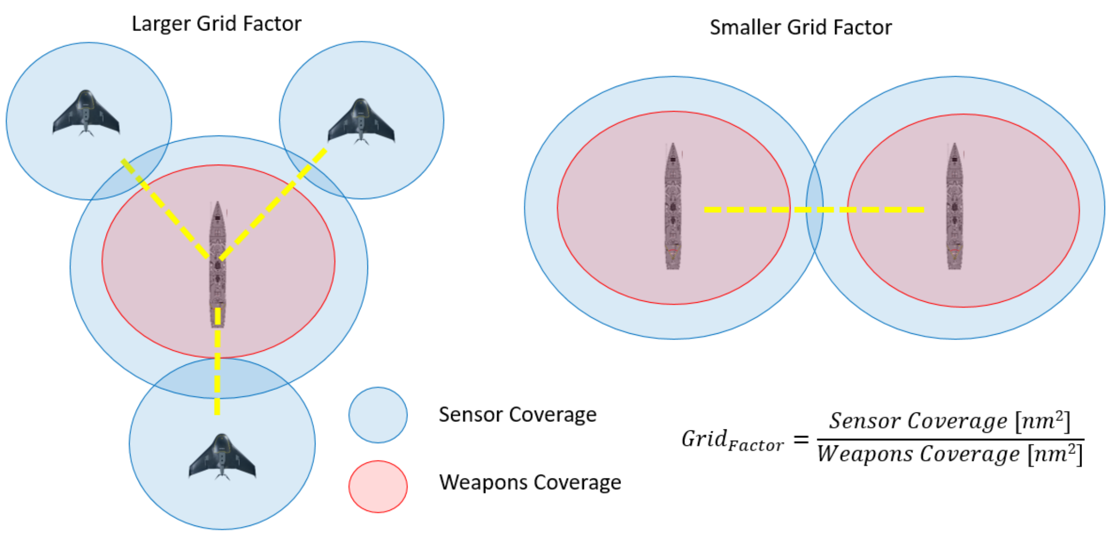

Figure 3. Visual Representation of Domain Grid Factor

B. MOE 2 – CUMULATIVE DETERRENCE COVERAGE

According to *A Cooperative Strategy for 21st Century Seapower*, "We achieve deterrence by convincing potential enemies that they cannot win or that the cost of aggression would be unacceptable (Department of the Navy 2015). This function supports the naval missions of defending the homeland, deterring conflict, and strengthening partnerships.” A collective psychological effect cannot be quantified, due to the varying global threats and constantly changing environment that the Navy must adapt to. However, having assets deployed and underway will contribute to a psychological effect similar to the way assets are employed in today’s fleet. Particularly, BMD and STW-capable assets coupled with ships and nuclear submarines positioned to act at all times can convince potential enemies that “the cost of aggression would be unacceptable.” Therefore, a “Cumulative Deterrence Coverage” is defined as the MOE to measure Deterrence:

MOE 2: Cumulative Deterrence Coverage, $\boldsymbol{\Sigma = \varepsilon_{BMD} * \varepsilon_{STW} * \varepsilon_{SHIPS} * \varepsilon_{SUBS}}$

where

ε_{BMD} = Ratio of Operational Area BMD Weapon Coverage =

$$\frac{Area\ Covered\ by\ BMD\ Weapons\ by\ All\ BMD{-}Capable\ Platforms\ (nm^2)}{Total\ Operational\ Area\ Required\ to\ Be\ Covered\ (nm^2)}$$

ε_{STW} = Ratio of Strike-Capable Platforms Deployed and Underway =

$$\frac{Total\ Number\ of\ Strike\ Capable\ Platforms\ Underway\ in\ the\ 2035\ Fleet}{0.25 * \frac{2}{3} * Total\ Number\ of\ Strike\ Capable\ Platforms\ in\ the\ 2017\ Fleet}$$

ε_{SHIPS} = Ratio of Ship Platforms Deployed and Underway =

$$\frac{Total\ Number\ of\ Ship\ Platforms\ Underway\ in\ the\ 2035\ Fleet}{0.25 * \frac{2}{3} * Total\ Number\ of\ Ship\ Platforms\ in\ the\ 2017\ Fleet}$$

ε_{SUBS} = Approximate Ratio of Submarines Deployed and Underway =

$$\frac{Total\ Number\ of\ Submarines\ Underway\ in\ the\ 2035\ Fleet}{0.25 * \frac{2}{3} * Total\ Number\ of\ Submarine\ Platforms\ in\ the\ 2017\ Fleet}$$

Note: all numbers are completely notional and do not reflect the actual deployed force levels.

All ratios (ε_{BMD}, ε_{STW}, ε_{SHIPS}, and ε_{SUBS}) are multiplied to calculate Cumulative Deterrence Coverage, Σ. This study assumes that approximately 25% of all platforms in the fleet will be deployed at any given time. Furthermore, of those platforms deployed, approximately 66% (⅔) are assumed to be kept underway at any given time. Therefore, the denominators in the ratios are a standard (proportion of the 2017 fleet platforms) with which the numerators (2035 fleet platforms that can be underway) are compared. All ratio denominators will be less than 1.0 since not every platform in the 2017 fleet is deployed and underway. However, A Cumulative Deterrence Coverage less than 1.0 represents a lesser achievement of Deterrence in 2035 than that in 2017, whereas a Cumulative Deterrence Coverage greater than 1.0 represents a relatively greater achievement of Deterrence in 2035 than that in 2017.

To assure the effectiveness of any proposed fleet, the measured ratios need to exist within reasonable bounds. Therefore, each ratio factor will have associated criteria that must met. For each term of MOE 2, limits are imposed, subject to the input of stakeholders. For example:

- Ratio of operational area BMD weapon coverage, ε_{BMD}, must be at least 0.9.
- Ratio of strike-capable platforms deployed and underway, ε_{STW}, must be at least 0.8.
- Ratio of ship platforms deployed and underway, ε_{SHIPS} , must be at least 0.8.
- Ratio of submarines deployed and underway, ε_{SUBS}, must be at least 0.8.

By establishing these criteria, the fleet can be ensured to achieve individual ratios of 0.8; additionally, at least 90% of the global operational areas will be covered by Navy BMD assets immediately able to respond and in 2035, the Navy can have at least 80% of the quantity of platforms that were underway at any given time in 2017.

C. MOE 3 – WEAPON DENSITY

As explained in *A Cooperative Strategy for 21st Century Seapower*, "Sea control allows naval forces to establish local maritime superiority while denying an adversary that same ability. Forward naval forces employ a full spectrum of layered capabilities for the destruction of enemy naval forces, suppression of enemy sea commerce, and protection of vital sea lanes, including ports of embarkation and debarkation, which enables strategic sealift and facilitates the arrival of follow-on forces (Department of the Navy 2015)." Therefore, the Navy must keep sea lanes available for use and must provide protection over those sea lanes in order to establish sea control. Assuming continued diplomacy retains the sea lanes available to the Navy today, the ability to protect those sea lanes must be quantified. The amount of SUW-specific munitions available for deployment per square nautical mile can measure the ability of the fleet to deny an adversary local maritime superiority, given sea lanes are available. Therefore, a "Weapon Density" is defined as the MOE to measure Sea Control:

MOE 3: Weapon Density, $\boldsymbol{D_W = \frac{N_{SUW}}{A}}$

where

$N_{SUW} = MOP_{SUW}$

A = Total required sea lanes to be covered by the fleet (nm^2)

MOP_{SUW}= Maximum possible number of surface targets that can be engaged in 24 hours

Note: Critical areas of operation are measured in Appendix N.

Similar to MOE 2, criteria must be established for Weapon Density in order to provide adequate capability for the Fleet to achieve Sea Control. Additionally, weapon coverage must also be considered alongside weapon density and the area of sea lanes differs between each area of responsibility for the Combatant Commands (COCOMs). Therefore, a "Ratio of Weapon Coverage" criterion is defined in order to supplement MOE 3. A limit can be imposed, subject to the input of stakeholders. For example:

- Ratio of Weapon Coverage, $w = \frac{W_i}{A_i}$ must be at least 0.9 per geographic region.

where

i = Geographic Region

W_i = SUW Weapon Coverage of All Platforms in Geographic Region i (nm^2) (Value defined by user; original report results based on quantity of weapons present on available ships as defined in appendix A.)

A_i = Total Required Sea Lanes to be Covered in Geographic Region i (nm^2)

The MOE 3 Criterion ensures that consideration is given to the areas of responsibility for each Combatant Command in support of the global Weapon Density. Different platforms will offer different quantities of SUW munitions as shown in Figure 4. Therefore, the platform composition of the fleet architecture will determine MOE 3.

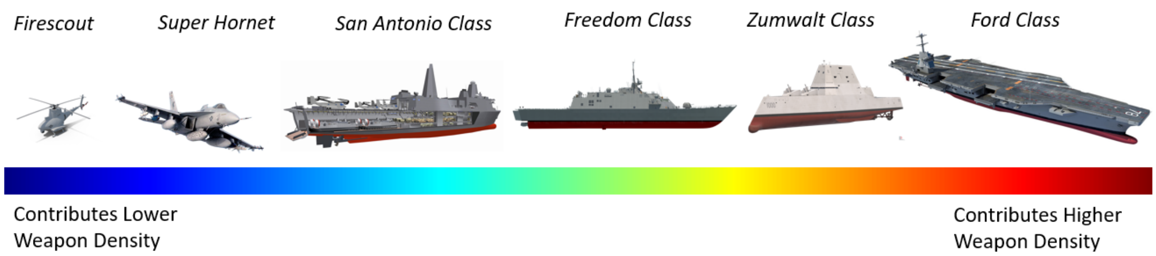

Figure 4. Weapon Density Contribution

D. MOE 4 – CUMULATIVE POWER PROJECTION

Power Projection is defined in *A Cooperative Strategy for 21st Century Seapower* as "the ability of a nation to apply all or some of its elements of national power—diplomatic, informational, military, or economic—to respond to crises, contribute to deterrence, and enhance regional stability. Naval power projection includes conventional strikes against targets ashore, integrated kinetic strikes and non-kinetic fires against enemy forces, advance force operations, raids, and all forms of amphibious operations, from ship-to-objective maneuver and sea-based fire support to forces ashore to missions conducted by Naval Special Warfare and Special Operations Forces (Department of the Navy 2015)." The scope of the Fleet Architecture encompasses the military element of national power. Power Projection can be measured in a similar manner to Deterrence, in that having particular assets deployed and underway will allow the Navy to project power in a moment's notice. Assets that contribute most to Power Projection include strike-capable assets, amphibious warfare ships (supplemented with Marine personnel and equipment), and nuclear submarines. Therefore, a "Cumulative Power Projection" is defined to as MOE 4 to measure the ability of the Fleet Architecture to achieve Power Projection:

MOE 4: Cumulative Power Projection, $\boldsymbol{\rho = \varepsilon_{STW} * \varepsilon_{AMW} * \varepsilon_{SUBS}}$

where

ε_{STW} = Ratio of Strike-Capable Assets Deployed AND Underway =

$$\frac{Total\ Number\ of\ Strike\ Capable\ Platforms\ Underway\ at\ Any\ Given\ Time\ in\ the\ 2035\ Fleet}{0.25 * \frac{2}{3} * Total\ Number\ of\ Strike\ Capable\ Platforms\ in\ the\ 2017\ Fleet}$$

ε_{AMW} = Ratio of Amphibious Ships Deployed AND Underway =

$$\frac{Total\ Number\ of\ Amphibious\ Ship\ Platforms\ Underway\ at\ Any\ Given\ Time\ in\ the\ 2035\ Fleet}{0.25 * \frac{2}{3} * Total\ Number\ of\ Amphibious\ Ship\ Platforms\ in\ the\ 2017\ Fleet}$$

ε_{SUBS} = Ratio of Submarines Deployed AND Underway =

$$\frac{Total\ Number\ of\ Submarines\ Underway\ at\ Any\ Given\ Time\ in\ the\ 2035\ Fleet}{0.25 * \frac{2}{3} * Total\ Number\ of\ Submarine\ Platforms\ in\ the\ 2017\ Fleet}$$

These ratios are calculated in a similar fashion to MOE 2. As previously mentioned, this study assumes that approximately 25% of all platforms in the fleet will be deployed at any given time. Furthermore, of those platforms deployed, approximately 66% will be underway at any given time. All ratio denominators will be less than 1.0 since not every platform in the 2017 fleet is deployed and underway. However, A Cumulative Power Projection less than 1.0 represents a lesser achievement of Power Projection in 2035 than that in 2017 whereas a Cumulative Power Projection greater than 1.0 represents a relatively greater achievement of Power Projection in 2035 than that in 2017.

However, the ratios need to be within acceptable bounds. Therefore, each ratio factor will have associated criteria that can be met. For each term of MOE 4, limits are imposed, subject to the input of stakeholders. For example:

- Ratio of Strike-Capable Platforms Deployed and Underway, ε_{STW}, must be at least 0.8.
- Ratio of Amphibious Ship Platforms Deployed and Underway, ε_{AMW}, must be at least 0.8.
- Ratio of Submarines Deployed and Underway, ε_{SUBS}, must be at least 0.8.

By establishing these criteria, the fleet can be ensured to achieve individual ratios of 0.8. In 2035, the Navy can have at least 80% of the quantity of platforms that were underway at any given time in 2017.

E. MOE 5 – FLEET FLEXIBILITY

Fleet Flexibility is a MOE derived for this study to ensure that every numbered fleet that possesses platforms (Fleet Forces, 3rd Fleet, 4th Fleet, 5th Fleet, 6th Fleet, and 7th Fleet) is capable of performing each of the eight warfare areas defined previously. A flexible fleet architecture would mean that every numbered fleet that possesses platforms can perform Strike Warfare, Anti-Air Warfare, Surface Warfare, Anti-Submarine Warfare, Electronic Warfare, Mine Warfare, Amphibious Warfare, and Ballistic Missile Defense if called upon. Therefore, a "Fleet Flexibility" MOE is defined as the degree to which the resultant fleet architecture is flexible among warfare areas:

$$\textbf{MOE 5: Fleet Flexibility, } \boldsymbol{\tau = \frac{\sum F_j}{6}}$$

where

F_j = Flexibility score of Numbered Fleet j

Mathematically, Fleet Flexibility, τ, is an average. If all six numbered fleets with platforms possessed platforms that allowed them to participate in all eight warfare areas, then Fleet Flexibility = 8, meaning all numbered fleets can perform any warfare area at any given time.

Ideally, the quantitative equations used to calculate MOE's and other evaluated metrics favor a flexible fleet. Individual platform warfare area contributions are calculated from a platform which is heavily focused on the warfare area in question. The platform could not maintain its attributed level of combat effectiveness across all warfare areas at all times. For example, a DDG which is focused on ASW will be much more effective at conducting ASW than it would be if it were conducting simultaneous ASW, BMD, SUW, and STW missions. However, a DDG contributes to all of its possible warfare areas as if it were concentrating on each warfare area simultaneously. Using this method produces a flexible fleet because platforms which are able to perform a wide variety of missions contribute more to the MOPs and MOEs in question than single mission ships. Because this ‘fixed points’ method was used to model the fleet optimization, a specific and unique flexibility metric was not used in this study.

F. MEASURES OF PERFORMANCE

The MOEs described in the previous section measure the ability of the final fleet architecture to meet the essential functions of the Navy and achieve flexibility between warfare areas. However, in order to implement SBD in the design process of creating a fleet architecture, this study uses a unique Measure of Performance (MOP) for each warfare area. Given the large scope of factors and varying degrees of time which can be quantified to measure the performance of the fleet in each warfare area, the MOPs are given a scope of 24-hour periods. For example, the MOP for Strike Warfare is the maximum number of potential targets destroyed throughout a 24-hour operational period. The MOPs for each warfare area are defined below:

Strike Warfare

MOP_{STW} = Maximum Number of Targets that could be Destroyed per 24-Hour Period (in units of $\frac{Integer}{24\,hrs}$)

Anti-Air Warfare

MOP_{AAW} = Maximum Number of Targets that could be Destroyed per 24-Hour Period (in units of $\frac{Integer}{24\,hrs}$)

Surface Warfare

MOP_{SUW} = Maximum Number of Targets that could be Destroyed per 24-Hour Period (in units of $\frac{Integer}{24\,hrs}$)

Anti-Submarine Warfare

MOP_{ASW} = Maximum Number of Targets that could be Destroyed per 24-Hour Period (in units of $\frac{Integer}{24\ hrs}$)

Electronic Warfare (EW)

MOP_{EW} = Number of Electronic-Attack Capable Assets

Mine Warfare (MIW)

MOP_{MIW} = Maximum Number of Mines that could be Cleared per 24-Hour Period (in units of $\frac{Integer}{24\ hrs}$)

Amphibious Warfare

MOP_{AMW} = Number of marine expeditionary units (MEU's) Capable of Being Carried

The MOPs are used to measure each individual platform's contribution to total fleet capability. The final fleet architecture will be built upon these assumptions as described in Section V.

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V. OPTIMIZING A FLEET

A. INTRODUCTION

For any optimization effort, the naval fleet architecture's value must be quantifiable. The chosen quantification methodology breaks down each platform's warfighting capabilities (CAPs) into the eight warfare areas (Strike Warfare, Anti-Submarine Warfare, Air Warfare etc.) which are the platform's MOPs. The quantified MOPs for all ships are then combined cumulatively to compute fleet MOPs or "Fleet warfighting capabilities." The possibilities of using synergistic effects and/or diminishing returns were explored but a simple additive method is used as it most accurately reflects the effective employment of distributed tactics to fight the fleet.

For a simple visual example of the basic fleet quantification method refer to Table 3 which shows NOTIONAL MOPs attributable to each CVN and each Guided Missile Cruiser (CG). A full accounting of all MOPs used for every platform is presented in Appendix A. If we assemble a "fleet" consisting only of one CVN and two CGs, this fleet would have a Strike MOP of 101 (40 from the CVN plus 30.5 from each CG) and an Electronic Warfare MOP of 14 (10 from the CVN and 2 from each CG). In this way, the main objective function seeks to maximize the fleet's warfighting capabilities by selecting the number of each class of ship to build which provides the Navy with the greatest capabilities in the eight warfare areas.

Table 3. NOTIONAL MOPs Example

	Strike	AAW	SUW	ASW	EW	MIW	AMW	BMD
CVN	40	40	40	7	10	0	0	0
CG	30.5	30.5	46	34	2	0	0	30.5

Maximizing all eight MOPs simultaneously is accomplished in the main objective function discussed in section V.B. The goal of the objective function, stated briefly is 'pick the right mix of platforms to maximize each warfare area, without excessively disadvantaging any particular warfare area.' In this tiny example, the CVN dominates in STW and EW, while the CG dominates in BMD. This fleet is not balanced, however, as it has no MIW or AMW capabilities. More platforms have to be added to achieve those capabilities.

Notes on the Spreadsheet Model:

While reducing the performance of a particular warfare area down to a single number, several assumptions are made, and a few 'points of concern' are addressed to make sure that the results provide a value to the assessments.

The first point is the balancing of the MOPs. Each MOP is based on a very different scale. For example; the Strike MOP is based on number of targets that could be engaged and the Amphibious Warfare MOP is based on number of Marine Expeditionary Units capable of being embarked. These MOPs must somehow be normalized before simultaneously optimizing them or the costlier MOP "points" will be heavily neglected. In other words; it is cheaper to add one 'strike point' with one missile than to add an 'amphibious warfare point' with entire additional MEU. The method chosen for the normalization of MOPs is to compare each MOP subject to optimizing to the Baseline 2017 Fleet MOP. A ratio of 'baseline 2017 points' over 'proposed future 2035 points' is used. By this method the baseline fleet, by definition, is given a score of 1.0 for all MOPs and the future fleet MOP values can be intuitively understood as a percentage increase or decrease from today's fleet's capability. For example, a Strike Warfare score of 1.4 would equate to a fleet which has 140% of the Strike warfare capability of today's fleet or a 40% increase in capability over today's fleet. Similarly, a 0.9 would indicate only 90% of the capability of today's fleet, or a 10% decrease. Normalizing the MOPs in this way surmounts the challenge presented by differently scaled MOPs.

Another complication to effectively optimize all eight MOPs simultaneously is for all warfare areas to be considered equally important. By introducing a weighting factor, which can be applied to the normalized MOP score, we can manipulate the importance that the optimization main objective function places on each warfare area. In order for the objective function to properly function, each warfare area must contain weighted values provided by stakeholders and subject matter experts. Changing these weightings has no effect on the optimization function until all of the constraints are satisfied. After the constraints are all satisfied, the selected warfare area weights will affect the preferential spending of the remaining budget money to maximize the fleet's warfighting capabilities.

The objective of the optimization model is to maximize the cumulative weighted warfare capabilities compared to the baseline 2017 Fleet. This only occurs after all constraints are satisfied. These constraints can change drastically depending on the user inputs which are described below.

B. CONSTRAINTS

The objective function is constrained by the following circumstances:

- **<u>Minimum Ship Constraint:</u>** This report does not generate a future unconstrained dream fleet as if starting from a clean slate. This study's purpose is to produce meaningful insight into the way to move forward toward a better and more effective fleet in 2035, starting from what we have now. To meet this end we assume no ships will be decommissioned prior to the end of their expected service life. To this effect, we identify the number of each class of ship which are planned to still be within their operational life in 2035. This is the number that the fleet will contain if no new ships are constructed between now and 2035 and ships will be retired at the end of their design life. This number will serve as the constraint on the minimum number of each ship type and is referred to as "Lower P." A full fleet accounting is included in Appendix O.
- **<u>Maximum Ship Constraint:</u>** There are impositions on the number of ships which can realistically be constructed in the given time frame. The Lower-P for each ship class plus the maximum number of that class of ship which can be constructed by 2035 gives us the maximum number of each class of ship that could feasibly be serving in 2035. This number is referred to as "Upper-P"

- **<u>Budget constraint:</u>** The modified SCN budget will not be exceeded by the objective function when the mathematical model is selecting platforms to maximize the fleet's capabilities. A further discussion of SCN budget constraints is included in Table 4 and Appendix L.

- **<u>Set-Based design derived requirement:</u>** The SBD implementation is based on the definition of "Set" established for this study. Each set has a requirement for each warfare area to meet a certain level of capability. This level of capability is expressed as a relation to the 2017 fleet's capabilities. For example; a set which predicts a BMD heavy future may not requires as much focus on the surface warfare domain. Such a set may necessitate a 15% increase in BMD capabilities when compared to the BMD capabilities of 2017's fleet. At the same time, an SUW capability which is only 80% of the 2017 fleet's capability may suffice. This is expressed as a BMD requirement of 1.15 and an SUW requirement of 0.8. These parameters are defined for every warfare area and every set which is being considered. The objective function solution picks the most stringent requirement (highest number) for each warfare area across all sets considered and sets this level as the minimum acceptable performance for that warfare area. This method seeks to build a fleet which meets minimum required capabilities in all warfare areas for all of the sets being considered.

- **<u>Set-Based design compromise factor:</u>** It is possible to input values into the spreadsheet in which an acceptable fleet cannot be designed within the given constraints. A simple "compromise factor" has been built into the objective function which can be used to scale the SBD derived requirements to a level where a solution can be computed. If there simply is not enough money to build enough ships to deal with every set being considered, replacing the default compromise factor of 1 with a number less than 1 like 0.9 reduces all of the SBD derived warfare area requirements by 10% (0.85 would indicate a 15% reduction etc.) in an attempt to establish a feasible problem to solve. This compromise factor can be replaced with any number to tailor the output and find the best possible answer to the many possible sets considered. This is effectively saying "With the given constraints, a 90% solution to all of the possible situations we may face in the future is the best we can do."

Optimization (Integer Linear Program)

Indices:

p = Platform
r = Warfare Area (BMD, STW, SUW, AAW, ASW, EW, MIW, AMW) (8 total)
$p \in S$ (SCN Platforms)
$p \in A$ (Non-SCN Platforms)

Decision Variables:

X_p = Number of Platforms p

Data:

$Cost_p$= Cost of platform p (units = FY$2015)
$Budget$= $164 billion
$CAP_{p,r}$= Capability (MOP contribution) of platform p *(warfare area index r, platforms contribution to each warfare area*)
min_r= Minimum capability (MOP contribution) of warfare area contribution, r
max_r=Maximum capability (MOP contribution) of warfare area contribution, r
$Lower_p$ = Minimum number of platforms in 2035 (number of platforms from 2017 still commissioned in 2035)
$Upper_p$= Maximum number of platforms in 2035 [$Lower_p$ plus the number of platforms that can be built between 2017 and 2035 (18 years)]
$DECK_p$= Maximum number of aircraft deck space available on platform, p

Objective Function (Main):

1. Maximize: $\sum_{p,r} CAP_{p,r} X_p$
   Subject To:
   Between minimum ship count and maximum construction rate
   $Lower_p \leq X_p \leq Upper_p$ for each p
   Capability greater than minimum defined
   $\sum_p CAP_{p,r} X_p \geq min_r \; for \; each \; r$

Capability less than maximum defined

$\sum_p CAP_{p,r} X_p \leq max_r \ for \ each \ r$

Flight Deck Constraint

$\sum_{p \in A} X_p \leq \sum_{p \in S} DECK_p X_p$

Budget Constraint

$\sum_p Cost_p X_p \leq Budget$

Integer Constraint

$X_p \geq 0 \ and \ Integer$

The main objective function expresses the fleet's MOPs in all warfare areas, *r*, simultaneously, in order to select a number for each platform, *p*, while keeping all parameters within the listed constraints. In other words, the main objective function selects the numbers and types of platform most optimal to accomplish the requirements defined by the sets for an alternative fleet architecture in the 2035 timeframe.

<u>Objective Function (Individual Warfare Areas):</u>

2. Maximize: $\sum_p CAP_{p,r} X_p \ \ for \ each \ r$

Subject To:

$\sum_p CAP_{p,r} X_p \leq max_r \ for \ each \ r$

$\sum_p CAP_{p,r} X_p \geq min_r \ for \ each \ r$

$Lower_p \leq X_p \leq Upper_p \ for \ each \ p$

$\sum_{p \in A} X_p \leq \sum_{p \in S} DECK_p X_p$

$\sum_p Cost_p X_p \leq Budget$

$X_p \geq 0 \ and \ Integer$

The individual warfare area objective function maximizes the fleet's MOP in only one warfare area, *r*. This optimization problem is solved eight times, one for each warfare area. The optimization serves to assist in defining the feasible regions for each warfare area by establishing the optimal data point that defines the most capability (MOP) for the warfare area. In other words, the individual warfare area objective function defines the upper right corner of the feasibility region in each warfare area (see next chapter).

VI. RESULTS

A. SET-BASED DESIGN RESULTS

As previously described, feasibility regions are established for each warfare area in order to bound the requirements (MOPs) for the fleet within the budget constraint, the optimal capability (max_r) and the minimum capability (min_r) for each warfare area. These feasibility regions are the requirements intervals that consummate SBD for this study. The resulting feasibility regions for each warfare area are provided below.

The entire feasibility region has a budget ceiling constraint of $164,346 (FY$M2035). This number is significantly reduced considering the original SCN of $257,000 (FY$M2035). Outfitting, Overhaul, Refueling, Support ships, and Port Facilities Ships, all contribute to the drastic reduction in budget.

Table 4. Total SCN Budget Accounting. Source: Assistant Secretary of the Navy Finance and Comptroller (2017)

Cost $M	
257,000	**Total SCN Budget**
37,000	CVN Refueling and Overhaul
4,550	Expeditionary Sea Base (ESB) costs
6,400	LHA(R) Upgrade Plan
2,000	Expeditionary Fast Transport (8)
13,650	TAO Refueling (21)
1,350	Towing, Salvage, Rescue (15)
4,400	Moored Training Ship (4)
2,030	Landing Craft (58)
11,700	‘Outfitting’ ($650M/yr) to 2035
7,140	Ship to Shore Connector (102)
990	Service Craft (90)
1,400	LCAC (landing craft air cushion) Service Life Extension Program
44	Yard Patrol Service Life Extension Program (12)
164,000	**Remaining Budget**

The budget is not actually reduced; however, the SEA-26 Capstone addresses only what we consider fighting ships. In order to observe what a future fleet would look like we had to reduce the budget to account for the "support ships and activities" or our future fleet's capabilities would be largely inflated and inaccurate.

1. Strike Warfare

The most-constraining set for STW is Set 3, providing a constraint of 5,387 targets engaged per 24-hour period. Sets 1, 2, and 4 are not included as bounds for the green feasibility region because Set 3 is the most limiting set. The calculated maximum capability is found to be 7,710 targets engaged per 24-hour period, thus yielding the green feasibility region depicted below.

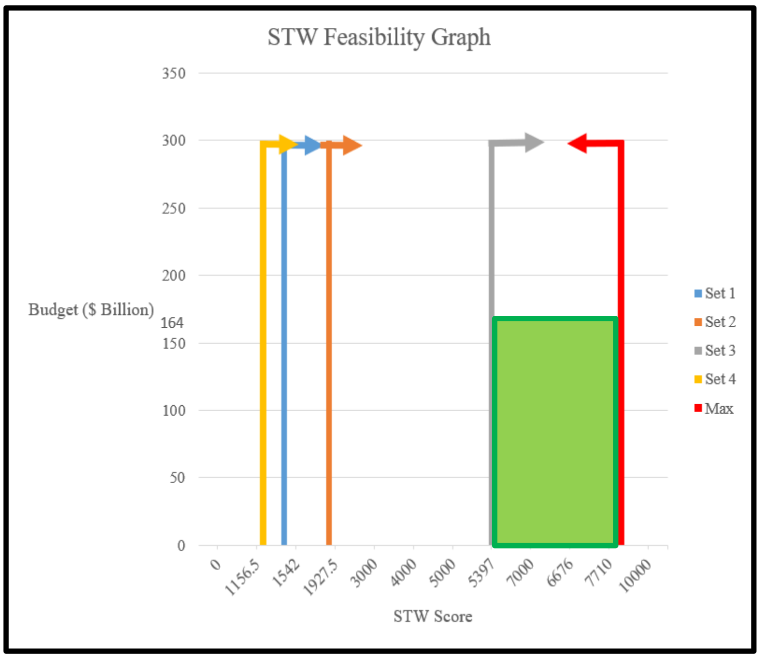

Figure 5. STW Feasibility Region

2. Anti-Air Warfare

The most-constraining set for AAW is Set 2, providing a constraint of 3,119 targets per 24-hour period. Sets 1, 3, and 4 are not included as bounds for the green feasibility region because Set 2 is the most limiting set. The calculated maximum capability is found to be 4,799 targets engaged per 24-hour period, thus yielding the green feasibility region depicted below.

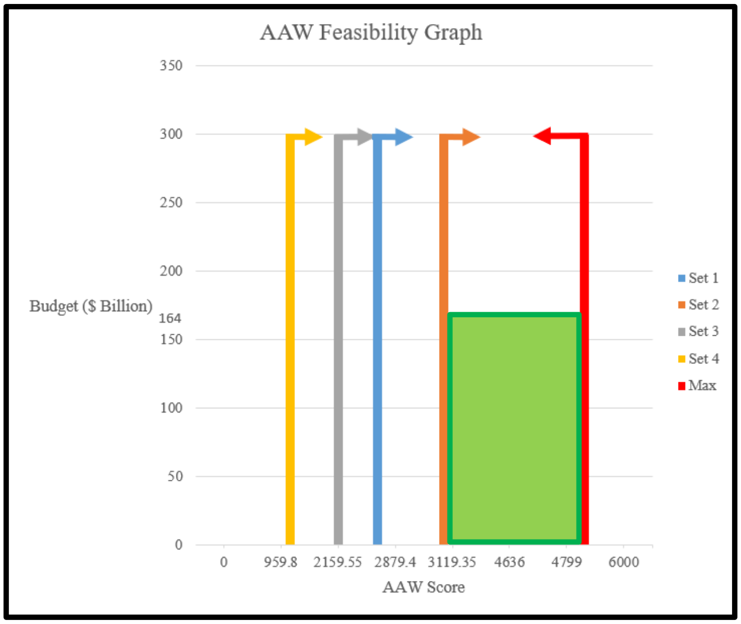

Figure 6. AAW Feasibility Region

3. Surface Warfare

The most-constraining set for SUW is Set 2, providing a constraint of 5,833 targets per 24-hour period. Sets 1, 3, and 4 are not included as bounds for the green feasibility region because Set 2 is the most limiting set. The calculated maximum capability is derived as 8,333 targets engaged per 24-hour period, thus yielding the feasibility region depicted below.

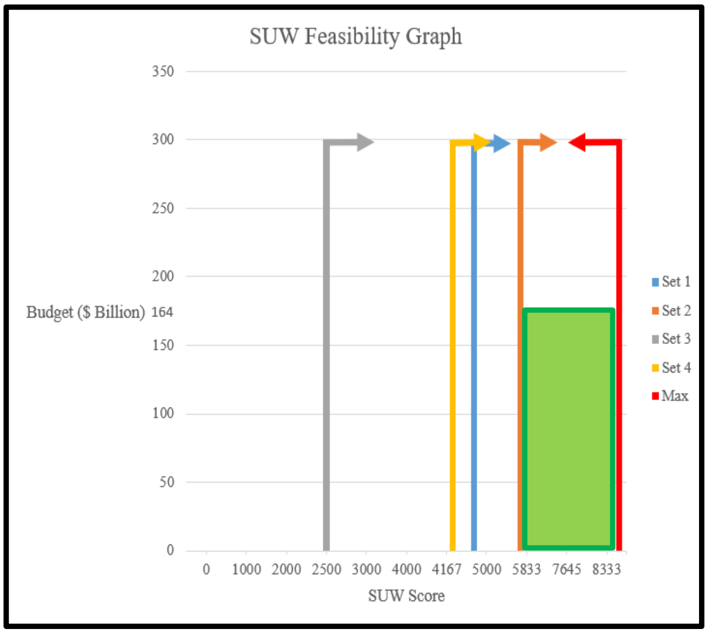

Figure 7. SUW Feasibility Region

4. Anti-Submarine Warfare

The most-constraining set for ASW is Set 2, providing a constraint of 2,888 targets per 24-hour period. Sets 1, 3, and 4 are not included as bounds for the green feasibility region because Set 2 is the most limiting set. The calculated maximum capability is derived as 4,813 targets engaged per 24-hour period, thus yielding the feasibility region depicted below.

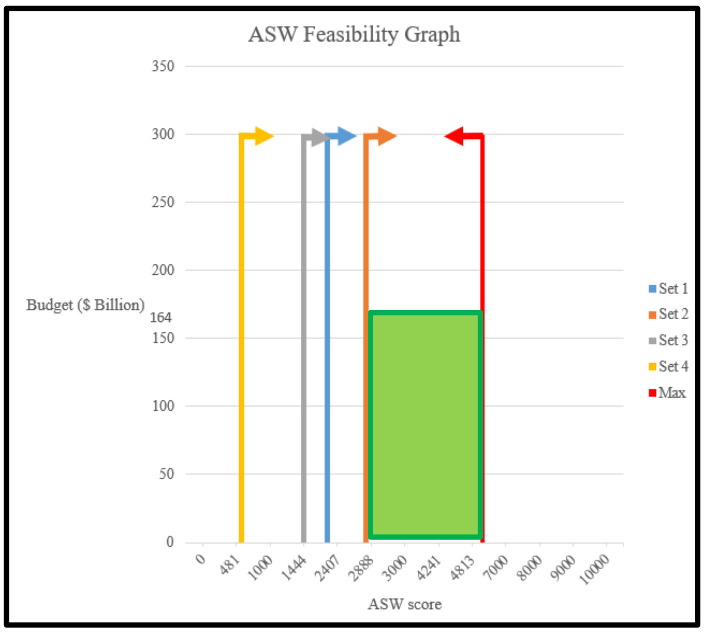

Figure 8. ASW Feasibility Region

5. Electronic Warfare

The most-constraining set for EW is Set 4, providing a constraint of 405 electronic-attack capable assets. Sets 1, 2, and 3 are not included as bounds for the green feasibility region because Set 4 is the most limiting set. The calculated maximum capability is derived as 476 electronic-attack capable assets, thus yielding the green feasibility region depicted below.

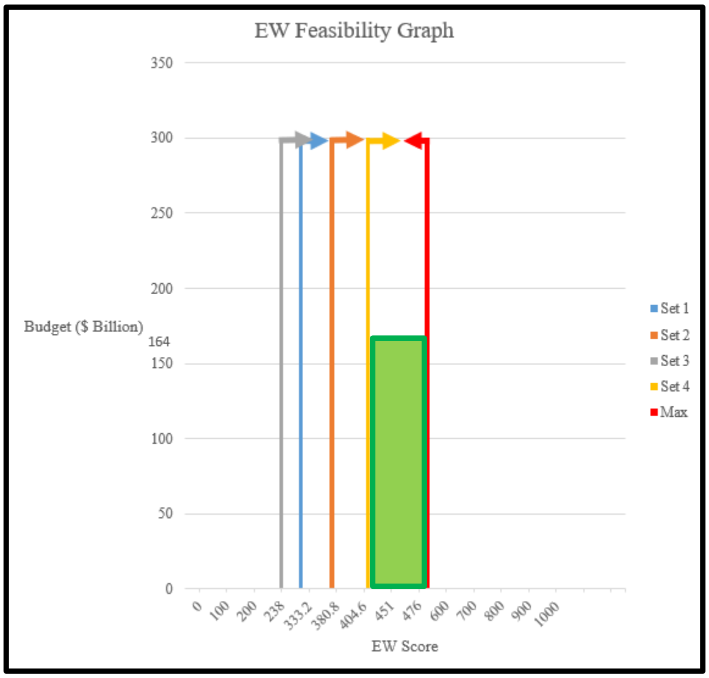

Figure 9. EW Feasibility Region

6. Anti-Mine Warfare

The most-constraining set for MIW is Set 4, providing a constraint of 230 mines cleared per 24-hour period. Sets 1, 2, and 3 are not included as bounds for the green feasibility region because Set 4 is the most limiting set. The calculated maximum capability is derived as 288 mines cleared per 24-hour period, thus yielding the green feasibility region depicted below.

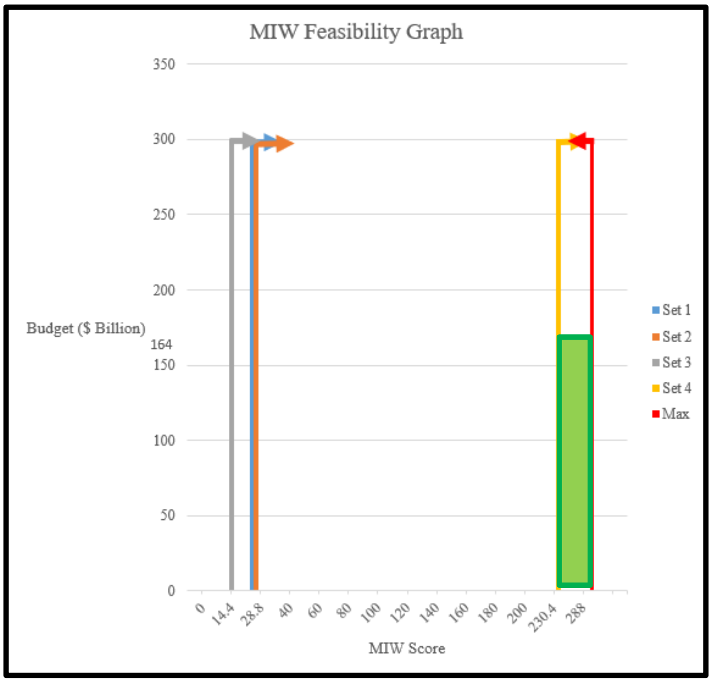

Figure 10. MIW Feasibility Region

7. Amphibious Warfare

The most-constraining set for AMW is Set 4, providing a constraint of 17 MEU's delivered. Sets 1, 2, and 3 are not included as bounds for the green feasibility region because Set 4 is the most limiting set. The calculated maximum capability was derived as 20 MEU's, thus yielding the green feasibility region depicted below.

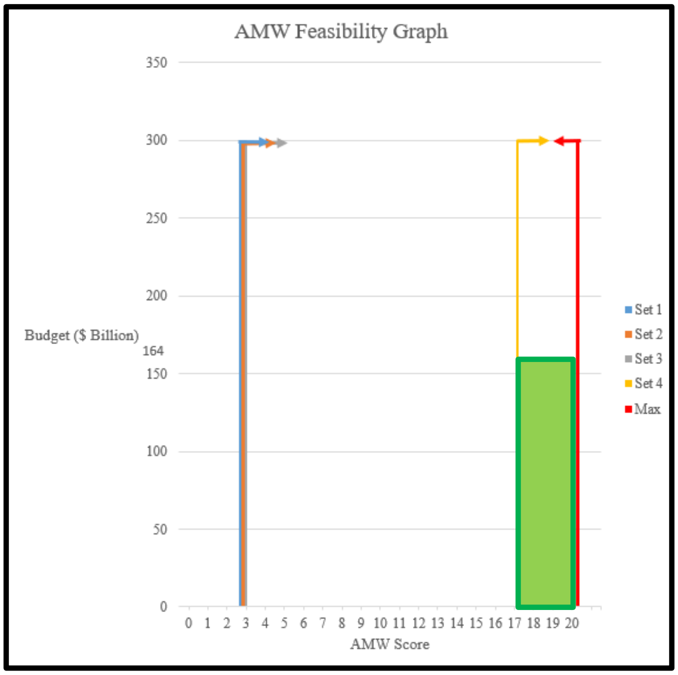

Figure 11. AMW Feasibility Region

8. BMD Warfare

The most-constraining set for BMD is Set 3, providing a constraint of 2,063 targets engaged per 24-hour period. Sets 1, 2, and 4 are not included as bounds for the green feasibility region because Set 3 is the most limiting set. The calculated maximum capability is derived as 3,438 targets engaged per 24-hour period, thus yielding the green feasibility region depicted below.

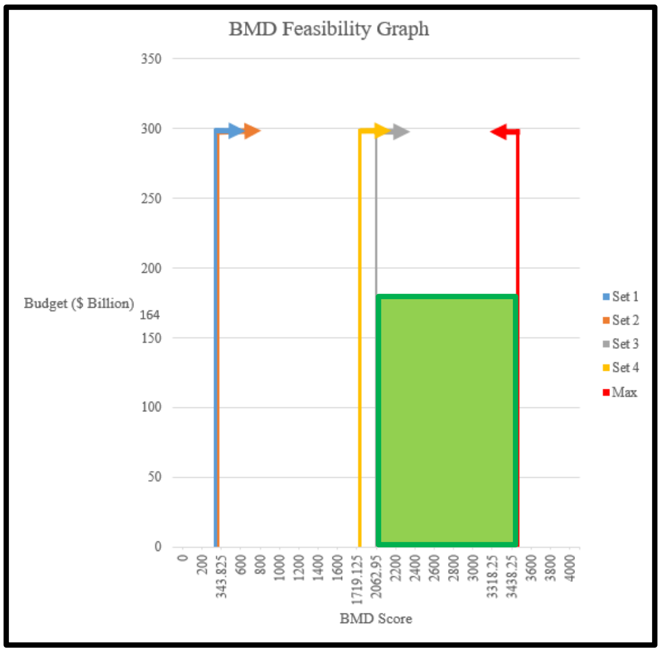

Figure 12. BMD Feasibility Region

9. The Future Fleet

Optimizing for all 8 warfare areas simultaneously yields the platform allocation depicted in Table 5. Military sealift-command (MSC) ships are included for total accountability, but were not part of the $164B fiscal constraint.

Table 5. 2035 Platform Allocation with UxVs

Ship Class	**Number in 2035**
CVN	9
CG	12
DDG	94
DDG-1000	4
LCS	45
Patrol	9
Mine Warfare	18
LHA	7
LHD	12
LPD	19
LSD	21
CVL (25-30 aircraft)	2
Ambassador Class Patrol Ship	19
MDUSV	0
SSN	16
SSBN	10
TERN (See Appendix J)	288

Ship Class	Number in 2035
Fire Scout	278
Triton	10
XLDUUV	10
MSC (Not accounted for with AMW)	88
GRAND TOTAL:	**297 fighting ships** **88 MSC** **576 UAVs** **10 UUVs**

Figure 13 depicts the capability distribution of the 2035 fleet against a normalized 2017 fleet.

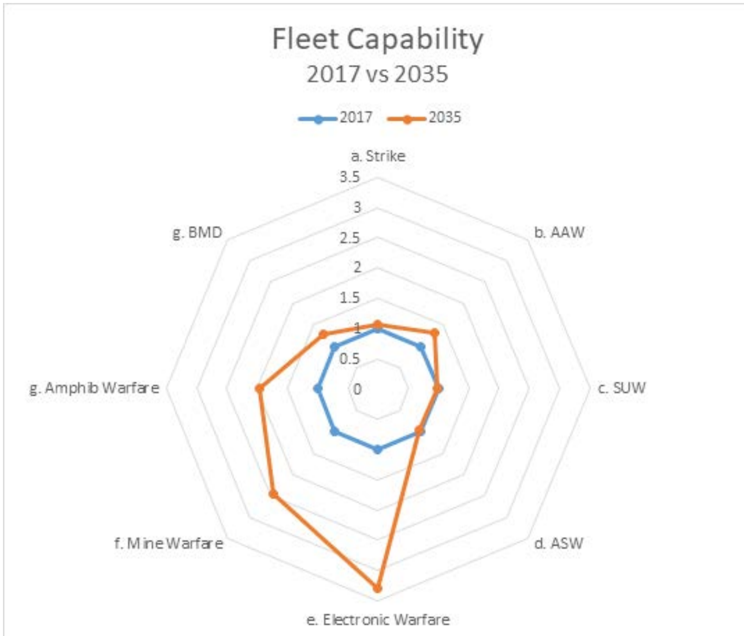

Figure 13. Fleet Capability Chart

The resulting 2035 fleet yields a fleet with marginal decreases in SUW and ASW, marginal increases in AAW, STW, and BMD, and marked improvements in AMW, EW, and MIW. Optimizing for all warfare areas resulted in the following MOPs.

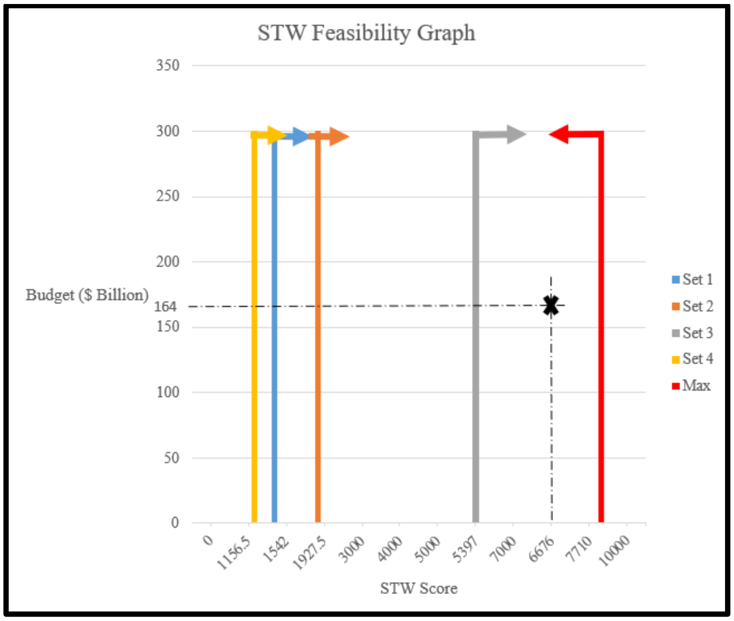

Figure 14. 6,676 STW Targets per 24 Hours

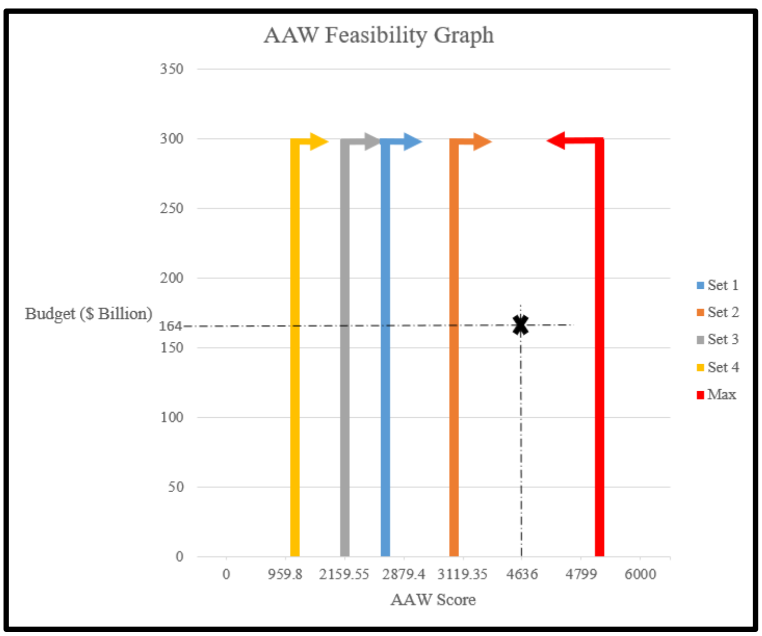

Figure 15. 4,636 AAW Targets per 24 Hours

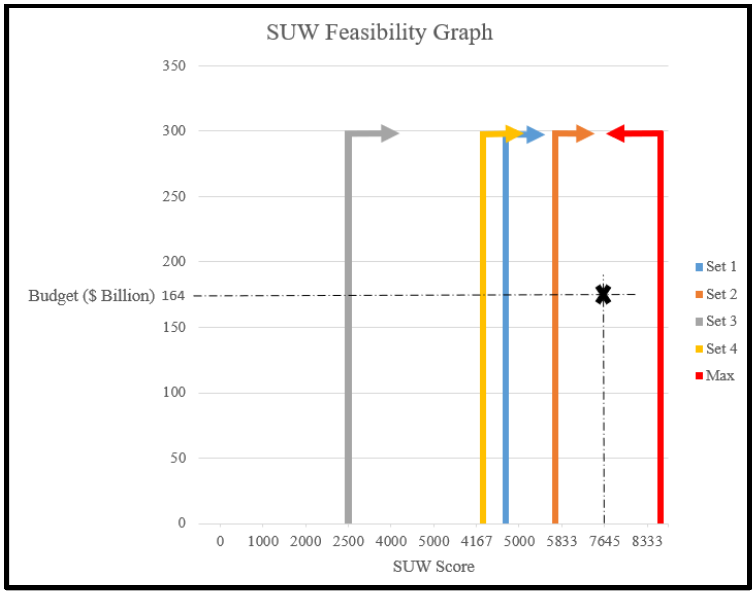

Figure 16. 7,645 SUW Targets per 24 Hours

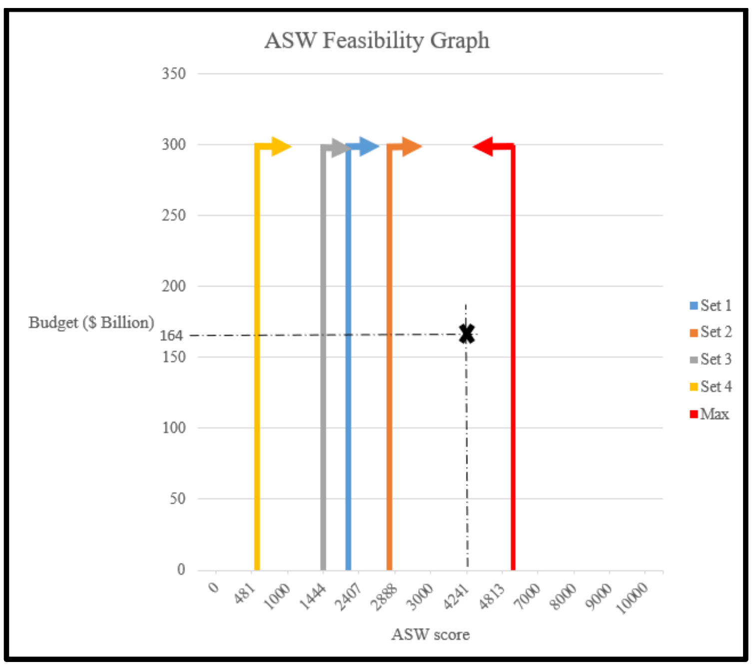

Figure 17. 4,241 ASW Targets per 24 Hours

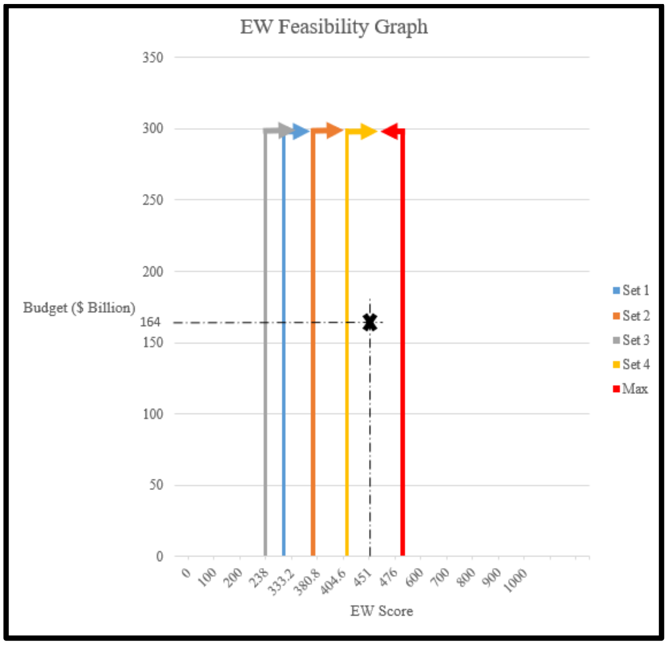

Figure 18. 451 Electronic-Attack Capable Assets

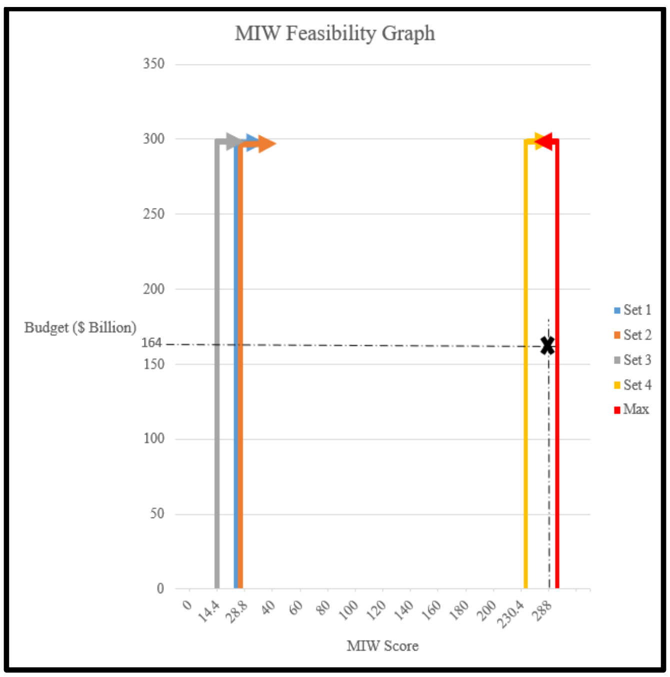

Figure 19. 288 Mines Cleared per 24 Hours

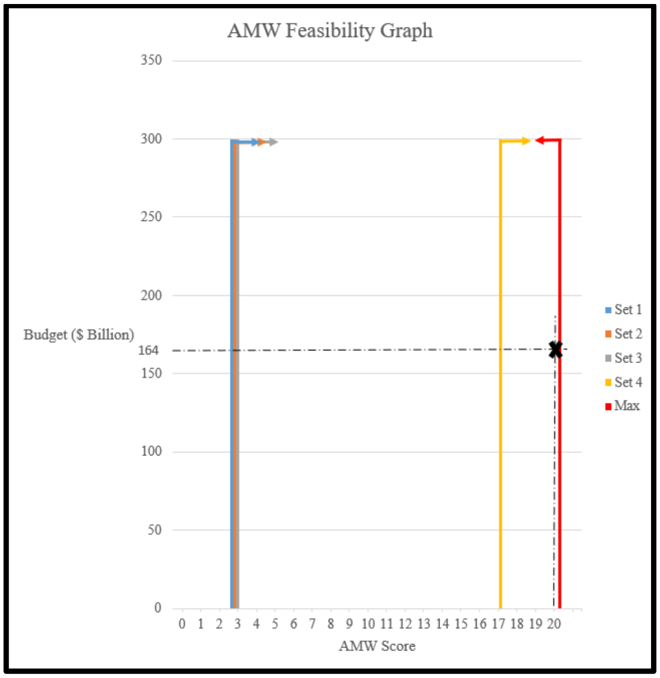

Figure 20. 20 MEUs Delivered

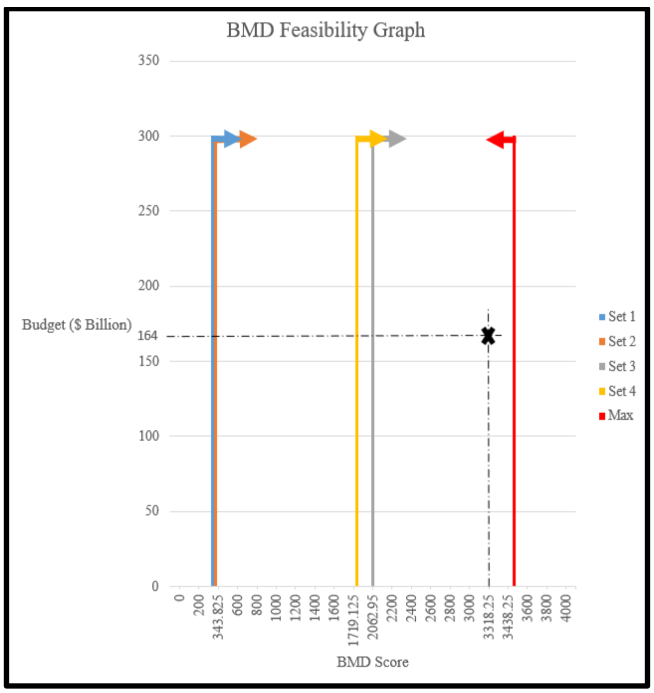

Figure 21. 3,318 Targets per 24 Hours

B. RESULTANT MEASURES OF EFFECTIVENESS

Our final analysis yielded the following MOEs:

1. MOE 1 – Domain Grid Factor (All Domain Access)

The final fleet's domain grid factor, η, scores a 3.84, with the air domain factor, $\frac{S_A}{W_A}$, scoring 1.00, the surface domain factor, $\frac{S_S}{W_S}$, scoring 0.97, and the subsurface domain factor, $\frac{S_U}{W_U}$, scoring 1.87. Individually, S_A = 1.00, S_S = 0.97, S_U = 0.11, W_A = 1.00, W_s = 1.00, and W_U = 0.06. Given the criteria listed, several factors do not meet 0.8 or greater. Specifically, S_U is lesser than 0.8. This is due to the fact that the total area of responsibility for subsurface sensor coverage does not equate to the required surface sensor coverage (which was used as the general quantity for measuring all domains); therefore, a subsurface sensor coverage ratio lesser than 0.8 is acceptable. Ocean bathymetry limits the amount of space that undersea platforms can occupy and sense compared to the surface domain. The subsurface weapon coverage ratio, W_U , is less than 0.8 due to similar reasons; the fleet architecture does not allow sufficient weapons coverage to cover a majority of the undersea domain. The criteria listed are not hard requirements, but may be modified based on stakeholder needs.

2. MOE 2 – Cumulative Deterrence Coverage (Deterrence)

The 2035 fleet scores a cumulative deterrence coverage of 6.23, making it a 6 times greater deterrent force than today's fleet.

3. MOE 3 – Weapon Density (Sea Control)

The 2035 fleet's weapon density scores 0.0077, making it equivalent to today's score of 0.0077.

4. MOE 4 – Cumulative Power Projection (Power Projection)

The 2035 fleet's power projection score of 1.35 signifies it has 35% more platforms underway than today's fleet.

5. MOE 5 – Fleet Flexibility

The fleet has a flexibility of 8, signifying every fleet commander is fully flexible across all 8 warfare areas.

VII. UNMANNED SYSTEMS

A. COST AND FLEET CAPABILITIES ANALYSIS GIVEN THE ADDITION OF UNMANNED SYSTEMS

Under manning and subsequently reduced capabilities in the U.S. military has been a problem that has plagued the U.S. services for many years. While in the past increased recruiting efforts and bumps in patriotism due to international conflicts have been enough to fill this manning and capabilities gap, today these efforts simply will not suffice. In the past 20 years proposals from government and department of defense have suggested filling the growing manning and capabilities gap with unmanned systems, namely ones that can be made cheap and replaceable.

Since the tasking statement for SEA-26 does not specifically require the use of Unmanned Systems in our fleet architecture we have taken the liberty of running our fleet architecture model with and without UxVs in order to compare the two results and conduct sensitivity analysis.

Our model without UxVs, as it always does, makes sure to stay within the given SCN budget when considering a fleet architecture for 2035. Figure 22 displays the results with all constraints previously explained in the methodology section. Of note is the Objective Cell that scored 1.246 which is a relative term that considers the assigned weight given to each warfare area and the current capabilities as of 2017. Individual warfare areas relative to today's navy's capabilities are displayed in the "Relative Score" row.

Arbitrary Weight (Must add to 100%)	27.0%	20.0%	15.0%	10.0%	10.0%	8.0%	6.0%	4.0%	100% (must
Relative Score	1.016	1.226	0.889	0.884	1.418	2.398	2	1.26868668	Relative Score
Weighted Score	0.274	0.245	0.133	0.088	0.142	0.192	0.12	0.05074747	Weighted Score
SBD Derived Minimum Relative Score	80%	80%	80%	80%	80%	80%	80%	80%	SBD Derived Mir
								0.80	SBD Compromise
						2035 FLEET SCORE		11.10	
						OBJECTIVE CELL		1.246	
	a. Strike	b. AAW	c. SUW	d. ASW	e. Electronic Warfare	f. Mine Warfare	g. Amphib Warfare	g. BMD	

Figure 22. Fleet Capabilities W/O UxVs

Figure 23 displays the result when adding UxVs as an option to increase fleet capabilities. As is clearly evident in the results, the addition of UxVs increases the Navy's warfare capabilities. However, the reader must be reminded that UAVs are *not* included in the SCN budget. Funding for all of the UxV platforms in this model comes from several procurement sources. The 19% increase in overall fleet capability must be funded by sources other than the existing SCN budget. Fleet Capabilities With UxVs

Arbitrary Weight (Must add to 100%)	27.0%	20.0%	15.0%	10.0%	10.0%	8.0%	6.0%	4.0%	100% (must t
Relative Score	1.065	1.306	0.976	0.948	3.286	2.441	1.95	1.26868668	Relative Score
Weighted Score	0.288	0.261	0.146	0.095	0.329	0.195	0.117	0.05074747	Weighted Score
SBD Derived Minimum Relative Score	80%	80%	80%	80%	80%	80%	80%	80%	SBD Derived Min
								0.80	SBD Compromise
						2035 FLEET SCORE		13.24	
						OBJECTIVE CELL		1.482	
	a. Strike	b. AAW	c. SUW	d. ASW	e. Electronic Warfare	f. Mine Warfare	g. Amphib Warfare	g. BMD	

Figure 23. Fleet Capabilities with UxVs

While gaining a 19% fighting capability increase is significant, we also consider how this increase will be manufactured. Since it is not unreasonable for defense contractors to build and supply the Navy with large numbers of TERN and Fire Scout

UAVs using existing manufacturing lines, we placed an unlimited upper bound for these platforms in order to give a larger feasibility region. However, an infinite number of UAVs is not realistic so we constrained the number of TERNs and Fire Scouts by the maximum number of ships with UAV carrying capable flight decks. The other UxVs considered by the model are the Triton (UAV) and the extra-large displacement unmanned underwater vehicle (XLDUUV) which we bound by build rate of 10 by 2035. Given these constraints the figure below outlines UxV numbers considered optimal by our fleet architecture.

In the end we can see that the overall cost tradeoff for an increase of 19% in fleet capabilities is 5.7 billion dollars. To put this in perspective, this is roughly the cost of one SSBN or half the cost of one CVN. While improving fleet capabilities by 19%, this $5.7 billion cost is not an SCN expense, and does not result in an additional monetary expense within our model.

TERN	$ 5.00	$0	$7	$2,131	$1,440	0	0	0	288
Fire Scout	$ 3.00	$0	$4	$1,234	$834	0	0	0	278
Triton	$ 80.00	$0	$118	$1,184	$800	0	0	0	10
XLDUUV	$ 80.00	$0	$118	$1,184	$800	0	0	0	10
GRAND TOTAL:		$636,920		$866,869	$164,308		225	141	297
566	<=	566	(Flight Deck Constraint)						
		UV cost	$5,734						

Figure 24. Numbers and Cost of UxVs

Figure 25 is the side-by-side visual comparison of possible future U.S. Navy fleet capabilities without and with UxVs respectively. Most notable is the drastic increase to Electronic Warfare and minimal, yet impactful, increases to AAW and ASW when adding UxVs to the 2035 fleet architecture.

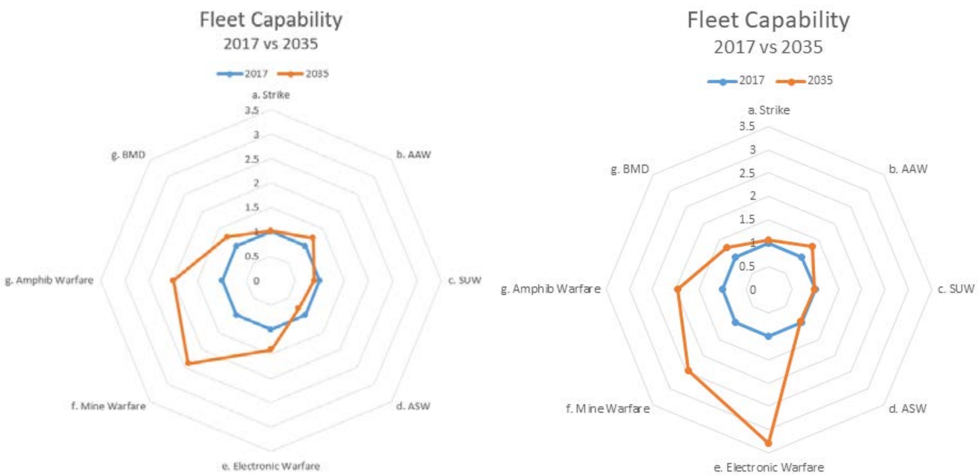

Figure 25. a) Fleet W/O UxVs b) Fleet with UxVs

VIII. THE FLEET ARCHITECTURE

A. NUMBER OF TOTAL VESSELS

307: This number includes 297 manned and 10 unmanned, surface and sub-surface fighting ships.

B. NUMBER OF MANNED VEHICLES

297: This number includes only 271 manned surface and 26 sub-surface ships.

C. NUMBER OF UNMANNED VEHICLES

586: This number includes zero unmanned surface, 10 unmanned sub-surface, and 576 unmanned air systems.

D. ACTIVITIES OF SHIP LIFE CYCLES

The length of the typical ship life cycle and training cycle has changed dozens of times over the last half century. This study is not concerned with the lifespan of a typical navy ship of 30 to 50 years, but is concerned with how a ship prepares for and recovers from a 6- to 9-month deployment.

The typical optimal fleet response plan (O-FRP) consists of maintenance, basic unit level training, integrated training, and sustainment. The plan "has been developed to enhance the stability and predictability for our Sailors and families by aligning carrier strike group assets to a new 36-month training and deployment cycle" as seen in Figure 26, according to USFF/CPFINST 3000.15 series, there are approximately 238 inspections, certifications, assessments, and visits (ICAVS) events that take time out of a ship's training cycle (U.S. Fleet Forces Command 2014).

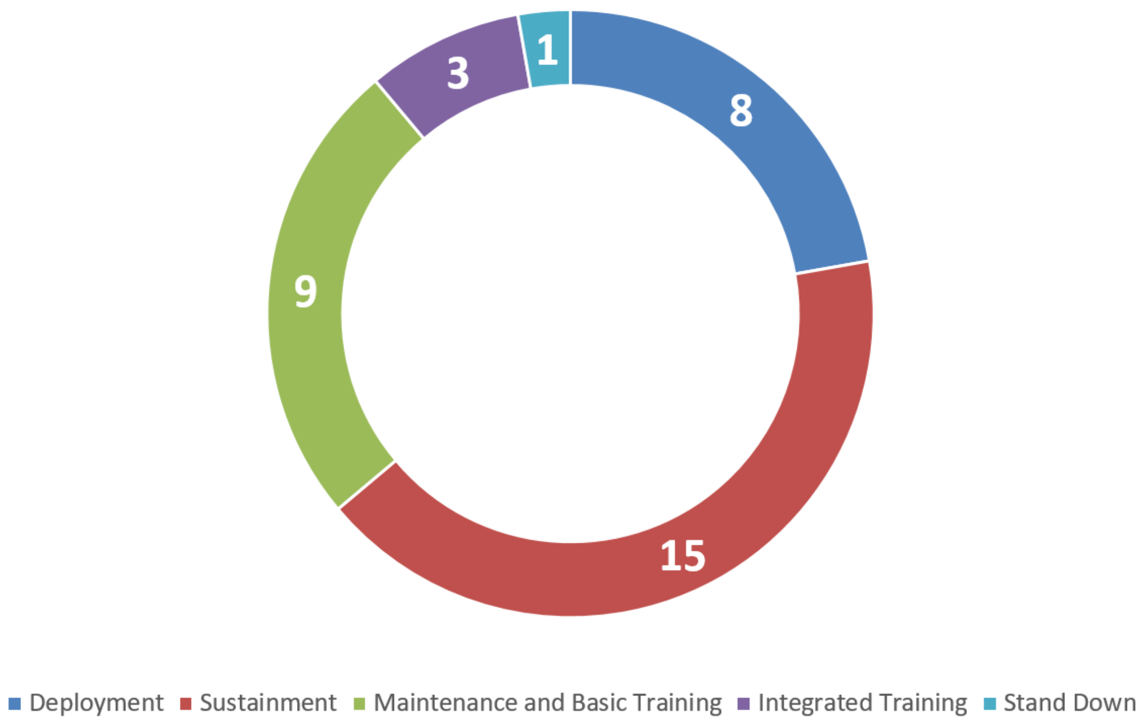

Figure 26. Current Optimized Fleet Response Plan (OFRP): Number of Months for Each Activity in a Training and Deployment Cycle. Source: U.S. Fleet Forces Command (2014).

Additionally, the O-FRP does not take into account cycle inefficiencies, schedule changes, and delays. There are also many certification and inspection bodies within the Navy that are often redundant in the same training cycle such as Afloat Training Group, Defense Readiness Reporting System-Navy, Type Commander Material Inspection, along with a myriad of other organizations.

With an assumed operational availability (A_o) of 0.25 and average deployment time of 8 months, this study proposes a 32-month ship cycle that resembles the following,

$$Ao = \frac{Deployment}{Deployment + Deployment\ Recovery}$$

$$0.25 = Availability = \frac{8\ mo\ deployment}{8\ mo\ deployment + 24\ mo\ recovery}$$

This study also recommends combining redundant ICAVs and abolishing the individual certification bodies and placing them under one Navy certification and training agency that will coordinate with the Board of Inspection and Survey. A proposed "certification period" will mitigate the schedule delays and inspection inefficiencies. The new ship cycle, or Improved Optimal Fleet Response Plan (IO-FRP), provides a realistic and predictable ship schedule is depicted in Figure 27.

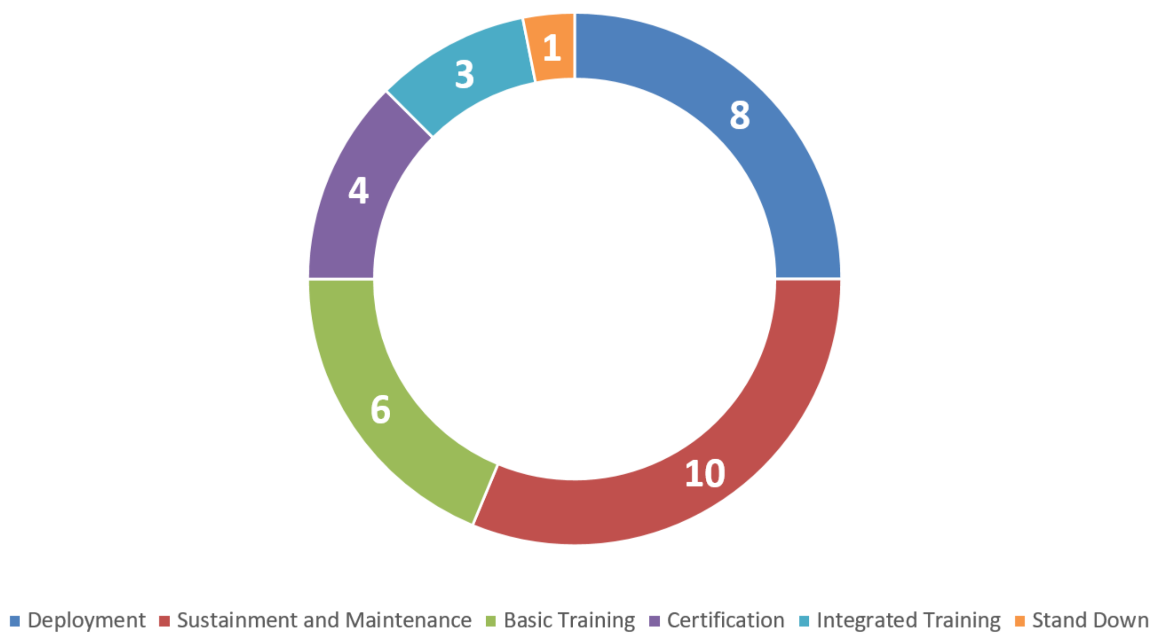

Figure 27. Proposed IOFRP Showing Number of Months in Deployment and Training Cycle

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IX. CONCLUSION

A. SUMMARY

In this work, the SEA-26 cohort leveraged systems engineering fundamentals and designed an alternative fleet architecture to the programmed force for the 2030–2035 timeframe. The team considered the anticipated dynamics of future naval combat, emerging technologies, and potential advisories trends in systems that threaten U.S. sea control. To the maximum extent possible, we investigated and used SBD to meet capability, capacity, and mission set requirements articulated in "A Design for Maintaining Maritime Superiority" (Department of the Navy 2016) and "*A Cooperative Strategy for 21st Century Seapower*" (Department of the Navy 2015). The fleet architecture includes the numbers, kinds, and sizes of vessels, numbers and types of associated manned and unmanned vehicles, and the basic capabilities of each of those platforms. Finally, the team assessed fleet architecture and design against the programmed force costs, and their ability to satisfy national and maritime strategy.

B. THE FINAL FLEET ARCHITECTURE

The resulting fleet architecture is presented in the Results section and has been reproduced at the bottom of this section for reference. The results clearly articulate the numbers and types of platforms in the 'optimum solution' generated by our main optimization model. It should be emphasized that this represents a feasible and optimal solution to the modeling of a very complex problem of a future fleet architecture. As such, it is valid under the clearly stated assumptions and measures of effectiveness and technical performance. Final recommendations should include a number of additional assumptions and measures, ranging from economical to social and political constraints. Nevertheless, the fleet architecture design methodology developed is very flexible and allows for a large number of studies to be completed providing rational guidance to future decision makers. Therefore, to stop the analysis at the hull count is incomplete and misses many important lessons from the exercise. Following are key findings about the fleet architecture and the fleet created by our work.

Reduced Emphasis on CVNs. While the capability to project power from the flight deck of a CVN is not in question, the cost associated with CVN construction and manning is. The objective function chose not to construct additional CVNs and instead divert the considerable cost savings to other types of warships to create additional fleet assets. For all the power and might of the carrier air wing, it can only be in one place at a time, and a more numerically larger fleet has its own value that is recognized by the main objective function.

High procurement of CG and DDG types of vessels. The main objective function recognizes the multi-mission capability and flexibility of these vessels, and it chooses to maximize their procurement.

'Gold Plated' platforms like DDG-1000, or extremely expensive platforms like submarines are not favored by the spreadsheet algorithm. While these are incredible national assets as modeled, their high cost is difficult to justify in comparison to less expensive conventional warships. However, this does not necessarily indicate that they are unnecessary. Rather, the lesson learned is that extremely expensive platforms must justify and quantify their value to the fleet in a different manner than their less expensive counterparts. Stealth has a value all its own, and this project did not attempt to quantify the advantages or disadvantages of low observable technologies and techniques. The choice to invest in high end stealth technologies for future platforms should be done at the individual program level in recognition of the considerable costs and possible advantages or disadvantages such technology adds to the system in question.

Expanded rolls for the Expeditionary Strike Group (ESG) and the CVL concept. The addition of new, more capable VTOL aircraft and UAVs has the potential to re-birth the CVL concept within the existing framework of our ESGs. The introduction of the F-35B Lightening II fighter aircraft to LHD and LHA amphibious assault ships will significantly increase their power projection. Additionally, more capable UAVs operating off relatively small amphibious ships (LPD, LSD) will provide large improvements in their strike and EW capabilities beyond those currently provided by the primarily manned helicopter detachments.

Cruiser-Destroyer (CRUDES) and aviation assets. While the current MH60R is an excellent platform for operation aboard CRUDES class ships, it faces limitations imposed by its manning compliment. Continuous flight operations can also significantly impact ship operations with frequent stops for fueling and/or crew changes. A 12-hour capable UAV could provide the CRUDES navy with expanded aviation support while the manned helicopter can undergo maintenance and crew rest takes place.

Table 6. 2035 Platform Allocation with UxVs (Repeated)

Ship Class	**Number in 2035**
CVN	9
CG	12
DDG	94
DDG-1000	4
LCS	45
Patrol	9
Mine Warfare	18
LHA	7
LHD	12
LPD	19
LSD	21
CVL (25-30 aircraft)	2
Ambassador class Patrol Ship	19
MDUSV	0
SSN	16
SSBN	10

Ship Class	Number in 2035
TERN	288
Fire Scout	278
Triton	10
XLDUUV	10
MSC	88
GRAND TOTAL:	**297 fighting ships 88 MSC 576 UAVs 10 UUVs**

C. ANALYSIS OF MEASURES OF EFFECTIVENESS

MOE 1, Domain Grid Factor, equates to 1.95. The sensor and weapon coverages are calculated from the platforms that are underway at any given time. Therefore, the sensor coverages in all domains are 1.95 times larger than the weapon coverages in all domains. In other words, the 2035 fleet can see nearly twice more than it can shoot.

MOE 2, Cumulative Deterrence, equated to 6.23. The collective ratio of BMD-capable platforms, STW-capable platforms, ship platforms, and submarine platforms in 2035 deployed and underway is 6.23 times more than the assumed ratios of these platforms that are assumed to be deployed and underway in 2017. Additionally, all MOE 2 criteria are met.

MOE 3, Weapon Density, equated to 0.010. This represents the distribution of the 2035 fleet architecture's SUW MOP over the total area of responsibility for all numbered fleets. Though no associated criterion was required for MOE 3, 0.010 is an improvement over the Weapon Density for the 2017 fleet architecture, 0.008. However, the individual weapon density of 5th Fleet was 0.180, which did not meet the criterion of 0.900. The low weapon density can be attributed to the low capacity of support facilities in the 5th Fleet AOR that results in a low presence of SUW-capable assets in the 5th Fleet AOR.

MOE 4, Cumulative Power Projection, equated to 1.35. The collective ratio of STW-capable platforms, AMW-capable platforms, and submarine platforms in 2035 deployed and underway is 1.35 times more than the assumed ratios of these platforms that are assumed to be deployed and underway in 2017. Additionally, all MOE 4 criteria are met.

MOE 5, Fleet Flexibility, equated 8. The manual allocation of assets of the fleet architecture to each numbered fleet resulted in the ability of each fleet to accomplish all eight warfare areas of concern in this study with the assets provided.

D. TECHNICAL RISKS WITH THE FINAL FLEET ARCHITECTURE

When considering the fleet architecture, there are a few primary concerns one of which is the technical risks involved with new or developing systems. The fleet that SEA-26 designed requires a large number of UxVs. As of today, UxVs are inherently a technical risk;, however, in order to minimize the risk in the 2035 fleet we restricted the fleet architecture options to highly developed, matured or already deployed UxVs. Although some of these platforms have not been tested in prolonged deployment or combat conditions, we have assumed that the next 18 years of development to FY2035 will provide ample time for additional development.

E. FURTHER RESEARCH AREAS

The analysis presented in this report analyzes the future in the broadest possible terms. The actual construction of the fleet requires much more detailed analysis of each system, and its integration into the future fighting force as a synergistic component of our overall capability. Further analysis also needs to consider additional MOEs and MOPs such as asset vulnerability and synergistic effects of multiple platforms operating in mutual support.

F. CONCLUSION

Designing a fleet architecture for the 2030–2035 timeframe is no easy task. Having a team with members of diverse warfare backgrounds contributed to the effectiveness of SBD. The requirements within the scope of fleet design were constantly evolving as different aspects of fleet design were uncovered. As mentioned earlier, this study describes a rational approach to a very complex problem within well documented technical and mathematical constraints. It can be used to provide guidance to decision makers with regards to proper fleet architectures for the future.

APPENDIX A. WARFARE POINTS

We define warfare points as the total capabilities a platform solely provides to a 24-hour engagement window within a warfare area. All platforms subject to this analysis were assigned “Warfare Points” with which to use for their comparisons. These points intend to compare the total capability each platform can bring to a 24-hour fight. Points are only compared within each warfare area, and not across warfare areas. For example; a good question to ask while assigning these values is; “how many DDGs does it take to match the strike power of a CVN?” Do NOT consider “why there so many more strike points compared to the number of amphibious points?”

Below we provide the warfare points we assign all platforms to all warfare areas. The warfare points for each platform are determined from their number of onboard systems, assets, and capabilities.

	a. STW	**b. AAW**	**c. SUW**	**d. ASW**	**e. Electronic Warfare**	**f. Anti-Mine Warfare**	**g. Amphib Warfare**	**h. Ballistic Missile Defense**
CVN	4 strike squadrons	4 strike squadrons	4 strike squadrons	1x MH-60R Squadron	1 EW squadron	-	-	-
Life = 50 years	3 strike sqdns used	3 strike sdns used	3 strike sdns used	4 aircraft used/ day		-	-	-
	10 aircraft / squadron	10 aircraft / squadron	10 aircraft / squadron		5 aircraft per squadron	-	-	-
	2 ‘strikes’ per aircraft	2 ‘strikes’ per aircraft	2 ‘strikes’ per aircraft	1 torpedo per aircraft	SLQ-32V4	-	-	-
	2 sorties per day	2 sorties per day	2 sorties per day	2 bonus for weapons placement	2 sorties per day	-	-	-
	=3*10*2*2	**=3*10*2*2**	**=3*10*2*2**	**=4*2**		-	-	-
	120 STW points	**120 AAW points**	**120 SUW points**	**8 ASW points**	**10 EW points**	**0 MW points**	**0 Amphib pts**	**0 BMD points**
	120	120	120	8	10	0	0	0
CG	2x full VLS launchers	2x full VLS launchers	2x deck Gun	128 tubes 1/4 ASROC (30pts)	SLQ-32V3	-	-	2x full VLS launchers
35 year life span	61 missiles per VLS (122 total)	61 missiles per VLS	8x Harpoon	2x MK 32 Torpedo launcher (2pts)		-	-	61 missiles per VLS
	1/4 land strike loaded	1/4 AAW SM-2	1/8 Tomahawk	2X H60R (1 at a time) (2pts)		-	-	1/4 BMD SM-6
		ESSM	2x CIWS			-	-	
			1/8 SM-6			-	-	
			2x MK 32 Torpedo			-	-	
			2x 25mm			-	-	
	30.5 strike points	**30.5 AAW points**	**46 SUW points**	**34 ASW point**	**2 EW Points**	**0 MW points**	**0 Amphib pts**	**30.5 BMD points**

	30.5	30.5	46	34	2	0	0	30.5
DDG	1.5x full VLS Launchers	1.5x full VLS Launchers	1x Deck Gun	64 tubes1/4 ASROC (18pts)	SLQ-32V2	-	-	1.5x full VLS Launchers
35 year life span	61 missiles per VLS	61 missiles per VLS	1x or 2x CIWS	2x MK 32 Torpedo (2pts)		-	-	61 missiles per VLS
	90 tubes	90 tubes	8x Harpoons	2X H60R (1 at a time) (2pts)		-	-	90 tubes
	1/4 land strike loaded	1/4 land strike loaded	2x 25mm			-	-	1/4 BMD SM-6
		ESSM	1/8 Tomahawk			-	-	
			1/8 SM-6			-	-	
			2x MK 32 Torpedo			-	-	
	22 strike points	**24 AAW points**	**37 SUW points**	**22 ASW point**	**2 EW Points**	**0 MW points**	**0 Amphib pts**	**30.5 BMD points**
	22	24	37	22	2	0	0	30.5
DDG-1000	80 tubes	80 tubes	80 tubes	80 tubes 1/4 ASROC (20pts)	ECM	-	-	80 tubes
	1/4 land strike loaded	1/4 land strike loaded	1/8 Tomahawk	2X LAMPS (2pts)		-	-	1/4 BMD SM-6
	railgun=20		1/8 SM-6			-	-	
			2x 30mm Gun			-	-	
	=20 + 20		2x155mm LRALAP					
			20					
	40 strike points	**20 AAW points**	**24 SUW points**	**22 SUW pts**	**2 EW Points**	**0 MW points**	**0 Amphib pts**	**20 BMD points**
	40	20	24	22	2	0	0	20
LCS	No VLS	No Offensive Caps	1x 57mm Gun	1x H-60R (1pt)	WBR-2000 ECM	MCM Module	-	-
		Self Defense only	2x 30mm Gun			MNV	-	-
		ASW Mod=1/2 of DDG cap=11	ASW Mod=1/2 of DDG cap=11	ASW Mod=1/2 of DDG cap=11		Firescout	-	-
	0 Strike Points	**1 AAW Points**	**3 SUW points**	**1 ASW point**	**1 EW Point**	**3 MW points**	**0 Amphib pts**	**0 BMD points**
	0	1	3	1	1	3	0	0
Patrol Craft	No VLS	None	2x 25mm (1/2 pt)	sonar?	slq32?	sonar?	carry seals?	-
			2x 40mm Grenade (1/2 pt)	None	None	None	None	-
			8x Griffin Missiles (8 pts)					-
	0 Strike Points	**0 AAW Points**	**10 SUW Points**	**0 ASW Points**	**0 EW Points**	**0 MW points**	**0 Amphib pts**	**0 BMD points**

	0	0	5	0	0	0	0	0
Mine Sweep	No VLS	None	None	VLS Side scan sonar mag tail	- -	None mag sweep mech sweep acoustic sweep 1 nm squared per day (better than LCS, therefore 5 points)	None	
	0 Strike Points	**0 AAW Points**	**0 AAW Points**	**0 ASW points**	**0 EW Points**	**5 MW points**	**0 Amphib pts**	**0 BMD points**
	0	0	0	0	0	5	0	0
LHA	2 strike squadrons 1 strike sqdn used 10 aircraft / squadron 2 'strikes' per aircraft 2 sorties per day =10*2*2	2 strike squadrons 1 strike sqdn used 10 aircraft / squadron 2 'strikes' per aircraft 2 sorties per day =10*2*3	2 strike squadrons 1 strike sqdn used 10 aircraft / squadron 2 'strikes' per aircraft 2 sorties per day =10*2*4	1/2 MH-60R Squadron 5 aircraft / ship 2 Aircraft used 1 torpedo per aircraft 2x a/c airborne simultaneously (2 pts) =2*2	1/2 EW squadron 3 aircraft per ship (3 points) SLQ-32V4 (2 pts)	None	1/2 MEU	
	40 strike points	**40 AAW points**	**40 SUW points**	**4 ASW points**	**5 EW points**	**0 MW points**	**1/2 Amphib pts**	**0 BMD points**
	40	40	40	4	5	0	0.5	0
LHD	1 strike squadron 6 aircraft / squadron 2 'strikes' per aircraft 2 sorties per day	1 strike squadron 6 aircraft / squadron 2 'strikes' per aircraft 2 sorties per day	1 strike squadrons 6 aircraft / squadron 2 'strikes' per aircraft 2 sorties per day	1/2 MH-60R Squadron 5 aircraft / ship 1 torpedo per aircraft 2x a/c airborne simultaneously (2 pts)		None	24012 sqft vehicle 145k ft^3 cargo 2 LCU 3 LCAC 6 LCM 40 AAV 1900 Marines	
	12 strike points	**12 AAW points**	**12 SUW points**	**2 ASW points**	**0 EW points**	**0 MW points**	**1/2 Amphib pts**	**0 BMD points**
	12	12	12	2	0	0	0.5	0

LPD-17	60% VLS for Strike	40% VLS for AAW	2x 30mm (1 pt)	2 VLS ASROCS	Self defense only. 1 point		1/4 MEU	
		8 pts, 2 RAM systems (21 self defense missiles each)	7 pts for rotary strike	1 pt, Nixie				
	=61*0.6	=0.4*61+8	=7+1					
	37 strike points	**32 AAW points**	**8 SUW points**	**3 ASW points**	**1 EW point**	**0 MW points**	**1/4 Amphib pts**	**0 BMD points**
	37	10	8	3	1	0	0.25	0
LSD	None	Self Defense only	8x harpoon	2x MH-60R	Self defense only. 1 point	Mine Hunting Suite	1/4 MEU	none
			2x CIWS	1 aircraft used/ day 1 torpedo per aircraft 1 bonus for weapons placement		3/5 value of dedicated minesweep		
				=1+1				
	0 Strike Points	**1 AAW Points**	**8 SUW points**	**2 ASW points**	**1 EW point**	**3 MW points**	**1/4 Amphib pts**	**0 BMD points**
	0	1	8	2	1	3	0.25	0
Light Carrier (25-30 planes)	2 strike squadrons	2 strike squadrons	2 strike squadrons	1/2 MH-60R Squadron	1/2 EW squadron	None		
	1 strike sqdn used	1 strike squadrons used	1 strike squadrons used	5 aircraft / ship	3 aircraft per ship (3 points)			
	10 aircraft / squadron	10 aircraft / squadron	10 aircraft / squadron	1 torpedo per aircraft				
	2 'strikes' per aircraft	2 'strikes' per aircraft	2 'strikes' per aircraft	2x a/c airborne simultaneously (2 pts)	SLQ-32V4 (2 pts)			
	2 sorties per day	2 sorties per day	2 sorties per day	2x points for mutual attack				
	=10*2*2	=10*2*3	=10*2*4	=2*2				
	40 strike points	**40 AAW points**	**40 SUW points**	**4 ASW points**	**5 EW points**	**0 MW points**	**0 Amphib pts**	**0 BMD points**
	40	40	40	4	5	0	0	0
Ambassador class Patrol Craft	1 Deck Gun	1 CIWS	8 Harpoon					
		1 RAM						
	3 strike points	**2 AAW points**	**8 SUW points**	**1 ASW points**	**1 EW points**	**0 MW points**	**0 Amphib pts**	**0 BMD points**
	3	2	8	1	1	0	0	0

MDSUV (ACTUV)			4 Harpoons	1 ASROC				
	0 strike points	**0 AAW points**	**4 SUW points**	**1 ASW points**	**0 EW points**	**0 MW points**	**0 Amphib pts**	**0 BMD points**
	0	0	4	1	0	0	0	0
SSN	*Difficult to quantify VLS mod with Harpoon missiles		Large torpedo magazine capacity high lethality per weapon					
	10 strike points	**0 AAW points**	**60 SUW points**	**40 ASW points**	**0 EW points**	**0 MW points**	**0 Amphib pts**	**0 BMD points**
	10	0	60	40	0	0	0	0
SSBN	154 TLAM		Torpedo capability	Torpedo capability				
	154 strike points	**0 AAW points**	**40 SUW points**	**30 ASW points**	**0 EW points**	**0 MW points**	**0 Amphib pts**	**0 BMD points**
	154	0	40	30	0	0	0	0
TERN	4 Hellfire (1/2 point each)		4 Hellfire (1/2 point each)		1 ECMW			
	1 strike points	**0 AAW points**	**2 SUW points**	**0 ASW points**	**1 EW points**	**0 MW points**	**0 Amphib pts**	**0 BMD points**
	2	0	2	0	1	0	0	0
Fire Scout	APKWS System		APKWS System	1 lightweight torpedo	simple onboard EW system			
	1/4 strike points	**0 AAW points**	**1/4 SUW points**	**1 ASW points**	**1 EW points**	**0 MW points**	**0 Amphib pts**	**0 BMD points**
	0.25	0	0.25	1	1	0	0	0
Triton					Advanced EW system			
	0 strike points	**0 AAW points**	**0 SUW points**	**0 ASW points**	**2 EW points**	**0 MW points**	**0 Amphib pts**	**0 BMD points**
	0	0	0	0	2	0	0	0
XLDUUV			4 lightweight torps 1/2 points for low maneuverability of system	4 lightweight torps				
	0 strike points	**0 AAW points**	**2 SUW points**	**2 ASW points**	**0 EW points**	**0 MW points**	**0 Amphib pts**	**0 BMD points**
	0	0	2	2	0	0	0	0

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APPENDIX B. CARRIER STRIKE GROUPS (CSG)

A carrier strike group (CSG) consists of a Nimitz or Ford class carrier (CVN), one Ticonderoga class Cruiser (CG), two to four Arleigh Burke class guided missile destroyers (DDGs), zero to one fast attack submarine (SSN), and one supply ship (T-AO/ T-AOE).

On board the CVN, a carrier air wing (CVW) is embarked during the CSGs deployment. A CVW consists of approximately 70 aircraft including 40 strike aircraft among four strike fighter squadrons (VFAs), 5 electronic attack aircraft in one electronic attack squadron (VAQ), four airborne early warning aircraft in one carrier airborne early warning squadron (VAW), eight helicopters in one helicopter sea combat squadron (HSC), eleven helicopters in one helicopter maritime strike squadron (HSM), and two logistics aircraft in one fleet logistics support squadron (VRC).

We assume a mix of Nimitz class (CVN-68) and Ford class (CVN-78) aircraft carriers are present in the 2030–2035 fleet architecture. As of 2017, there are only two additional Ford class carriers scheduled to be commissioned: USS John F. Kennedy (CVN-79) in 2020 and USS Enterprise (CVN-80) in 2025 to replace USS Nimitz (CVN-68) and USS Dwight D. Eisenhower (CVN-69) respectively (O'Rourke 2017).

The key effectiveness of the CSG is the ability to use maneuverability by allowing the tactical flexibility and "stealthiness" to deny targeting to an adversary. Meanwhile, the CSG concept relies upon keeping the assets and ships of the strike group concentrated in order to conduct "power projection" operations from an airfield at sea or from vertically launched land attack cruise missiles. The carrier serves as the capital ship while the other ships in the strike group bear the responsibility of supporting and protecting her.

Future capabilities of the CVN include the employment of unmanned aircraft. This implies that the future CVW may include mixed squadrons of manned and unmanned platforms.

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APPENDIX C. AMPHIBIOUS READY GROUP (ARG)

According to General James F. Amos, USMC, "Forward-deployed amphibious forces remain a uniquely critical and capable component of our national strategic demands presence crisis response, power projection and theater security cooperation (U.S. Marines Corps 2017)." The amphibious ready group (ARG) consists of an amphibious assault ship (LHD/LHA), amphibious transport dock ship (LPD), dock landing ship (LSD), two Arleigh Burke class guided missile destroyers (DDGs), and one supply ship (T-AO/T-AOE)

Embarked on the various large amphibious ships will be a marine expeditionary unit (MEU). Each MEU includes a ground combat element of a Marine infantry battalion, aviation combat element, battalion sized logistics element, and a command element. "An amphibious operation is a military operation launched from the sea by an amphibious force (AF) to conduct landing force (LF) operations within the littorals (U.S. Marine Corps 2017)." As the focus of the ARG is amphibious operations, it should be categorized differently from the other warfare area-centric concepts.

The 2016 Center for Strategic and Budgetary Assessments (CSBA) Study (Clark and Sloman 2016) recommends additional San Antonio class LPDs and America class LHAs. Additionally, the authors recommend three additional LHAs and eight LPDs be stationed forward as part of the Forward Deployed Naval Force (FDNF) in the Pacific, Mediterranean and Arabian Gulf. While these LPDs and LHAs are assigned to the expeditionary fighting force, additional LPDs could be repurposed and re-designated as CVLs. The combat potential of an LPD operating F-35 Lightening II aircraft gives considerable strike potential to a ship not usually considered to have any strike capability.

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APPENDIX D. LIGHT CARRIER GROUP (CLG) CONCEPT

The light carrier group (CLG) concept explores the potential use of repurposing a San Antonio class (LPD-17) from an Amphibious Transport Dock Ship into a Light UAV Carrier (CVL-17). The CVL would serve as a high value unit capable of launching, recovering, commanding, and maintaining several squadrons of UAVs. Three to four DDGs or LCSs would serve as supporting composite warfare commanders.

As the cost of a manned strike aircraft can be many times higher than that of an unmanned drone, the use of UAVs in military applications carries much less monetary risk. Not only are the UAVs a cost-effective manned aircraft replacement, the CVL will be a cost-effective UAV carrier in place of a larger and more expensive Nimitz or Ford class CVN. The CLG would be deployed to regions where air, communications relays, and ISR assets are required, but do not require the amount strike and command and control capability that a CSG and CAW provides. The DDGs or LCSs assigned to the CLG would augment the AAW, ASW, SUW, and strike warfare areas.

The existing LPD-17 class will provide an outstanding hull for conversion into a CVL-17 class carrier equipped with VTOL UAVs. Compartments dedicated to troop berthing and vehicle storage will be converted to UAV storage racks to optimize the number of aircraft embarked (Bradley, Daniel, Hanks, and McKelvey 2009). The Landing Force Operations Center will be converted to UAV controller console stations. Launch and recovery systems will need to be added, but need not be robust and dynamic of those onboard Nimitz and Ford class carriers.

UAVs embarked would be Group 1 (Small), Group 2 (Medium), and Group 3 (Large) types of fixed and rotary winged unmanned aerial systems (UASs). The composition and organization of a Light Carrier Air Wing would mimic that of a full Carrier Air Wing (CVW), but would focus on ISR and communications based platforms. They would include, but not be limited to unmanned strike fighter squadrons (VFUs), unmanned electronic attack squadrons (VQUs), unmanned airborne early warning/ISR Squadrons (VWUs), unmanned communications relay squadrons (VCUs), unmanned helicopter combat squadrons (HSUs), and helicopter maritime strike squadrons (HMUs). Additionally, a manned helicopter sea combat squadron detachment (HSC) will be embarked for search and rescue and anti-terrorism/force protection requirements.

APPENDIX E. UNMANNED UNDERWATER GROUP (UUG) CONCEPT

The anti-submarine warfare continuous trail unmanned vessel (ACTUV) is an UUV with the capability to track diesel electric submarines (Walan 2017). As of 2017, this maritime system is able to deploy for several months and cover thousands of miles under sparse supervision (Walan 2017). While the ACTUV's primary mission is ASW, its mission set it expendable for a variety of configurations to potentially include SUW, STW, and AAW. A UUG would consist of 1–2 DDG and 4 ACTUV, Supply Ship, support ship specifically for ACTUV Maintenance/Repair as needed. Maritime Patrol P-3 or P-8 Squadrons (VP) have the ability to augment the UUG as required.

UUGs can potentially alleviate the need for several Arleigh Burke class, Freedom class, and Independence class vessels to conduct ASW operations and patrols so that their capability is not restricted to one warfare area. ASW operations require a large sensor coverage to weapons coverage ratio as detection and classification of adversary submarines are far more important than an overwhelming amount of ordnance as submarines typically operate independently. Therefore, only one or two weapons capable manned platforms are required in this type of operating environment.

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APPENDIX F. BATTLESHIP BATTLE GROUP CONCEPT

The battleship was the first rate ship of the line from the late 1800s until the middle of World War II. The Battle of Midway Sea proved the importance of carrier based strike aircraft. However, in the height of the missile age, the risks associated with Nimitz or Ford class Carriers conducting strike operations and Arleigh Burke class destroyers conducting naval surface fire support (NSFS) in the range of coastal anti-ship cruise missile (ASCM) batteries are far too high (Honan 1984). A Zumwalt class DDG-1000 reclassified as a battleship would reinforce and enhance the future fleet in two ways. First, a battleship armed with a railgun system with a notional range of 220 nm would alleviate the overtasked and overvalued Aegis ships so they will not have to conduct NSFS within 12nm offshore, well within coastal defense batteries (Freebird 2017). Second, recognizing that battleship and its destroyer escorts equipped with a long range kinetic gun and tomahawk land attack cruise missiles (TLAMs) would increase the number of "Capital Ships" that the Navy could deploy to minor global "hotspots." In an era of rising third-state threats, when strategic global crisis arises, the President will no longer have to ask questions like "Where is the nearest carrier?"

A critical concept of Imperial Japanese Navy (IJN) battleship tactics during the Pacific War was to use the largest possible gun to outrange the enemy. Extended weapon ranges allowed the IJN to strike the enemy before he could retaliate (Stille, 2014). Railguns will serve as the battlegroup's main force strike weapon to render enemy ASCM batteries, missile interceptors, surface to air missile sites (SAMs), or anti-aircraft artillery (AAA) ineffective. The vanguard force consisting of its Aegis destroyer escort force will conduct anti-air defense and conduct long-range TLAM strike operations. Additional considerations could include specific ranges for long range NSFS through the use of the Navy Rail Gun given a classification upgrade.

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APPENDIX G. DOD UAV CLASSIFICATION

Table 7. DOD UAV Classification. Adapted from U.S. Army UAS Center for Excellence (2010).

Category	Size	Maximum Gross Takeoff Weight (lbs)	Normal Operating Altitude (ft)	Airspeed (knots)
Group 1	Small	0-20	<1,200 Above Ground Level	<100
Group 2	Medium	21-55	<3,500	<250
Group 3	Large	<1320	<18,000 Mean Sea Level	<250
Group 4	Larger	>1320	<18,000 Mean Sea Level	Any airspeed
Group 5	Largest	>1320	>18,000	Any airspeed

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APPENDIX H. LCS FUTURE MISSION MODULE CONSIDERATIONS IN SBD

The littoral combat ship (LCS) was designed to counter three main threats: small surface attack threats in the form of fast attack craft (FAC) and fast inshore attack craft (FIAC), diesel/electric submarine threats, and mine threats (Knowles 2016). mission modules (MM) custom tailored to these three threats allow for the LCS rapidly modify and shift its capabilities and equipment to meet a dynamic range of mission requirements. Additionally, the modular MM allow a single LCS platform to be quickly installed with a single specific MM that can be swapped out with another platform or stored ashore for future use. Each MM contains mission specific equipment, so the appropriate technology can be selected for the MM. These MMs are developed incrementally to allow changes as new technology becomes available (Knowles 2016).

As of 2017, PMS 420, LCS MM, has proved initial operational capability for the SUW MM, technical evaluation for the Mine-Countermeasure MCM MM, and proof of concept for the ASW MM (PMS-420 2017). The SBD design methodology coincides directly with the LCS MM concept. Just as SBD allows for the design effort to fluctuating and defers a final decision, LCS MM allows for the empty mission bay to serve as the design space and defers the MM decision until the detailed mission requirements are defined and understood. Once a large number of alternative MMs are considered, unit commanders can analyze the design space from their own unique perspective and optimize their own design and commit to a MM.

LCS is a focused-mission surface combatant to potentially replace our legacy small surface combatants; Oliver Hazard Perry-class Frigates, Avenger class MCMs, and patrol craft. The ship, independent of an embarked mission, package provides air warfare self-defense capability with anti-air missiles, a high rate of fire 57mm gun, 3D air search radar, electronic warfare systems, and decoys for electronic warfare (Stackley and Rowden 2016). With cost as a main constraint, assuming three MMs for a single platform greatly increases the capability and capacity of the fleet architecture.

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APPENDIX I. MEDIUM DISPLACEMENT UNMANNED SURFACE VESSEL MDUSV FUTURE CONSIDERATIONS IN SBD

The MDUSV in an unmanned surface vessel designed to track submarines (Walan 2017). The operational strategy of distributed lethality involves the process of employing all surface assets as surface combatants. The future of the MDUSV could possibly involve the employment of SUW and ASW offensive capabilities to enhance the manned platforms they support. With two areas on the deck of the MDUSV dedicated for additional mission capability, the Harpoon Block II Extended Range and deck mounted Anti-Submarine Rockets could be employed to significantly enhance the offensive capabilities.

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APPENDIX J. TERN FUTURE CONSIDERATIONS IN SBD

The TERN UAV is a DARPA sponsored program to develop a VTOL ‘fixed wing’ type of aircraft to perform a variety of missions from helicopter capable warships. The DARPA website offers the following amplification;

> Tern is an advanced technology development program that seeks to design, develop, and demonstrate a medium-altitude long-endurance (MALE) unmanned aircraft system and related technologies that enable future launch, recovery, and operations from small ships. The program seeks to develop systems and technologies to enable a future air vehicle that could provide persistent ISR and strike capabilities beyond the limited range and endurance provided by existing helicopter platforms. (Drozeski 2017)
>
> Tern seeks to enable on-demand, ship-based unmanned aircraft system (UAS) operations without extensive, time-consuming, and irreversible ship modifications. It would provide small ships with a “mission truck” that could transport ISR and strike payloads long distances from the host vessel. A modular architecture would enable field-interchangeable mission packages for both overland and maritime missions. It would be able to operate from multiple ship types in elevated sea states. (Drozeski 2017)

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APPENDIX K. XLDUUV FUTURE CONSIDERATIONS IN SBD

The Extra-Large Displacement UUV (XLDUUV), is a 54-inch diameter UUV that can be launched from the pier or a large mission-specific mothership at sea (Eckstein 2017). While current capabilities in MIW, ASW, and SUW have not been proven, the vision is for the XLDUUV's potential contribution in stealth, endurance, and sensor capacity to alleviate the need for dedicated manned surface vessels and aircraft to conduct extensive ASW operations.

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APPENDIX L. ADDITIONAL BUDGETARY CONSIDERATIONS

The Assistant Secretary of the Navy Finance and Comptroller (2017) reports the Department of the Navy (DON) budget maintains consistency with the overarching themes of the Department of Defense (DOD) budget including:

- Sustain global demand for Naval Forces;
- Continue readiness reset;
- Recapitalize and modernize Naval Forces;
- Address the competitive environment;
    - Fund high end fight and game changing capabilities;
    - Restore and increase modernization programs;
    - Retain counterterrorism/counterinsurgency competencies;
- Improve cyber resilience; and
- Focus on Responsible Military Spending (ASN Finance and Comptroller 2017).

Maintaining a robust Fleet and adaptable Marine Corps requires investments in platforms and systems to address today's wide-range of operations. Some major considerations to the main optimization model's budget constraint include the following committed programs under shipbuilding and conversion, Navy. Additional:

- (3) Zumwalt class DDG-1000s $13.5B total by 2022.
- CVN refueling and overhaul programs $33.7B by 2024. Cost estimation growth $37.0B total by 2035 based upon anticipated fleet architecture and pace of CVN overhaul.
- (7) Expeditionary sea dock (ESD) and Expeditionary Sea Base (ESB) cost $4.6B total by 2035.
- (8) Expeditionary fast transport (EPF) cost $2.0B total by 2035.
- (21) Fleet replenishment oiler (TAO) cost $13.7B total by 2035.
- (15) Towing salvage and rescue ship (ATS) cost $1.4B total by 2035.
- (2) Moored training ship cost $2.2B total by 2035.
- (58) Landing craft utility (LCU-1700) cost $2.0B total by 2035.
- Outfitting (Repairs, equipage, consumables, and allowances) cost $11.7B by 2035.
- (102) Ship-to-shore connector (SSC), Landing Craft Air Cushion (LCAC) replacement, cost $7.1B by 2035.
- (90) Service craft cost $0.9B by 2035 (Assistant Secretary of the Navy Finance and Comptroller 2017).

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APPENDIX M. STAKEHOLDER QUESTIONNAIRE

The Fleet Architecture of 2030–2035 has many stakeholders, each with different backgrounds of study, requirements interpretation, and methods to achieve those requirements. Stakeholder analysis helps understand stakeholder's needs and concerns and uses that knowledge to make the final product successful.

Stakeholder analysis serves a dual purpose. First, the stakeholders are the main source of information for determining the capability needs, system requirements, and constraints. Secondly, stakeholder analysis is done because we recognize our systems are developed for people, within the context of an organization, and collectively these people have enormous influence the success of the project. Any new system development implies change, consequently the program needs to conduct change management. Stakeholder analysis and engagement is part of the change management process and is done to ensure acceptance of the system (Giachetti, 2010). The following is a list of stakeholders and the questionnaire submitted for their feedback.

I. U.S. Fleet Forces Command: ADM Phil Davidson

POCs:
Captain Robert Gamberg, USN, USFF N7 robert.gamberg@navy.mil
Dr. William Reiske, USFF N8/9 william.reiske@navy.mil
CAPT David Wickersham, USFF, N8/9 david.wickersham@navy.mil

II. OPNAV (N9):

Cdr Kyle Gantt (Branch Head, Future Ships, OPNAV N96F3)
Tim Mierzwicki (Future Surface Combatant AoA) timothy.mierzwicki@navy.mil
Mr. Mike Novak, SES, OPNAV N9I B michael.j.novak1@navy.mil

III. Others:

Mr William Glenny, Director Future Warfare Institute, glenneyw@usnwc.edu
CAPT Kurt Sellerberg, Director, Distributed Lethality Task Force kurt.sellerberg@navy.mil
Mr. David Yoshihara, SES, USPACFLT N00 David.Yoshihara@navy.mil
Mr. Joseph Murphy, Director, Navy Warfare Development Command (NWDC), Joseph.murphy1@navy.mil
CAPT Charles Good, NPS Surface Warfare Chair, cpgood@nps.edu

IV. Example Questionnaire:

Disclaimer: The following questions are meant to be informative, based on U.S. Navy needs, and provide insight to our model's assumptions. None of the information provided will be directly attributed to specific individuals.

Definitions: Set-Based Design

Our model defines a "set" as a possible future, and derives the requirements that the corresponding fleet architecture must have to meet the needs of that possible future. Some sets we are currently exploring are:

Set 0: Baseline, today's fleet.
Set 1: Surface-Focused fleet based on Captain Wayne Hughes' "A New Navy Fighting Machine" fleet design.
Set 2: Surface and Unmanned focused, with emphasis on South China Sea / Pacific Theater
Set 3: BMD focused.
Set 4: Green and Brown water focused.

Data and Ratios

Data points and ratios are derived to assess or constrain the different fleet architectures. In the absence of stakeholder input we will hypothesize these values. To the best of your ability, while maintaining this document unclassified, we request the following data points.

For each numbered fleet's Operational Area:

- What is the minimum percentage that must be covered for SUW?
- What is the minimum percentage that must be covered for AAW?
- What is the minimum percentage that must be covered for BMD?

For each numbered fleet, at any given time:

- Of the total number of strike capable assets, what percentage is required to be deployed and underway?

- Of the total number of ships, what percentage are required to be deployed and underway?

- Of the total number of nuclear submarines, what percentage are required to be deployed and underway?

- Of your total number of amphibious ships what percentage are required to be deployed and underway?

- In order to maintain amphibious operations, how many Marine-carrying Littoral Craft are required in each fleet?

- In order to maintain sea control, how many mine-clearing vessels are required in your fleet?

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APPENDIX N. AREA CALCULATIONS

The following AOR depictions are used in the calculation of weapon density (MOE 3), and derived from the hypothetical geographical locations of a given fleet's Naval operations. Each graphic is derived from assumptions of the current numbered fleet's expected AOR in the 2030–2035 timeframe. These area assumptions are derived for this study, however the areas can be refined by further analysis and outsider input.

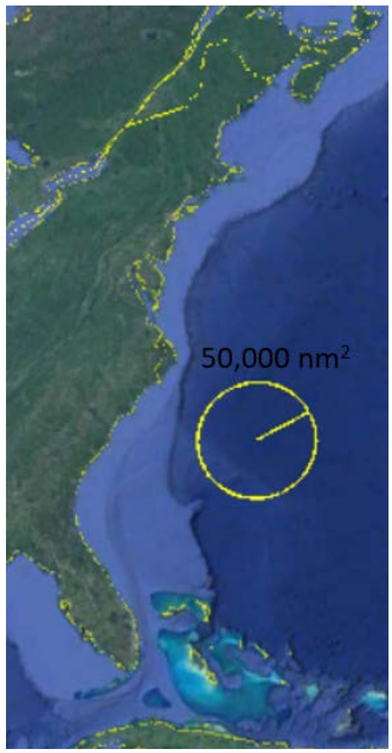

Figure 28. Fleet Forces AOR. Source: Google Maps (2017)

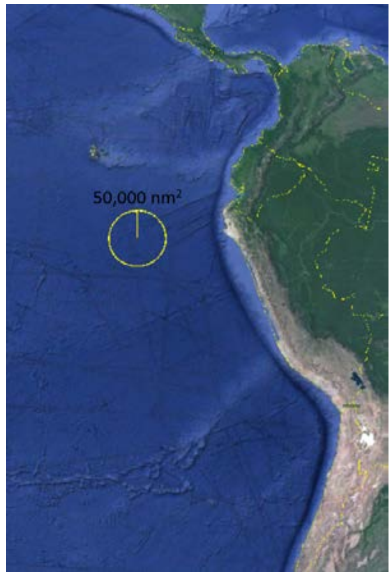

Figure 29. 4th Fleet AOR, South America. Source: Google Maps (2017).

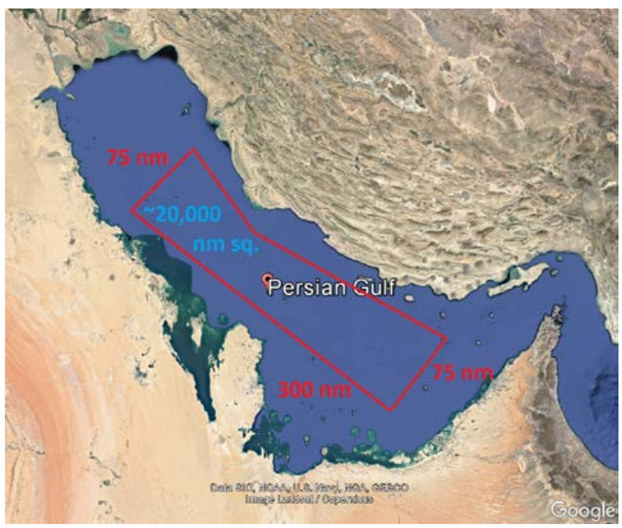

Figure 30. 5th Fleet AOR, Arabian Gulf. Source: Google Maps (2017).

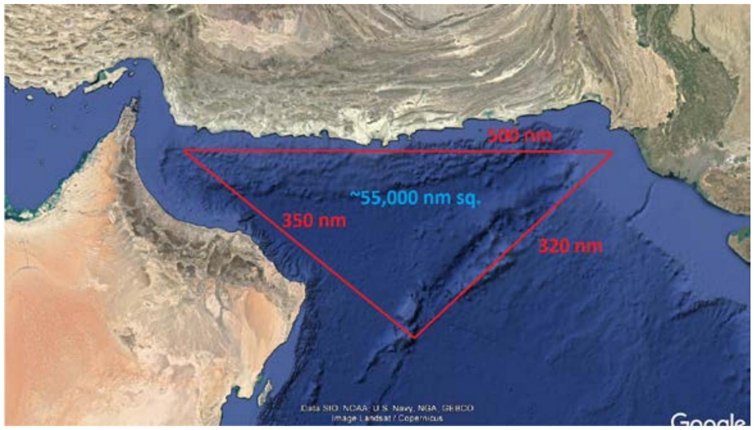

Figure 31. 5th Fleet AOR, Gulf of Oman. Source: Google Maps (2017).

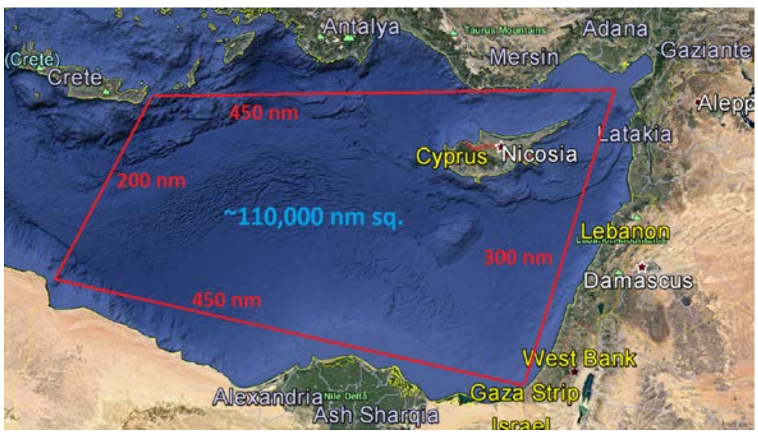

Figure 32. 6th Fleet AOR, Mediterranean Sea. Source: Google Maps (2017).

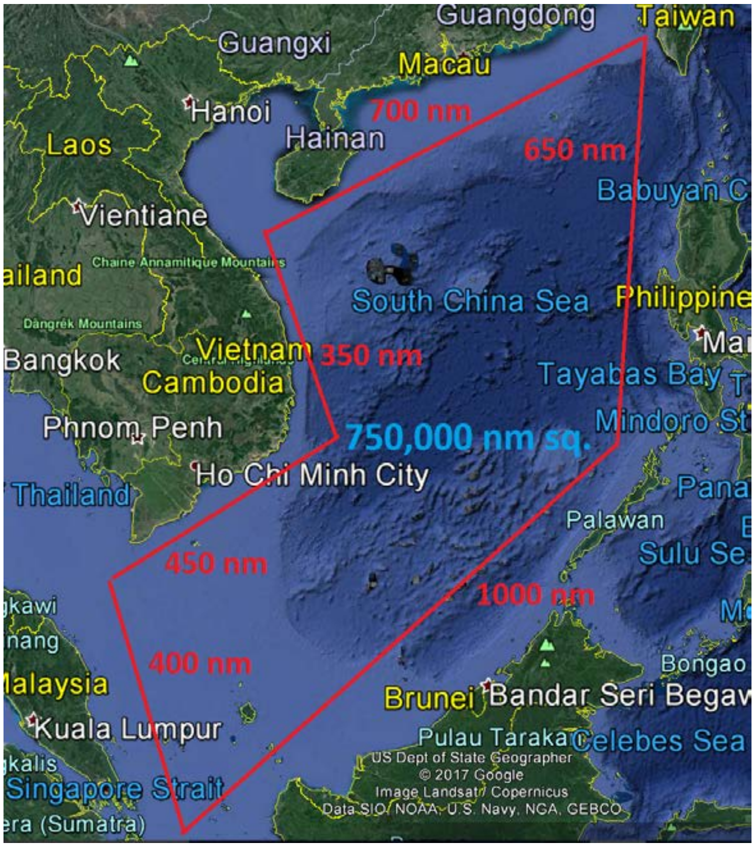

Figure 33. 7th Fleet AOR, South China Sea. Source: Google Maps (2017).

APPENDIX O. SHIP LIFE-CYCLE CONSIDERATIONS

Table 8. Commissioning and Decommissioning Dates of U.S. Navy Ships. Red Implies Scheduled Decommissioning Prior to 2035. Source: Naval Vessel Register (2017).

Name	**Hull**	**Class**		**Commissioning Date**	**Decommissioning Date**
USS Ponce	AFSB(I)-15	*Austin*	Afloat forward staging base	10 July 1971	1 July 2006
USS Pueblo	AGER-2	*Banner*	Technical research ship/ Spy ship	7 April 1945	29 March 1980
USS Emory S. Land	AS-39	*Emory S. Land*	Submarine tender	7 July 1979	28 June 2014
USS Frank Cable	AS-40	*Emory S. Land*	Submarine tender	29 October 1979	20 October 2014
USS Bunker Hill	CG-52	*Ticonderoga*	Cruiser	20 September 1986	11 September 2021
USS Mobile Bay	CG-53	*Ticonderoga*	Cruiser	21 February 1987	12 February 2022
USS Antietam	CG-54	*Ticonderoga*	Cruiser	6 June 1987	28 May 2022
USS Leyte Gulf	CG-55	*Ticonderoga*	Cruiser	26 September 1987	17 September 2022
USS San Jacinto	CG-56	*Ticonderoga*	Cruiser	23 January 1988	14 January 2023
USS Lake Champlain	CG-57	*Ticonderoga*	Cruiser	12 August 1988	4 August 2023
USS Philippine Sea	CG-58	*Ticonderoga*	Cruiser	18 March 1989	9 March 2024
USS Princeton	CG-59	*Ticonderoga*	Cruiser	11 February 1989	3 February 2024
USS Normandy	CG-60	*Ticonderoga*	Cruiser	9 December 1989	30 November 2024
USS Monterey	CG-61	*Ticonderoga*	Cruiser	16 June 1990	7 June 2025

Name	Hull	Class		Commissioning Date	Decommissioning Date
USS Chancellorsville	CG-62	*Ticonderoga*	Cruiser	4 November 1989	26 October 2024
USS Cowpens	CG-63	*Ticonderoga*	Cruiser	9 March 2019	28 February 2054
USS Gettysburg	CG-64	*Ticonderoga*	Cruiser	22 June 2019	13 June 2054
USS Chosin	CG-65	*Ticonderoga*	Cruiser	12 January 2020	3 January 2055
USS Hue City	CG-66	*Ticonderoga*	Cruiser	14 September 1991	5 September 2026
USS Shiloh	CG-67	*Ticonderoga*	Cruiser	18 July 1992	10 July 2027
USS Anzio	CG-68	*Ticonderoga*	Cruiser	2 May 2012	24 April 2047
USS Vicksburg	CG-69	*Ticonderoga*	Cruiser	14 November 1992	6 November 2027
USS Lake Erie	CG-70	*Ticonderoga*	Cruiser	10 May 1993	1 May 2028
USS Cape St. George	CG-71	*Ticonderoga*	Cruiser	12 June 2021	3 June 2056
USS Vella Gulf	CG-72	*Ticonderoga*	Cruiser	18 September 1993	9 September 2028
USS Port Royal	CG-73	*Ticonderoga*	Cruiser	4 July 1994	25 June 2029
Ships	Commissioning Date	Expected Life			
USS Nimitz	CVN-68	*Nimitz*	Aircraft carrier	3 May 1975	20 April 2025
USS Dwight D. Eisenhower	CVN-69	*Nimitz*	Aircraft carrier	18 October 1977	6 October 2027
USS Carl Vinson	CVN-70	*Nimitz*	Aircraft carrier	13 March 1982	29 February 2032
USS Theodore Roosevelt	CVN-71	*Nimitz*	Aircraft carrier	25 October 1986	12 October 2036

Name	Hull	Class		Commissioning Date	Decommissioning Date
USS Abraham Lincoln	CVN-72	*Nimitz*	Aircraft carrier	11 November 1989	30 October 2039
USS George Washington	CVN-73	*Nimitz*	Aircraft carrier	4 July 1992	22 June 2042
USS John C. Stennis	CVN-74	*Nimitz*	Aircraft carrier	9 December 1995	26 November 2045
USS Harry S. Truman	CVN-75	*Nimitz*	Aircraft carrier	25 July 1998	12 July 2048
USS Ronald Reagan	CVN-76	*Nimitz*	Aircraft carrier	12 July 2003	29 June 2053
USS George H.W. Bush	CVN-77	*Nimitz*	Aircraft carrier	10 January 2009	29 December 2058
USS Gerald R. Ford	CVN-78	*Gerald R. Ford*	Aircraft carrier	22 July 2017	10 July 2067
USS Kidd	DDG-100	*Arleigh Burke*	Destroyer	9 June 2007	31 May 2042
USS Zumwalt	DDG-1000	*Zumwalt*	Destroyer	15 October 2016	7 October 2051
USS Gridley	DDG-101	*Arleigh Burke*	Destroyer	10 February 2007	1 February 2042
USS Sampson	DDG-102	*Arleigh Burke*	Destroyer	3 November 2007	25 October 2042
USS Truxtun	DDG-103	*Arleigh Burke*	Destroyer	25 April 2009	16 April 2044
USS Sterett	DDG-104	*Arleigh Burke*	Destroyer	9 August 2008	1 August 2043
USS Dewey	DDG-105	*Arleigh Burke*	Destroyer	6 March 2010	25 February 2045
USS Stockdale	DDG-106	*Arleigh Burke*	Destroyer	18 April 2009	9 April 2044
USS Gravely	DDG-107	*Arleigh Burke*	Destroyer	20 November 2010	11 November 2045
USS Wayne E. Meyer	DDG-108	*Arleigh Burke*	Destroyer	10 October 2009	1 October 2044
USS Jason Dunham	DDG-109	*Arleigh Burke*	Destroyer	13 November 2010	4 November 2045

Name	Hull	Class		Commissioning Date	Decommissioning Date
USS William P. Lawrence	DDG-110	*Arleigh Burke*	Destroyer	19 May 2011	10 May 2046
USS Spruance	DDG-111	*Arleigh Burke*	Destroyer	1 September 2011	23 August 2046
USS Michael Murphy	DDG-112	*Arleigh Burke*	Destroyer	5 September 2012	28 August 2047
USS John Finn	DDG-113	*Arleigh Burke*	Destroyer	15 July 2017	6 July 2052
USS Rafael Peralta	DDG-115	*Arleigh Burke*	Destroyer	29 July 2017	20 July 2052
USS Arleigh Burke	DDG-51	*Arleigh Burke*	Destroyer	4 July 1991	25 June 2026
USS Barry	DDG-52	*Arleigh Burke*	Destroyer	12 December 1992	4 December 2027
USS John Paul Jones	DDG-53	*Arleigh Burke*	Destroyer	18 December 1993	9 December 2028
USS Curtis Wilbur	DDG-54	*Arleigh Burke*	Destroyer	19 March 1994	10 March 2029
USS Stout	DDG-55	*Arleigh Burke*	Destroyer	13 August 1994	4 August 2029
USS John S. McCain	DDG-56	*Arleigh Burke*	Destroyer	2 July 1994	23 June 2029
USS Mitscher	DDG-57	*Arleigh Burke*	Destroyer	10 December 1994	1 December 2029
USS Laboon	DDG-58	*Arleigh Burke*	Destroyer	18 March 1995	9 March 2030
USS Russell	DDG-59	*Arleigh Burke*	Destroyer	20 May 1995	11 May 2030
USS Paul Hamilton	DDG-60	*Arleigh Burke*	Destroyer	27 May 1995	18 May 2030
USS Ramage	DDG-61	*Arleigh Burke*	Destroyer	22 July 1995	13 July 2030
USS Fitzgerald	DDG-62	*Arleigh Burke*	Destroyer	14 October 1995	5 October 2030
USS	DDG-63	*Arleigh*	Destroyer	21 October 1995	12 October 2030

Name	Hull	Class		Commissioning Date	Decommissioning Date
Stethem		*Burke*			
USS Carney	DDG-64	*Arleigh Burke*	Destroyer	13 April 1996	5 April 2031
USS Benfold	DDG-65	*Arleigh Burke*	Destroyer	30 March 1996	22 March 2031
USS Gonzalez	DDG-66	*Arleigh Burke*	Destroyer	12 October 1996	4 October 2031
USS Cole	DDG-67	*Arleigh Burke*	Destroyer	8 June 1996	31 May 2031
USS The Sullivans	DDG-68	*Arleigh Burke*	Destroyer	19 April 1997	10 April 2032
USS Milius	DDG-69	*Arleigh Burke*	Destroyer	23 November 1996	15 November 2031
USS Hopper	DDG-70	*Arleigh Burke*	Destroyer	6 September 1997	28 August 2032
USS Ross	DDG-71	*Arleigh Burke*	Destroyer	28 June 1997	19 June 2032
USS Mahan	DDG-72	*Arleigh Burke*	Destroyer	14 February 1998	5 February 2033
USS Decatur	DDG-73	*Arleigh Burke*	Destroyer	29 August 1998	20 August 2033
USS McFaul	DDG-74	*Arleigh Burke*	Destroyer	25 April 1998	16 April 2033
USS Donald Cook	DDG-75	*Arleigh Burke*	Destroyer	4 December 1998	25 November 2033
USS Higgins	DDG-76	*Arleigh Burke*	Destroyer	24 April 1999	15 April 2034
USS O’Kane	DDG-77	*Arleigh Burke*	Destroyer	23 October 1999	14 October 2034
USS Porter	DDG-78	*Arleigh Burke*	Destroyer	20 March 1999	11 March 2034
USS Oscar Austin	DDG-79	*Arleigh Burke*	Destroyer	19 August 2000	11 August 2035
USS Roosevelt	DDG-80	*Arleigh Burke*	Destroyer	14 October 2000	6 October 2035
USS	DDG-81	*Arleigh*	Destroyer	10 March 2001	1 March 2036

Name	Hull	Class		Commissioning Date	Decommissioning Date
Winston S. Churchill		*Burke*			
USS Lassen	DDG-82	*Arleigh Burke*	Destroyer	21 April 2001	12 April 2036
USS Howard	DDG-83	*Arleigh Burke*	Destroyer	20 October 2001	11 October 2036
USS Bulkeley	DDG-84	*Arleigh Burke*	Destroyer	8 December 2001	29 November 2036
USS McCampbell	DDG-85	*Arleigh Burke*	Destroyer	17 August 2002	8 August 2037
USS Shoup	DDG-86	*Arleigh Burke*	Destroyer	22 June 2002	13 June 2037
USS Mason	DDG-87	*Arleigh Burke*	Destroyer	12 April 2003	3 April 2038
USS Preble	DDG-88	*Arleigh Burke*	Destroyer	9 November 2002	31 October 2037
USS Mustin	DDG-89	*Arleigh Burke*	Destroyer	26 July 2003	17 July 2038
USS Chafee	DDG-90	*Arleigh Burke*	Destroyer	18 October 2003	9 October 2038
USS Pinckney	DDG-91	*Arleigh Burke*	Destroyer	29 May 2004	21 May 2039
USS Momsen	DDG-92	*Arleigh Burke*	Destroyer	28 August 2004	20 August 2039
USS Chung-Hoon	DDG-93	*Arleigh Burke*	Destroyer	18 September 2004	10 September 2039
USS Nitze	DDG-94	*Arleigh Burke*	Destroyer	5 March 2005	25 February 2040
USS James E. Williams	DDG-95	*Arleigh Burke*	Destroyer	11 December 2004	3 December 2039
USS Bainbridge	DDG-96	*Arleigh Burke*	Destroyer	12 November 2005	3 November 2040
USS Halsey	DDG-97	*Arleigh Burke*	Destroyer	30 July 2005	21 July 2040
USS Forrest Sherman	DDG-98	*Arleigh Burke*	Destroyer	28 January 2006	19 January 2041

Name	Hull	Class		Commissioning Date	Decommissioning Date
USS Farragut	DDG-99	*Arleigh Burke*	Destroyer	10 June 2006	1 June 2041
USS Lewis B. Puller	ESB-3	*Montford Point*	Expeditionary mobile base	17 August 2017	7 August 2057
USS Blue Ridge	LCC-19	*Blue Ridge*	Amphibious command ship	14 November 1970	28 October 2039
USS Mount Whitney	LCC-20	*Blue Ridge*	Amphibious command ship	16 January 1971	30 December 2039
USS Freedom	LCS-1	*Freedom*	Littoral combat ship	8 November 2008	29 October 2048
USS Gabrielle Giffords	LCS-10	*Independence*	Littoral combat ship	10 June 2017	31 May 2057
USS Independence	LCS-2	*Independence*	Littoral combat ship	16 January 2010	6 January 2050
USS Fort Worth	LCS-3	*Freedom*	Littoral combat ship	6 August 2012	27 July 2052
USS Coronado	LCS-4	*Independence*	Littoral combat ship	27 January 2014	17 January 2054
USS Milwaukee	LCS-5	*Freedom*	Littoral combat ship	21 November 2015	11 November 2055
USS Jackson	LCS-6	*Independence*	Littoral combat ship	5 December 2015	25 November 2055
USS Detroit	LCS-7	*Freedom*	Littoral combat ship	22 October 2016	12 October 2056
USS Montgomery	LCS-8	*Independence*	Littoral combat ship	10 September 2016	31 August 2056
USS America	LHA-6	*America*	Amphibious assault ship	11 October 2014	1 October 2054
USS Wasp	LHD-1	*Wasp*	Amphibious assault ship	6 July 1989	26 June 2029
USS Essex	LHD-2	*Wasp*	Amphibious assault ship	24 August 1992	14 August 2032
USS Kearsarge	LHD-3	*Wasp*	Amphibious assault ship	16 October 1993	6 October 2033
USS Boxer	LHD-4	*Wasp*	Amphibious	11 February 1995	1 February 2035

Name	Hull	Class		Commissioning Date	Decommissioning Date
			assault ship		
USS Bataan	LHD-5	*Wasp*	Amphibious assault ship	20 September 1997	10 September 2037
USS Bonhomme Richard	LHD-6	*Wasp*	Amphibious assault ship	15 August 1998	5 August 2038
USS Iwo Jima	LHD-7	*Wasp*	Amphibious assault ship	30 June 2001	20 June 2041
USS Makin Island	LHD-8	*Wasp*	Amphibious assault ship	24 October 2009	14 October 2049
USS San Antonio	LPD-17	*San Antonio*	Amphibious transport dock	14 January 2006	4 January 2046
USS New Orleans	LPD-18	*San Antonio*	Amphibious transport dock	5 March 2007	23 February 2047
USS Mesa Verde	LPD-19	*San Antonio*	Amphibious transport dock	15 December 2007	5 December 2047
USS Green Bay	LPD-20	*San Antonio*	Amphibious transport dock	24 January 2006	14 January 2046
USS New York	LPD-21	*San Antonio*	Amphibious transport dock	7 November 2009	28 October 2049
USS San Diego	LPD-22	*San Antonio*	Amphibious transport dock	19 May 2012	9 May 2052
USS Anchorage	LPD-23	*San Antonio*	Amphibious transport dock	4 May 2013	24 April 2053
USS Arlington	LPD-24	*San Antonio*	Amphibious transport dock	6 April 2013	27 March 2053
USS Somerset	LPD-25	*San Antonio*	Amphibious transport dock	1 March 2014	19 February 2054
USS John P. Murtha	LPD-26	*San Antonio*	Amphibious transport dock	8 October 2016	28 September 2056
USS Whidbey Island	LSD-41	*Whidbey Island*	Dock landing ship	9 February 1985	27 January 2039
USS Germantown	LSD-42	*Whidbey Island*	Dock landing ship	8 February 1986	26 January 2039
USS Fort McHenry	LSD-43	*Whidbey Island*	Dock landing ship	8 August 1987	26 July 2039

Name	Hull	Class		Commissioning Date	Decommissioning Date
USS Gunston Hall	LSD-44	*Whidbey Island*	Dock landing ship	22 April 1989	10 April 2039
USS Comstock	LSD-45	*Whidbey Island*	Dock landing ship	3 February 1990	22 January 2039
USS Tortuga	LSD-46	*Whidbey Island*	Dock landing ship	17 November 1990	5 November 2039
USS Rushmore	LSD-47	*Whidbey Island*	Dock landing ship	1 June 1991	20 May 2039
USS Ashland	LSD-48	*Whidbey Island*	Dock landing ship	9 May 1992	28 April 2039
USS Harpers Ferry	LSD-49	*Harpers Ferry*	Dock landing ship	7 January 1995	27 December 2039
USS Carter Hall	LSD-50	*Harpers Ferry*	Dock landing ship	30 September 1995	19 September 2039
USS Oak Hill	LSD-51	*Harpers Ferry*	Dock landing ship	8 June 1996	29 May 2039
USS Pearl Harbor	LSD-52	*Harpers Ferry*	Dock landing ship	27 April 1998	17 April 2039
USS Warrior	MCM-10	*Avenger*	Mine countermeasures ship	7 April 1993	31 March 2023
USS Gladiator	MCM-11	*Avenger*	Mine countermeasures ship	18 September 1993	11 September 2023
USS Ardent	MCM-12	*Avenger*	Mine countermeasures ship	18 February 1994	11 February 2024
USS Dextrous	MCM-13	*Avenger*	Mine countermeasures ship	9 July 1994	1 July 2024
USS Chief	MCM-14	*Avenger*	Mine countermeasures ship	5 November 1994	28 October 2024
USS Sentry	MCM-3	*Avenger*	Mine countermeasures ship	2 September 1989	26 August 2019

Name	Hull	Class		Commissioning Date	Decommissioning Date
USS Champion	MCM-4	*Avenger*	Mine countermeasures ship	8 February 1991	31 January 2021
USS Devastator	MCM-6	*Avenger*	Mine countermeasures ship	6 October 1990	28 September 2020
USS Patriot	MCM-7	*Avenger*	Mine countermeasures ship	18 October 1991	10 October 2021
USS Scout	MCM-8	*Avenger*	Mine countermeasures ship	15 December 1990	7 December 2020
USS Pioneer	MCM-9	*Avenger*	Mine countermeasures ship	7 December 1992	30 November 2022
USS Constitution	None	Original six frigates	Classic frigate	1 October 1797	28 September 1812
USS Firebolt	PC-10	*Cyclone*	Patrol boat	10 June 1995	6 June 2010
USS Whirlwind	PC-11	*Cyclone*	Patrol boat	1 July 1995	27 June 2010
USS Thunderbolt	PC-12	*Cyclone*	Patrol boat	7 October 1995	3 October 2010
USS Shamal	PC-13	*Cyclone*	Patrol boat	27 January 1996	23 January 2011
USS Tornado	PC-14	*Cyclone*	Patrol boat	24 June 2000	21 June 2015
USS Tempest	PC-2	*Cyclone*	Patrol boat	21 August 1993	17 August 2008
USS Hurricane	PC-3	*Cyclone*	Patrol boat	15 October 1993	11 October 2008
USS Monsoon	PC-4	*Cyclone*	Patrol boat	22 January 1994	18 January 2009
USS Typhoon	PC-5	*Cyclone*	Patrol boat	12 February 1994	8 February 2009
USS Sirocco	PC-6	*Cyclone*	Patrol boat	11 June 1994	7 June 2009
USS Squall	PC-7	*Cyclone*	Patrol boat	4 July 1994	30 June 2009

Name	Hull	Class		Commissioning Date	Decommissioning Date
USS Zephyr	PC-8	*Cyclone*	Patrol boat	15 October 1994	11 October 2009
USS Chinook	PC-9	*Cyclone*	Patrol boat	28 January 1995	24 January 2010
USS Henry M. Jackson	SSBN-730	*Ohio*	Ballistic missile submarine	6 October 1984	26 September 2026
USS Alabama	SSBN-731	*Ohio*	Ballistic missile submarine	25 May 1985	15 May 2027
USS Alaska	SSBN-732	*Ohio*	Ballistic missile submarine	25 January 1986	15 January 2028
USS Nevada	SSBN-733	*Ohio*	Ballistic missile submarine	16 August 1986	5 August 2028
USS Tennessee	SSBN-734	*Ohio*	Ballistic missile submarine	17 December 1988	7 December 2030
USS Pennsylvania	SSBN-735	*Ohio*	Ballistic missile submarine	9 September 1989	30 August 2031
USS West Virginia	SSBN-736	*Ohio*	Ballistic missile submarine	20 October 1990	9 October 2032
USS Kentucky	SSBN-737	*Ohio*	Ballistic missile submarine	13 July 1991	2 July 2033
USS Maryland	SSBN-738	*Ohio*	Ballistic missile submarine	13 June 1992	3 June 2034
USS Nebraska	SSBN-739	*Ohio*	Ballistic missile submarine	10 July 1993	30 June 2035
USS Rhode Island	SSBN-740	*Ohio*	Ballistic missile submarine	9 July 1994	28 June 2036
USS Maine	SSBN-741	*Ohio*	Ballistic missile	29 July 1995	18 July 2037

Name	Hull	Class		Commissioning Date	Decommissioning Date
			submarine		
USS Wyoming	SSBN-742	*Ohio*	Ballistic missile submarine	13 July 1996	3 July 2038
USS Louisiana	SSBN-743	*Ohio*	Ballistic missile submarine	6 September 1997	27 August 2039
USS Ohio	SSGN-726	*Ohio*	Guided missile submarine	11 November 1981	1 November 2023
USS Michigan	SSGN-727	*Ohio*	Guided missile submarine	11 September 1982	31 August 2024
USS Florida	SSGN-728	*Ohio*	Guided missile submarine	18 June 1983	7 June 2025
USS Georgia	SSGN-729	*Ohio*	Guided missile submarine	11 February 1984	31 January 2026
USS Seawolf	SSN-21	*Seawolf*	Attack submarine	19 July 1997	11 July 2030
USS Connecticut	SSN-22	*Seawolf*	Attack submarine	11 December 1998	3 December 2031
USS Jimmy Carter	SSN-23	*Seawolf*	Attack submarine	19 February 2005	11 February 2038
USS Bremerton	SSN-698	*Los Angeles*	Attack submarine	28 March 1981	20 March 2014
USS Jacksonville	SSN-699	*Los Angeles*	Attack submarine	16 May 1981	8 May 2014
USS Olympia	SSN-717	*Los Angeles*	Attack submarine	17 November 1984	9 November 2017
USS Providence	SSN-719	*Los Angeles*	Attack submarine	27 July 1985	19 July 2018
USS Pittsburgh	SSN-720	*Los Angeles*	Attack submarine	23 November 1985	15 November 2018
USS Chicago	SSN-721	*Los Angeles*	Attack submarine	27 September 1986	19 September 2019
USS Key West	SSN-722	*Los Angeles*	Attack submarine	12 September 1987	3 September 2020
USS Oklahoma	SSN-723	*Los Angeles*	Attack submarine	9 July 1988	1 July 2021

Name	**Hull**	**Class**		**Commissioning Date**	**Decommissioning Date**
City					
USS Louisville	SSN-724	*Los Angeles*	Attack submarine	8 November 1986	31 October 2019
USS Helena	SSN-725	*Los Angeles*	Attack submarine	11 July 1987	2 July 2020
USS Newport News	SSN-750	*Los Angeles*	Attack submarine	3 June 1989	26 May 2022
USS San Juan	SSN-751	*Los Angeles*	Attack submarine	6 August 1988	29 July 2021
USS Pasadena	SSN-752	*Los Angeles*	Attack submarine	11 February 1989	3 February 2022
USS Albany	SSN-753	*Los Angeles*	Attack submarine	7 April 1990	30 March 2023
USS Topeka	SSN-754	*Los Angeles*	Attack submarine	21 October 1989	13 October 2022
USS Scranton	SSN-756	*Los Angeles*	Attack submarine	26 January 1991	18 January 2024
USS Alexandria	SSN-757	*Los Angeles*	Attack submarine	29 June 1991	20 June 2024
USS Asheville	SSN-758	*Los Angeles*	Attack submarine	28 September 1991	19 September 2024
USS Jefferson City	SSN-759	*Los Angeles*	Attack submarine	29 February 1992	20 February 2025
USS Annapolis	SSN-760	*Los Angeles*	Attack submarine	11 April 1992	3 April 2025
USS Springfield	SSN-761	*Los Angeles*	Attack submarine	9 January 1993	1 January 2026
USS Columbus	SSN-762	*Los Angeles*	Attack submarine	24 July 1993	16 July 2026
USS Santa Fe	SSN-763	*Los Angeles*	Attack submarine	8 January 1994	31 December 2026
USS Boise	SSN-764	*Los Angeles*	Attack submarine	7 November 1992	30 October 2025
USS Montpelier	SSN-765	*Los Angeles*	Attack submarine	13 March 1993	5 March 2026

Name	Hull	Class		Commissioning Date	Decommissioning Date
USS Charlotte	SSN-766	*Los Angeles*	Attack submarine	16 September 1994	8 September 2027
USS Hampton	SSN-767	*Los Angeles*	Attack submarine	6 November 1993	29 October 2026
USS Hartford	SSN-768	*Los Angeles*	Attack submarine	10 December 1994	2 December 2027
USS Toledo	SSN-769	*Los Angeles*	Attack submarine	24 February 1995	16 February 2028
USS Tucson	SSN-770	*Los Angeles*	Attack submarine	18 August 1995	9 August 2028
USS Columbia	SSN-771	*Los Angeles*	Attack submarine	9 October 1995	30 September 2028
USS Greeneville	SSN-772	*Los Angeles*	Attack submarine	16 February 1996	7 February 2029
USS Cheyenne	SSN-773	*Los Angeles*	Attack submarine	13 September 1996	5 September 2029
USS Virginia	SSN-774	*Virginia*	Attack submarine	23 October 2004	15 October 2037
USS Texas	SSN-775	*Virginia*	Attack submarine	9 September 2006	1 September 2039
USS Hawaii	SSN-776	*Virginia*	Attack submarine	5 May 2007	26 April 2040
USS North Carolina	SSN-777	*Virginia*	Attack submarine	3 May 2008	25 April 2041
USS New Hampshire	SSN-778	*Virginia*	Attack submarine	25 October 2008	17 October 2041
USS New Mexico	SSN-779	*Virginia*	Attack submarine	27 March 2010	19 March 2043
USS Missouri	SSN-780	*Virginia*	Attack submarine	31 July 2010	23 July 2043
USS California	SSN-781	*Virginia*	Attack submarine	29 October 2011	20 October 2044
USS Mississippi	SSN-782	*Virginia*	Attack submarine	2 June 2012	25 May 2045
USS Minnesota	SSN-783	*Virginia*	Attack submarine	7 September 2013	30 August 2046

Name	Hull	Class		Commissioning Date	Decommissioning Date
USS North Dakota	SSN-784	*Virginia*	Attack submarine	25 October 2014	17 October 2047
USS John Warner	SSN-785	*Virginia*	Attack submarine	1 August 2015	23 July 2048
USS Illinois	SSN-786	*Virginia*	Attack submarine	29 October 2016	21 October 2049

Table 9. U.S. Navy Ships Under Construction or Planned. Source: Naval Vessel Register (2017).

Vermont (SSN 792)	(SSN 792)	Construction began May 2014
Oregon	(SSN 793)	Construction began September 2014
Montana	(SSN 794)	Construction began April 2015
Hyman G. Rickover	(SSN 795)	Construction began September 2015
New Jersey	(SSN 796)	Construction began March 2016
Iowa	(SSN 797)	Construction began September 2016
Massachusetts	(SSN 798)	Construction began March 2017
Idaho	(SSN 799)	Under contract
Arkansas	(SSN 800)	Under contract
Utah	(SSN 801)	Under contract
PCU Ralph Johnson	(DDG 114),	Under construction
PCU Thomas Hudner	(DDG 116)	Under construction
PCU Paul Ignatius	(DDG 117)	Under construction
PCU Daniel Inouye	(DDG 118)	Under construction
PCU Delbert D. Black	(DDG 119)	Under construction
PCU Carl M. Levin	(DDG 120)	Under construction
PCU Frank E. Petersen, Jr.	(DDG 121)	Under construction
John Basilone	(DDG 122)	Pre-construction
Lenah H. Sutcliffe Higbee	(DDG 123)	Pre-construction
Harvey C. Barnum, Jr.	(DDG 124)	Pre-construction

PCU Michael Monsoor	(DDG 1001)	Under construction
PCU Lyndon B. Johnson	(DDG 1002)	Under construction

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