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MISSION ENGINEERING FOR HYBRID FORCE 2025

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Monterey, CA; Naval Postgraduate School

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

SYSTEMS ENGINEERING ANALYSIS CAPSTONE REPORT

MISSION ENGINEERING FOR HYBRID FORCE 2025

by

Jeremy J. Brown, Nicholas C. Coker, Alyson C. Groff,
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June 2022

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ABSTRACT

This report focuses on the mission engineering process for a hybrid force in 2025. Updated tasking from OPNAV N9I emphasized the necessity of focusing on the benefits of using cost-conservative unmanned systems. Specifically, the focus was placed on the near-peer competitor China and the problems that could be expected in an anti-access/area denial (A2/AD) situation in the South China Sea. The Naval Surface Warfare Center mission engineering approach was used to identify specific vignettes for proposed alternative fleet architectures and then analyzed using combat simulation and optimization models. Research on performance characteristics and cost were compiled on current unmanned systems, specifically those in development at a high technology readiness level. Proposed unmanned systems architectures were developed as solutions to the A2/AD problem and proposed vignettes. The unmanned systems architectures were then run through an optimization model to maximize system performance while minimizing cost. The results of the architecture optimization were then input into modeling and simulation. The overall effectiveness of each architecture in each vignette were then compared to find the most effective solution. An analysis of the results was performed to show the expected mission effectiveness and proposed cost of utilizing the proposed solution unmanned architectures. The most effective architectures included search, counter swarm, delivery, and attack systems.

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LIST OF ACRONYMS AND ABBREVIATIONS

A2/AD	anti-access area denial
ABMS	agent-based modeling and simulation
AI	artificial intelligence
AIS	automatic identification system
ASCM	anti-ship cruise missile
ASUW	anti-surface warfare
C2	command and control
C4I	command, control, communications, computers, and intelligence
C5I	command, control, communications, computers, cyber, and intelligence
C5ISRT	C5I, surveillance, reconnaissance, and targeting
CEC	cooperative engagement capability
CIV	civilian
CIWS	close-in weapon system
CMO	Command Modern Operations
CNO	Chief of Naval Operations
CONOPS	concept of operations
COTS	commercial off the shelf
CRS	Congressional Research Service
CRUSER	Consortium for Robotics and Unmanned Systems Education and Research
CSG	carrier strike group
C-SWARM	counter-swarm
DDG	guided-missile destroyer
DMO	distributed maritime operations
DON	Department of the Navy
EABO	expeditionary advanced base operations
EE	electrical engineering
EM	electro-magnetic
EO/IR	electro-optical / infrared

EOD	explosive ordnance disposal
ES	electronic signature
ESSM	Evolved Seasparrow Missile
FONOPS	freedom of navigation operations
FY	fiscal year
GDP	gross domestic product
GNSS	Global Navigation Satellite Systems
GPS	global positioning system
HAPS	high-altitude platform-station
HAW	home-all-the-way
HE	high explosive
IAI	Israel Aerospace Industries
IAMD	integrated air and missile defense
INS	inertial navigation system
IS	Israel
ISR	intelligence surveillance and reconnaissance
LD	large diameter
LM	loitering munitions
LOCE	littoral operations in a contested environment
LPD	landing platform dock
MDUSV	medium displacement unmanned surface vessel
ME	mechanical engineering
ME	mission engineering
ML	machine learning
MOE	measure of effectiveness
MOP	measure of performance
MOS	measure of success
MOVES	modeling virtual environments and simulation
MST	maritime strike tomahawk
MUM-T	manned-unmanned teaming

NOA	naval operational architecture
NPS	Naval Postgraduate School
NSWC	Naval Surface Warfare Center
NUS	National University of Singapore
NWP	naval warfare publication
NWSI	Naval Warfare Studies Institute
OA	operations analysis
PK	probability of kill
PLAN	People's Liberation Army Navy
PRC	People's Republic of China
RPA	robotic process automation
SAG	surface action group
SAM	surface to air missile
SE	system engineering
SEA	systems engineering analysis
SEAD	suppression of enemy air defenses
SM	standard missile
SN	Singapore
SoS	system of systems
SSO	space systems operation
TDSI	Temasek Defense System Institute
TRL	technological readiness level
TVM	track-via-missile
UAS	unmanned aerial system
UAV	unmanned aerial vehicle
UGV	unmanned ground vehicles
UNCLOS	United Nations Convention on the Law of the Sea
US	United States
USA	United States of America
USMC	United States Marine Corps

USN	United States Navy
USV	unmanned surface vessel
UUV	unmanned undersea vessel
UXS	unmanned systems
VTOL	vertical take-off and landing
WAS	wide area search
WBS	work breakdown structure
WIC	Warfare Innovation Continuum

EXECUTIVE SUMMARY

A. INTRODUCTION

The Systems Engineering Analysis 31 cohort was tasked by Chief of Naval Operations Warfare Integration Division (OPNAV N9I) with identifying a solution to close an expected capability gap with the PRC in the year 2025 (Boensel 2021). The solution system must be cost efficient and capable of delivery by the year 2025. The SEA cohort utilized the mission engineering process to identify candidate future fleet architectures to solve the problem (Office of the Deputy Director for Engineering 2020).

B. PROBLEM STATEMENT

How might we counter the anti-access and area denial capabilities of near peer adversaries cost effectively by the year 2025?

C. CAPABILITIES NEED

Cost effectively adapt current capabilities and create a future architecture to enhance USN warfighting capabilities including presence, deception, ISR, and defensive and offensive capabilities in anti-access and area denied environments.

D. MISSION CHARACTERIZATION

Using the mission engineering process, the overall scenario for the generation of vignettes was set in the South China Sea in the year 2025. The PRC has executed its territorial claims of the nine-dash line and created an anti-access/area denial (A2/AD) zone. The PRCs expanding fleet, use of man-made islands, long range ASCMs, and the expanding use of unmanned systems place U.S. surface combatants at high risk. The overall mission is for a USN DDG to successfully conduct FONOPS within the A2/AD zone by increasing its lethality and survivability. Inside the overall scenario three vignettes were developed: OTH ISR, targeting, and engagement, threat unmanned aerial vehicle swarm, and threat UAV ISR asset providing targeting.

E. MISSION METRICS

The overall measure of mission success is the capability of USN forces operating in a near peer anti-access area denial environment. The measures of effectiveness that contribute to the measure of success are the level of increased survivability and lethality of the DDG in conjunction with the cost of the solution system.

F. DESIGN OF ANALYSIS

To analyze if the proposed solution system of systems (SoS) would achieve the stated measure of success, a value system was designed. Utilizing the Universal Naval Task list, the project team identified three tier-two tasks that the proposed solution system of systems would be required to complete to accomplish the mission (Department of the Navy 2008).

Evaluation of subsequent tasks under the three selected tasks was conducted to identify specific functions the proposed system would be required to complete. From this review four high level functions the candidate unmanned system would need to accomplish were identified. These functions are delivery, search, communication relay, and strike. For each of the functions measures of performance were selected to be used in Multi-attribute Value Analysis.

Multi-attribute Value Analysis was used to compare candidate systems that accomplish one or more of the four functions. The value of a system was derived by assigning a weight to each of the measures of performance based on that MOP's importance to accomplishing a specific function. Weights ranged from 1 to 5, with 5 indicating the most important MOP. The product of the MOP and weight was calculated, and each of the products were summed to attain the value of the system.

To identify feasible candidate systems, members of the project team each researched a different unmanned system and collected measures of performance for each candidate system. If the value for a specific unmanned system's MOP was not known, the value was inferred to be the same as an analogous system. If no such analogous system existed, the value was estimated using heuristics. For each of the functions, at least one system was identified that met the technological maturity to be considered for the hybrid force of 2025.

1. Proposed System of Systems

To accomplish all four functions, the combinations of candidate systems were permutated to create sixteen systems of systems. The system of systems value and cost was calculated for each of the alternatives. The system value was calculated by summing the value of each of the systems in each alternative.

2. Optimization

To generate alternatives for comparison the team generated architectures using an integer linear program. This was accomplished using Python's Pyomo optimization function. The linear program was created, constrained to better represent reality, and solved to generate alternative architectures optimized for performance, budget, and alternative contracting options, respectively.

3. Calculation of MOE using Salvo Combat Model

Modern missile warfare can be evaluated using the salvo combat model. This model was used to calculate the effectiveness of each of the SoS alternatives in each of the vignettes. The results demonstrate the importance of an over-the-horizon ISR platform, an independent weapons system to engage enemy UAV, the limited defensive power of current IAMD combat systems, and over-the-horizon search and targeting capability.

4. Spreadsheet Combat Simulation

Both the PRC and U.S. possess in depth integrated air and missile defense. To demonstrate this interaction, the different engagements were modeled in Microsoft Excel using an inverse binomial function. Each of the proposed fleet architectures was entered into a combat simulation for each of the three vignettes. To attain stochastic results the number of trials was set to 300 and each probability was given a range of possible values. The independent variables in the model can be categorized as either defensive or offensive variables. The defensive variables are the number of kills and probability of kill of integrated air and missile defense weapons on each unit. The offensive variables for the

PLAN are the number of hits by the YJ-18 ASCM and Harpy UAVs. The offensive variables for the USN are the number of offensive hits by the Maritime Strike Tomahawk, ASCM, and purposed strike UAVs.

The results of the simulations indicates the number of hits either on the enemy surface platform or on the USN surface unit. By comparing the number of hits with the proposed system to the baseline, a percentage of change was attained. The effectiveness of both offense and defense were weighted equally for our analysis allowing the high values for offensive and defensive percentage change to be summed to calculate a total percentage of change high and low.

5. Model Validation using Agent-Based Modeling and Simulations

Agent-based modeling and simulation (ABMS) was utilized to validate each of the envisaged system architectures against the desired MOE. ABMS aims to capture the stochastic, yet complex, nature of warfare engagement by modeling the interactions between agents. Monte-Carlo analysis was conducted to gather individual-level data on the performance of each system. Subsequent statistical analysis provided an avenue to ascertain and quantify the improvement each proposed system architecture achieves. To that end, Command: Modern Operations (CMO), a cross-domain modern wargaming computer software that aims to simulate tactical to operational level operations, was utilized as the simulation engine. CMO simulates rules-based agents that interreact with each other and the environment, comprising of weapon systems (Coyote, YJ-18, Chaff) and platforms (e.g. PLAN DDG, Luyang) in the scenario of interest. As compared to multi-attribute value analysis approach, CMO allows for quantitative system MOPs to be modelled, and their relative differences to be observable in simulation outcomes.

G. SPREADSHEET COMBAT SIMULATION RESULTS

The first results from the spreadsheet combat model simulated were the number of hits on the USN DDG by the PLAN DDG over three different iterations, attacking with only YJ-18, attacking only with Harpy, and a simultaneous YJ-18 and Harpy attack. The simultaneous YJ-18 and Harpy number of hits was used as the baseline value in the defensive MOE. Next, the two different defensive UAV systems were separately added to the combat model. The simulation was repeated for a Harpy only attack and simultaneous YJ-18 and Harpy attack. The defensive percentage change for each system was calculated using the previously described equation.

The next results were the number of hits on the PLAN DDG by the USN DDG over three different iterations. The results for attacking with only MST, attacking only with the ASUW UAV, and a simultaneous MST and ASUW attack were simulated. The MST only attack number of hits was used as the baseline value in the offensive MOE. Next, the seven different delivery systems were separately added to the combat model. The simulation was repeated for an ASUW UAV only attack and simultaneous MST and ASUW UAV attack. The offensive percentage change for each delivery system was calculated.

The equally weighted offensive and defensive percentage change are summed to calculate a total percentage of change both high and low. Based on the model, the expectation is such that with 0.95 confidence the addition of the SoS will increase the effectiveness of the surface unit by a percentage between the high and low value.

H. AGENT-BASED MODELING AND SIMULATION RESULTS

Broadly, it was concluded that the performance observed from the ABMS correlates with the performance MOE observed from the spreadsheet model. Significant improvement for both defensive and offensive MOEs was observed across all proposed architectures. This was expected, since the addition of any defensive weapon system on the DDG should reduce the number of direct hits on the fleet's DDG. Similarly, adding an offensive weapon system with enhanced OTH sense capability increases the number of weapons for direct action on the target.

Further analysis of the ratio of defensive and offensive MOE against the average number of weapons expended by each side showcased the improvement in the defensive MOE due to the additional counter-swarm weapon systems on the USN DDG. This addition was proven to be an effective broad-based improvement across all architectures. The most significant differences between the three proposed architectures arises from offensive MOE (%), where the performance system outperforms the other architectures.

Compared to the total number of weapons fired, it is expected that a better performing system would fire fewer weapons at the target while dealing more hits.

I. CONCLUSIONS

This work proves the danger presented to legacy surface warships by low-cost unmanned threat systems that can coordinate and attack with little warning and providing crews with little time to react. To avoid a mandatory increase in standoff range to increase survivability, extended range sensor systems and counter-UAS systems are necessary to close the expected capability gaps and provide access to denied areas. For these systems to be feasible and secure, high-bandwidth communication systems will be a required.

To address these needs, the recommended solution system utilizes the Dive-LD for delivery of the Coyote UAV platforms. Search and communication relay will be provided by two VBAT UAV platforms. This combination of platforms provides the highest increase of offensive and defensive capability per dollar of system cost. The Coyote UAV will also be used as a swarm to defend against threat UAV swarms and threat UAV ISR assets. Increasing the acquisition of solution systems will increase the survivability and lethality of the fleet and allow for additional investment in other fleet priority areas.

It is recommended that the system be improved by equipping the UAV platforms with additional passive sensors to exploit all parts of the electromagnetic spectrum enabling increased ability to detect adversary threats in all weather and combat conditions. Furthermore, the proposed solution system can be expanded to operate in many other domains and mission areas such as port defense and opposed egress.

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I. INTRODUCTION

The increasing capability of the People's Republic of China (PRC) surface fleet combined with advances in long range anti-ship cruise missiles (ASCM), militarized man-made islands, and the increased use of unmanned military systems places United States (US) surface combatants at risk while operating in and around the South China Sea. To date, the U.S. has been able to maintain the freedom of navigation throughout the world's oceans. The PRC's territorial claims of the nine-dash line and extensive development of militarized man-made islands hint at China's ambitions to execute territorial control of the South China Sea. These territorial claims combined with the People's Liberation Army Navy's (PLAN) increasing size and capability make anti-access area denial (A2/AD) situations within the South China Sea and possibly out to the first island chain more probable should a conflict erupt between the U.S. and the PRC (Biddle and Oelrich 2016). This places the U.S. Navy carrier strike group (CSG) at high risk when operating inside of the second island chain.

The PRC's military capability and spending continue to increase while the U.S. military budget continues to decline with respect to percent of gross domestic product (GDP). If this trend continues the PRC's military capability will soon exceed that of the United States. This capability gap must be addressed as soon as possible to prevent it from widening and to realign the U.S. military's effort and budget to provide a more capable fleet. Current U.S. industrial capability is weaker when compared with the Chinese. Thus, the U.S. will not be able to match Chinese production ship for ship. The U.S. must find a way to increase its military capability within its budget to prevent the PRC from being able to execute its territorial claims and counter an A2/AD scenario within the South China Sea. The Chief of Naval Operations (CNO) NAVPLAN 2021 and the Department of the Navy (DON) Unmanned Campaign Framework 2021 provide broad guidance on how to close the capability gap with the PRC.

The Systems Engineering Analysis 31 cohort was tasked by Chief of Naval Operations Warfare Integration Division (OPNAV N9I) with identifying a solution to close the capability gap with the PRC in the year 2045. Specifically, the tasking was to consider

"Mission Engineering for Hybrid Force 2045" (Boensel 2021). Following a site visit from the Deputy Director (N9IB) in November 2021, the team's tasking was updated to focus on a closer timeframe, the year 2025. The purpose of the SEA 31 research project is to determine the composition and efficacy of specific fleet architectures that would satisfactorily close the expected capability gap quickly and economically. The SEA 31 cohort proposes that small scale autonomous unmanned systems that are at a high technological readiness level (TRL) can be rapidly integrated into a surface action group (SAG) to provide a robust increase in defensive and offensive capabilities. These autonomous unmanned systems will economically increase the kinetic reach of SAGs, provide over-the-horizon targeting solutions for other weapons systems, and provide defense against unmanned threat swarms.

A. PROJECT BACKGROUND

The Systems Engineering Analysis program at Naval Postgraduate School in Monterey culminates in a team capstone project. The team receives funding and tasking from Chief of Naval Operations Warfare Integration Division that aims to increase the combat capability of the United States Navy. Project participants include active-duty officers from the United States Navy as well as officers from the National University of Singapore (NUS) Temasek Defense Systems Institute (TDSI). The cohort's diversity helped it approach the tasking statement from a wide variety of viewpoints. The cohort utilized a systems engineering process that was fused together with the mission engineering process. Problem definition was one of the most difficult and complex issues at the beginning of the project. With such a wide scope of areas to investigate in terms of naval warfare mission sets, it is hard to define which mission area is the most critical or will have the most benefit from the research project. The SEA team used the tasking statement along with the results of the Warfare Innovation Continuum and guidance from documents identified in the project tasking statement to help define the problem statement.

1. Warfare Innovation Continuum

Each year the Naval Postgraduate School hosts a Warfare Innovation Workshop that is a small piece to an overarching program called the Warfare Innovation Continuum

(Englehorn 2021). The Warfare Innovation Workshop invites military personnel, NPS faculty, and civilian members of industry and academia to participate in a week-long conference. The theme of the FY21-FY-22 WIC as stated in the WIC after action report is "Hybrid Force 2045." The workshop attendees were tasked with finding new and innovative solutions using developing technology to conduct future warfare in a fictional scenario set in the year 2045. The results of the Warfare Innovation Workshop are inputs to the SEA 31 capstone project. The Warfare Integration Workshop and SEA 31 capstone project are just a couple of pieces in the overall WIC structure as depicted in Figure 1.

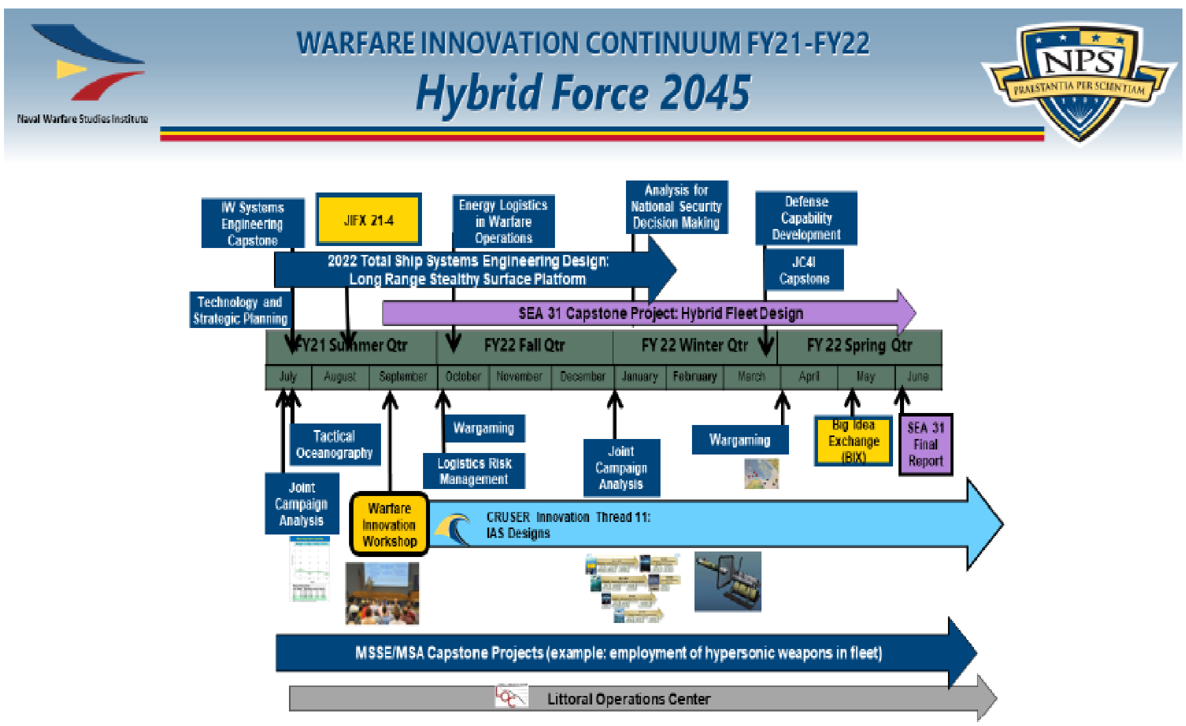

Figure 1. WIC and SEA31 Integration. Source: Englehorn (2021).

The workshop leads identified four emergent concepts during the Warfare Innovation Workshop with the first listed being most relevant to the SEA 31 capstone project. Many of the other proposed concepts were determined to not be at a sufficient TRL to be attainable by the year 2025 and thus not relevant to the SEA 31 area of study. These relevant concepts listed in the WIC 2021 After Action Report are:

- Future fleet design – a future fleet of “forward” high risk offensive and primarily unmanned systems with a more traditional sea control and defense force currently found in carrier strike group capabilities
- Human-in-the-loop machine learning – using human decision-making to wargame multiple tactical situations to farm a data base for supervised machine learning.
- Leveraging the undersea environment – across the spectrum of competition and warfare by creating sea floor infrastructure and capability.
- Autonomy in sustainment – sustainment, repair, and replacement through unmanned system platforms with additive manufacturing capability (Englehorn 2021).

2. Tasking Statement

Tasking for the SEA 31 capstone project was dependent on the results from the FY21 WIC workshop. The tasking summary for the FY21 WIC workshop taken from the WIC 2021 After Action Report and is as follows:

> This Naval Warfare Studies Institute (NWSI) and the Consortium for Robotics and Unmanned Systems Education and Research (CRUSER), sponsored Warfare Innovation Continuum (WIC) workshop was held 20–23 September 2021 concurrently on both the Monterey campus and the ‘Virtual Campus’ of the Naval Postgraduate School (NPS). The three-and-a-half-day experience facilitated focused interaction for NPS students with faculty from across the NPS campus, fleet officers, and guest engineers from Navy labs, warfare centers, system commands and industry.
>
> The September 2021 workshop ‘Hybrid Force 2045’ tasked participants to apply emerging technologies to shape the way we fight in a 2045 global conflict depicted in the fictional scenario ‘Hybrid War 2045.’ Concept generation teams were given the design challenge: How might emerging technologies, new operational concepts, and alternative fleet designs contribute to a more effective naval force across the spectrum from competition to conflict? How do the alternative fleet designs enhance the effectiveness and resilience of joint, combined and coalition forces across all domains? Following panel discussions and presentations from leading technical and policy experts, the teams and their embedded facilitators had fourteen hours of scheduled concept generation time to meet that challenge and presented their best concepts on the final morning of the workshop (Englehorn 2021).

Using the baseline built from the 2021 WIC workshop tasking the SEA 31 cohort tasking taken from the System Engineering Analysis Chair's memorandum titled "FY2021-22 SEA 31 Capstone Project: Tasking and Timelines" is:

> Reaping lessons learned from all WIC activities; SEA 31 will focus on 'Mission Engineering for Hybrid Force 2045'. The SEA team will analyze selected architectures for various missions, for instance: Full Spectrum ASW; Littoral Warfare (Strike); War at Sea Strike (Long Range Fires); Port/ Base Security; Integrated Air and Missile Defense; Maritime Interdiction Operations (Grey Zone activities); Protection of Underwater Infrastructures.
>
> Overarching concepts described in the CNO NAVPLAN, NWP-3, Unmanned Campaign Plan, and other guidance direct the basis of force development and deployment. SEA 31 may use the NSWC Mission Engineering approach to describe the functional requirements, networks, and platforms. SEA 31 also will use principles from systems engineering to identify future force requirements, capability gaps, and an architecture to meet those requirements. SEA 31 will then synthesize mission-by-mission approach into larger-scope fleet requirements.
>
> SEA 31 should anticipate an evolving threat; therefore, it is reasonable to envision that China and Russia employ many more Unmanned Systems in 2045. The above-mentioned mission areas may fit under the general concept of 'Swarm vs. Swarm for Sea Control', but SEA 31 should seek to identify areas of synergy across proposed mission-area solutions. (Boensel 2021)

3. Stakeholder Analysis

The stakeholders of this research are far-reaching both in academia and in military operations. The results of this research will be useful to OPNAV N9I for organizing future research and if the results prove promising, for immediate acquisition of proposed solution systems. If these solution systems are placed into the hands of the warfighter, the operational and tactical naval units will be the primary stakeholders of the results of the research. Also, if the system is put into operational use, a vast number of stakeholders will be involved such as military defense contractors, U.S. taxpayers, congress, as well as enemy and allied forces. The immediate stakeholders in the conduct of the SEA research along with their needs are provided in Table 1.

Table 1. List of Academic Stakeholders. Adapted from Hust and Kavall (2021).

Stakeholder	Title	Need
OPNAV N9I	Director, Warfare Integration (OPNAVN9I)	• Insight, analysis, and recommendations for future use of unmanned or emergent systems technology • Recommendations to close capability gaps with identification of tradeoffs
	Deputy Director, Integrated Warfare(N9IB)	
	OPNAV N9I Chair, Systems Engineering Analysis	• Recommendations for future SEA work • Relevant recommendations to OPNAV N9I
Systems Engineering Faculty	Systems Engineering Advisors	• Recommendations for future SEA work • Relevant recommendations to OPNAV N9I
Operations Research Faculty	Operations Research Advisor	
SEA31 Student Cohort		• Completion of graduation requirements • Application of critical thinking and reinforcement of curricula skills

B. PROJECT TEAM COMPOSITION

The Systems Engineering Analysis 31 cohort consists of active-duty officers from the United States Navy as well at international officers from Singapore and Israel. The diverse warfare specialty and undergraduate education of the officers allowed the team to approach solutions from a variety of perspectives. Table 2 is a list of the members of the SEA 31 team.

Table 2. SEA31 Team Composition

Last Name	Country	Service	Specialty	Undergraduate Studies	Graduate Studies
Brown	USA	USN	Submarines	Economics/Finance	308 SEA
Chan	SN	CIV	Aerodynamics	Aerospace Engineering	580 SE
Cheng	SN	SN Navy	Engineering	Mechanical Engineering	580 SE
Coker	USA	USN	Surface Warfare	Economics	308 SEA

Last Name	Country	Service	Specialty	Undergraduate Studies	Graduate Studies
Frydman	IS	IS Army	Infantry	Physics	590 EE
Goh	SN	SN Army	Intelligence	Computer Science	399 MOVES
Groff	USA	USN	Surface Warfare	General Engineering	308 SEA
He	SN	SN Air Force	Engineering	Electrical Engineering	580 SE
Johnson	USA	USMC	Logistics	Operations Research	360 OA
Lee	SN	SN Air Force	Engineering	Electrical Engineering	580 SE
Loh	SN	SN Air Force	Logistics	Electrical Engineering	364 SSO
Low	SN	SN Navy	Surface Warfare	Aeronautical Engineering	308 SEA
Neo	SN	SN Army	Joint Operations	Chemical Engineering	308 SEA
Ong	SN	SN Army	Signals	Physics	580 SE
Phua	SN	SN Army	Armor	Electrical Engineering	580 SE
Phua	SN	SN Army	Logistics	Materials Engineering	570 ME
Quah	SN	SN C4I	Imagery Intelligence	Mechanical Engineering	364 SSO
Rodrigo	USA	USN	Surface Warfare	Industrial Engineering	308 SEA
Schultz	USA	USN	Surface Warfare	Computer Science	308 SEA
Siew	SN	SN C4I	Imagery Intelligence	Mechanical Engineering	364 SSO
Sunda	USA	USN	Surface Warfare	Business Management	308 SEA
Tan	SN	CIV	Engineering	Electrical Engineering	368 CS
Tang	SN	SN Army	Armor	Aerospace Engineering	580 SE
Teo	SN	SN Army	Infantry	Aerospace Engineering	580 SE
Walker	USA	USN	Aviation	Mechanical Engineering	308 SEA

Last Name	Country	Service	Specialty	Undergraduate Studies	Graduate Studies
Yap	SN	CIV	Engineering	Mechanical Engineering	580 SE

The SEA team's organization adapted fluidly over time. Initially based off the tasking to explore "Mission Engineering for Hybrid Force 2045," the team divided into groups to investigate the needs of the different warfare areas in 2045 including surface, subsurface and grey zone operations. After the site visit from the Deputy Director of OPNAV N9I, the team structure changed to realign focus on the updated tasking to find a solution to an expected capability gap within the next five years. The Deputy Director provided a visual example during the meeting expressing the capability gap as a function of time and budget, this example is adapted in Figure 2.

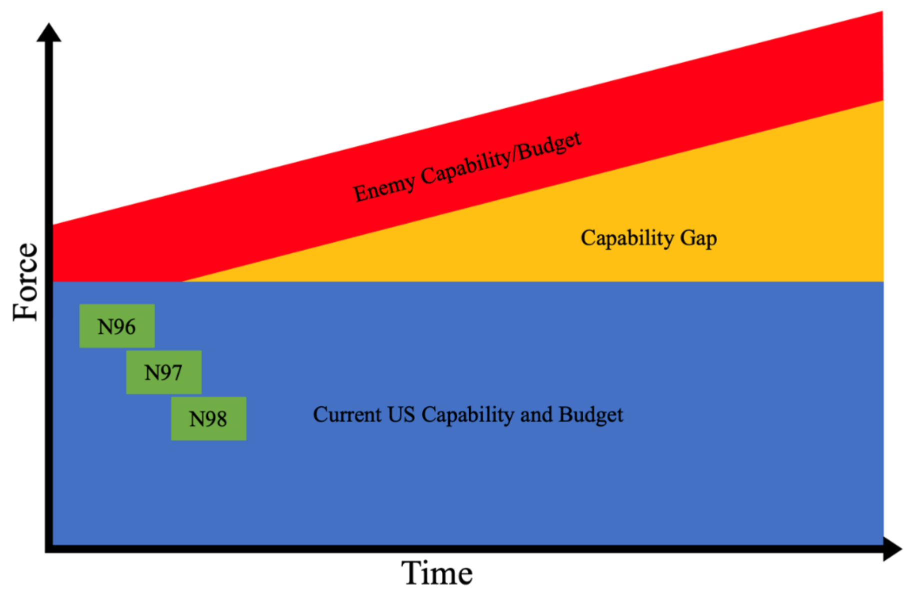

Figure 2. U.S. vs. Enemy Capability Gap. Adapted from Stewart (2021).

After the deputy director visit, the team was divided into two groups investigating the USN's kill chain and the PRC's naval kill chain to identify areas that would benefit most from an increase in U.S. capability or degrading the threat capability. After the problem statement was developed the team then used a modified mission engineering approach to satisfy the requirements. Team members were divided into areas of expertise within the mission engineering method in an overall coordinated effort.

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II. LITERATURE REVIEW

Several documents were listed in the SEA 31 tasking statement and were instrumental in the approach that the team took in defining the problem and developing the method for providing solution systems. The Chief of Naval Operations NAVPLAN 2021, Department of the Navy Unmanned Campaign Framework 2021, the Secretary of the Navy One Navy-Marine Corps Team: Strategic Guidance from the Secretary of the Navy 2021, and a report from the Congressional Research Service: Navy Force Structure and Shipbuilding Plans: Background and Issues for Congress 2021 were reviewed. Following is a summary of each of the documents and the key factors that contributed to the SEA 31 research project scope and problem definition.

A. CNO NAVPLAN 2021

1. Introduction of the CNO NAVPLAN

The CNO NAVPLAN outlined how the U.S. will execute the Tri-Service Maritime Strategy through an elaboration of the challenges faced and how the USN intends to overcome them with efforts focused on four key priorities: readiness, capabilities, capacity, and Sailors (Department of the Navy (DON) 2021). The top two priorities that are highly relevant to the SEA31 capstone project are capabilities and capacity.

2. Challenges Faced by the US

According to the CNO NAVPLAN, the PRC is currently the United States' most pressing long-term strategic threat (DON 2021). With her unsubstantiated claim of the nine-dash line, China is undermining the freedom to operate at sea and control resources beyond what is allowed under UNCLOS. The unlawful reclamation and militarization of the South China Sea allowed China to construct sophisticated networks of sensors, weapons, and forward deployment sites putting important waterways at risks. Since 2020, China has surpassed the U.S. as the world's largest fleet. China continues to aggressively build up her Navy with a variety of surface, subsurface, and air platforms. China utilizes the Maritime Militia forces and Coast Guard to conduct operations below the threshold of war; what is known today as the grey zone (DON 2021). In addition to her sea-going forces, China also operates the world's largest missile force and has a cyber force outnumbering the U.S. With those capabilities, China poses a tremendous threat to all domains of warfare including space and the information domain.

3. How to Overcome the Challenges

The U.S. need for sea control and power projection remains constant. However, the environment has changed drastically. Global waterways are now both contested and congested. The CNO NAVPLAN states, the Navy must be ready to control the seas at the time and place of their choosing, deny the use of the seas to the enemy while protecting friendly shipping in the congested environment (DON 2021). The enemy will contest the environment in space, cyberspace, and electromagnetic (EM) spectrum. To overcome the enemy, the following strategies outlined in the CNO NAVPLAN are relevant to the SEA31 capstone project. First, the Navy will have to be able to fight the enemy effectively in the space, cyberspace, and EM spectrum. This could include being able to fight effectively in communications and navigation denied environments. Secondly, the Navy must be able to project power ashore. Traditionally, ballistic missile submarines are utilized at the strategic level to project power throughout the world and provide deterrence to nuclear equipped nations. The Navy must also be able to project power ashore utilizing long range kinetic strikes. Thirdly, the Navy must maximize utilization of emerging technologies to gain the advantage. Machine learning (ML) and autonomous systems could be leveraged to gain the advantage. Lastly, the CNO NAVPLAN states, "should deterrence fail, the Navy will utilize concepts such as distributed maritime operations (DMO), littoral operations in a contested environment (LOCE) and expeditionary advanced base operations (EABO) to amass sea and shore-based fires from distributed platforms" (DON 2021). Dispersion of the forces decreases risk to the forces but makes command and control of those forces more difficult.

4. Capabilities – Deliver a More Lethal and Better-Connected Fleet

According to the CNO NAVPLAN 2021, there are three areas of focus on delivering capabilities for the Navy.

First, the focus on delivering emerging capabilities rests on maintaining command and control, communications, computers, cyber, intelligence, surveillance, reconnaissance, and targeting (C5ISRT) architectures that are highly adaptable and capable of change (DON 2021). This will allow the Navy to close the kill chain faster than the enemies. Even if systems are degraded, the Navy must be able to continue operating effectively. Placing weapons throughout the battlespace with increased offensive capabilities, maneuverability, and decreased vulnerability will negate the enemy's defensive advantage and force upon them operational dilemmas in combat.

Second, the CNO NAVPLAN also stated that all the Navy's platforms, weapons, and sensors will need to be connected in a strong Naval Operational Architecture (NOA) integrated into Joint All-Domain Command and Control (JADC2) (DON 2021). The NOA allows for the rapid sharing of information between distributed forces and enables enhanced situational awareness and information superiority. Rapidly developing technology associated with information systems must be incorporated into naval combat systems. The adaptation of emerging information technology will increase the capability of warfighters to project power ashore while striving to decrease costs.

Third, China is stockpiling a cache of many anti-aircraft and anti-surface combatant missiles. The CNO NAVPLAN outlines the need to get sensors in every environment within China's missile defense region. These sensors could be stationary or mobile and could be placed on legacy systems or new and emerging unmanned platforms (DON 2021). It follows suit that the Navy will also need increased capabilities when it comes to missile defense. The large number of missiles available to the adversary means that a ships defensive weapon supply could rapidly become exhausted. Ships must also adapt to emerging technology and be capable of defending against new electronic attack methods and directed energy weapons.

All above points were taken into consideration in the SEA 31 capstone project. As part of the project, the team explored improving the kill chain, be it by enhancing our own kill chain or by disrupting the enemy kill chain. Next, while a highly connected network would provide information superiority over the adversary, the uncertainty of China's capabilities to disrupt our C5ISR capabilities needs to be guarded against. This suggested that each fighting unit or surface action group should retain organic capabilities that would allow us the continue fighting effectively in a contested and degraded environment. Lastly, in addition to the suggested capabilities of directed energy and enhanced electronic warfare systems, the team explored emerging counter-swarm capabilities to improve the ships' defenses against swarming attacks.

5. Capacity – Deliver a Larger, Hybrid Fleet

To maintain sea control and denial and projection of power, the Navy needs to expand capacity. This is achieved through three primary means:

- Increasing numbers of submarines and smaller more affordable surface combatants to fight in a more distributed manner and with higher resiliency. For submarines, the Columbia-class acquisition will be prioritized as the Ohio-class submarines are phased out while the Virginia-class will continue to be built at sustainable rates. For surface combatants, emphasis will be on the new Constellation-class frigates. Fielding these in greater numbers will allow the Navy to realize its distributed concept of operations (DON 2021).

- Integrating unmanned platforms in all operational environments. These assets will provide commanders with enhanced options to fight and win by expanding the Navy's intelligence, surveillance, and reconnaissance (ISR), add depth to missile magazines, and provide additional means to keep the distributed force provisioned. A key enabler would be the man-machine (Sailors-unmanned platforms) operational integration (DON 2021).

- Integrating and working with operational partners, both internally and externally, to project the right naval power at the right place and right time. Internally, the Navy will more closely align with the Tri-service Maritime Strategy with the Marine Corps and Coast Guards. Externally, sailing and operating interchangeably with like-minded allies and partners to control the seas and project power in contested areas (DON 2021).

B. DEPARTMENT OF THE NAVY UNMANNED CAMPAIGN FRAMEWORK

1. Mission – Why Unmanned?

The DON Unmanned Campaign Framework 2021 outlines that the need to accelerate the development and delivery of new, innovative, capable unmanned platforms is increasing faster than ever (Harker et al. 2021). The advantage of unmanned platforms over manned platforms is clear. They allow U.S. forces to take more risks while suffering less from human flaws. Unlike humans, machines do not get tired, are very precise, and are not affected by the stressful nature of combat. The DON Unmanned Campaign Framework continues to state that another factor contributing to the Department of the Navy's decision to pursue an unmanned campaign is that many enabling technologies required for unmanned systems have reached a high level of maturity (Harker et al. 2021). The key technologies that have evolved in the past few years which make unmanned platforms more feasible are AI, autonomy, and C5ISR emphasizing connectivity. The growing need for such capabilities combined with the maturity level of technology presents an opportunity to boost the maritime warfighting capabilities of the U.S. Navy. According to the DON Unmanned Campaign Framework, eight domains ensure successful development and delivery:

- platforms and enablers
- strategy, concepts, and analysis
- fleet capability, capacity, readiness, and wholeness
- RDT&E/science and technology
- people, education, and talent
- logistics and infrastructure
- policy, law, and ethics
- communication and messaging. (Harker et al. 2021)

Through these eight areas of focus, the DON hopes to initiate a process through which a capability-based force will be rapidly developed to maintain the competitive edge against adversaries such as China and Russia. Since this is a new type of force, it is imperative to set guidelines for force building from the start. Those guidelines should ensure that the capability created at the end of the process is sustainable, survivable, scalable, agile, and trusted by warfighters and commanders. The DON has set a clear set of goals for this campaign:

- enhancing manned-unmanned teaming (MUM-T)
- creating a scalable infrastructure that can support the desired unmanned capabilities
- allowing fast R&D and testing iterations
- unifying solutions for many problems
- creating a capability-oriented force and not a platform-centric one. (Harker et al. 2021)

2. Portfolio – Where Are We Now?

The DON Unmanned Campaign Framework 2021 details the current portfolio of unmanned platforms including aerial, surface, subsurface, and ground platforms that operate under the USN and the USMC control (Harker et al. 2021). These platforms are meant to be used as part of a fully unmanned and MUM-T task force. The air portfolio includes a variety of platforms that focus on intelligence, surveillance, reconnaissance, and targeting at all levels. In addition, long endurance and refueling capabilities are included in some. One of the main force multipliers in the arsenal is operating from an aircraft carrier by carrier-based UAVs.

In the surface vehicle category, there is a wide range of capabilities. Many systems are modular and can carry many different payloads. Examples include sensor suites and loitering munitions. Unmanned Surface Vehicles (USVs) are useful for repetitive dangerous tasks, such as minesweeping. A key project in the USV portfolio is the Overlord program. This program aims to convert commercial vessels into autonomous ones, to prove the reliability of the concept (Harker et al. 2021).

Unmanned Undersea Vehicles (UUVs) are currently used for minesweeping missions, ISR, and mapping. Many existing platforms can accommodate many payloads of several types, while being deployed from a submarine or a ship. As with the surface vehicles, some platforms were developed out of existing commercial vehicles and were adapted to the military's needs. The main user of Unmanned Ground Vehicles (UGVs) is the USMC. UGVs are used for many tasks, such as striking, logistics, and explosive ordnance disposal (EOD). Despite ground autonomy presenting a challenging technological task, the USMC exploits commercial advancements to boost its warfighting capabilities. Creating a proactive environment while working with the U.S. Army and industry is essential to overcome the challenge.

The end goal of the Unmanned Campaign Framework is to create an environment in which key enablers and core technologies can produce modular, reliable, and relevant unmanned capabilities for fully unmanned and MUM-T configurations (Harker et al. 2021). This goal requires an emphasis on infrastructure, connectivity, appropriate facilities, and proper training and education of people.

3. Method – How Will We Get There?

The DON Unmanned Campaign Framework 2021 states that the challenges this mission is facing are numerous and spread across various domains. They include technological, educational, fiscal, and procedural hurdles to overcome. Addressing the technical problem alone will not evoke the full potential of unmanned systems (Harker et al. 2021). Since barriers exist across many fields, a well-planned campaign is needed. Such a campaign should include teaming up with the industry and academia to make this a joint effort.

According to the Unmanned Campaign Framework, a dynamic balance between connectivity, scaling, force integration, core technologies, and platform challenge solving is needed (Harker et al. 2021). Such a balance will require coordination between the entities involved. In addition, the framework includes a cognitive adaption, according to which solutions need to fit an array of problems, and the development should focus on creating a capability and not a platform. This agility is essential to maintain a scalable force in conflict without exhausting the system's resources.

Another important approach that must be adapted is the development and testing approach. According to the leader of the Aegis program at its earliest stage, Rear Admiral Wayne E. Meyer, the R&D philosophy should be "build a little, test a little, and learn a lot" (Meyer 2009). According to this approach, development should happen in incremental steps, and as such, the "Test, Prove, and Scale" section of the campaign framework is described (Harker et al. 2021).

Developing innovative unmanned systems and integrating them service-wide carries great risk. As part of the risk mitigation process, the DON aims to create an environment that allows a fast development-testing-operation cycle. As part of this effort, data, concepts, tactics, and procedures will be fed back from exercises to the development groups, allowing a fast-learning cycle and quick development iterations. Such an environment will enable converting prototypes to relevant end products quickly (Harker et al. 2021).

The U.S. military's unique needs, such as weaponization and rough operating environments, imply that academia and industry will not invest resources in military-oriented R&D without the military's guidance. Two effects that this has on the Unmanned Campaign Framework are (Harker et al. 2021):

- focused, driving, and decisive leadership is required from the DON
- adaptation of commercial platforms and core technologies is needed to exploit academia and industry's full potential. (Harker et al. 2021)

4. Adversary – Who Are We Facing?

The Chinese People's Liberation Army is rapidly incorporating the use of unmanned systems into their force structure, ranging from UAVs and robotic process automation (RPA) to UUVs, UGVs, and USVs (Kania 2018). The PLA is further making innovative advances in the research and development of swarming unmanned platforms and hypersonics. These advances are allowing the PLA to leverage unmanned platforms throughout a multi-domain battlespace, with a decided advantage in the field (Kania 2018).

It can be expected that the PLA will continue to increasingly incorporate unmanned platforms into their force structure. The PLA will likely leverage UAVs to support ISR capabilities, from battlefield reconnaissance to long range surveillance (Kania 2018). They will further leverage UAVs for remote cueing, battle damage assessment, and over-the-horizon targeting. PLA UAVs will likely be integrated into communications support, both as data relays and as localized satellite replacements in a denied environment (Kania 2018). UAVs will likely also be utilized in electronic warfare to conduct electronic reconnaissance, jamming, anti-radiation attacks, and as decoys for enemy weapons. PLA will likely further use UAVs to provide rapid response logistics for parts and medicine (Kania 2018).

Taking advantage of the PLA's early advantage of unmanned aviation complexes, the PLAN also carried out many USVs projects (Defence View 2021). Most of these projects performed unarmed patrol profiles demonstrating the capability to move in a unified manner. These USVs could also be used to determine the coordinates of adversaries before attacking. Theoretically, they can also perform suicide attacks by detonating themselves next to the side of surface ships.

The PLAN has conducted its first sea trials of the armed USV JARI, a 50-foot autonomous surface vehicle equipped with anti-air, anti-surface, and anti-subsurface weapons (Defence View 2021). China has described the USV JARI as a combat-ready "mini-AEGIS class destroyer" (Defence View 2021).

The development of these capabilities and their incorporation into the PLA force structure signals China's ideas of their importance in future warfare. The operationalization of unmanned forces and capabilities could fundamentally alter how the world's militaries approach warfare, and perhaps shift the future military balance.

C. SECNAV ONE NAVY-MARINE CORPS TEAM: STRATEGIC GUIDANCE FROM THE SECRETARY OF THE NAVY 2021

To meet the challenges posed by increasingly aggressive authoritarian states, the Secretary of the Navy published guidance, aligned with the CNO, Commandant of the Marine Corps, and Secretary of Defense, to inform the services' operational demands and warfighting needs of the future.

1. Introduction

Realizing the threat to maritime order and international norms posed by China and other aggressors, the Secretary of the Navy acknowledged the role that the Department of the Navy is expected to play to maintain world peace. The Navy must compete effectively within the gray zone to deter aggression and ensure victory should conflict arise. Due to the nature of conflict with China, the Navy must harness the advantage presented by the

Navy-Marine Corps Team. The Secretary of the Navy goes on to mention the priority of the services going forward as stated in SECNAV One Navy-Marine Corp Team: Strategic Guidance from the Secretary of the Navy 2021, "as our central governing concept, the top priority for the Department of the Navy will be to develop concepts of operations and capabilities that bolster deterrence and expand our warfighting advantages the People's Republic of China" (Del Toro 2021).

2. Enduring Priorities

The SECNAV Del Toro continues in his guidance to list three "Enduring Priorities" including "maintain maritime dominance in defense of our nation, empowering our people, and strengthening strategic partnerships" (2021). The most pertinent "Enduring Priority" to the conduct of the SEA 31 capstone report is the importance of projecting power abroad and being able to maintain freedom of navigation and to establish "maritime dominance in defense of our nation" (Del Toro 2021). Del Toro continues to outline the necessity for the U.S. to expand its presence into the U.S. Indo-Pacific Command theater so that U.S. forces are ready to rapidly transition from the competition phase with Russia or China to a combat scenario. Del Toro states that increasing readiness of the fleet is also a key factor in attaining dominance. Significant focus and investment need to be given to maintenance, infrastructure, and the supply chain. Additional focus needs to be given to cultivate new technology and find new ways to enhance warfighting capability including the use of unmanned systems (Del Toro 2021).

D. CONGRESSIONAL RESEARCH SERVICE: NAVY FORCE STRUCTURE AND SHIPBUILDING PLANS: BACKGROUND AND ISSUES FOR CONGRESS

This section of the literature review discusses the current and planned future Navy force structure as analyzed by the Congressional Research Service (CRS). The discussion is limited to the areas that are directly relevant to the SEA project team's approach and focus. The Navy's current force goal was established in 2016 with the goal of a 355-ship fleet (O'Rourke 2021). The ship types are shown in Table 3. This fleet volume and structure was planned to be achieved at an undetermined date, however, the FY2018 National

Defense Authorization Act requires this target to be met as soon as practicable (O'Rourke 2021).

Table 3. Ship Force-Level Goal. Adapted from O'Rourke (2021).

Ships Category	Number of Ships
Ballistic Missile Submarines (SSBNs)	12
Attack Submarines (SSNs)	66
Aircraft Carriers (CVNs)	12
Large Surface Combatants (i.e., cruisers [CGs] and Destroyers [DDGs])	104
Small Surface Combatants (i.e., frigates [FFGs], Littoral Combat Ships, and Mine Warfare Ships)	52
Amphibious Ships	38
Combat Logistics Force (CLF) ships (i.e., at-sea resupply ships)	32
Command and Support Ships	39
Total	**355**

The basis of the 355-ship goal is a force structure analysis which solicited combatant commanders on the types and capabilities necessary to meet national military strategies for warfighting and presence operations. This analysis was conducted in 2016 and only accounts for manned ships. Progress towards the 355-ship goal has been underway since 2019 as the Navy and Department of Defense plans to update the 355-ship goal while implementing a new fleet architecture that will utilize a distributed model (O'Rourke 2021). This new fleet architecture is planned to include several features that have not been included in past or current fleet designs such as (O'Rourke 2021):

- fewer large ships (combat, amphibious, and logistics)
- more smaller ships (combat, amphibious, and logistics)
- unmanned or lightly manned small surface vehicles.

This new distributed model should allow the Navy to better compete in A2/AD theaters while remaining technically feasible and affordable. This effort requires new shipbuilding programs to be undertaken to specifically provide smaller ships and small surface vehicles. More work will also be required to provide the unmanned platforms that the distributed architecture will require.

III. SYSTEM AND MISSION ENGINEERING

A. SYSTEM ENGINEERING PROCESS

From the various system engineering models shown in Figure 3, the project team adopted the "Vee" model as the starting point among other SE models such as the waterfall and spiral models to structure the management of the capstone project.

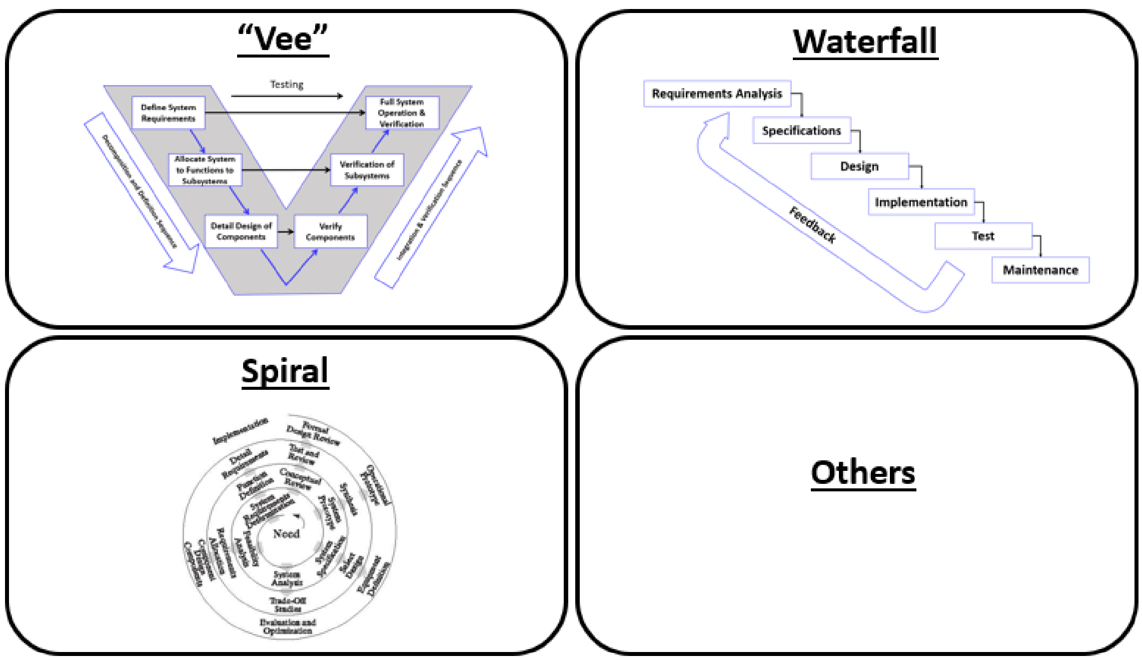

Figure 3. Types of Systems Engineering Process Models. Adapted from Blanchard and Fabrycky (2011, 36).

Shown in Figure 4, the "Vee" model describes the design and integration process for a system. The left side of the model begins with defining the stakeholders' needs that would be translated into system requirements. As the project progresses, activities such as the functional decomposition and definition are performed on the system of interest to help create the detailed design of its subsystems. Once the components of the subsystems are developed, the project progresses to the right side of the model, which involves verification and validation activities. The purpose of the verification activities is to ensure that the developed components can meet the desired specifications. On the other hand, the validation activities seek to ensure that the developed system can meet the operational requirements. The iterative nature of the design process from operational to system-level design would further help to ensure the stakeholders' needs are reviewed at every phase of the project (Blanchard and Fabrycky 2011, 37).

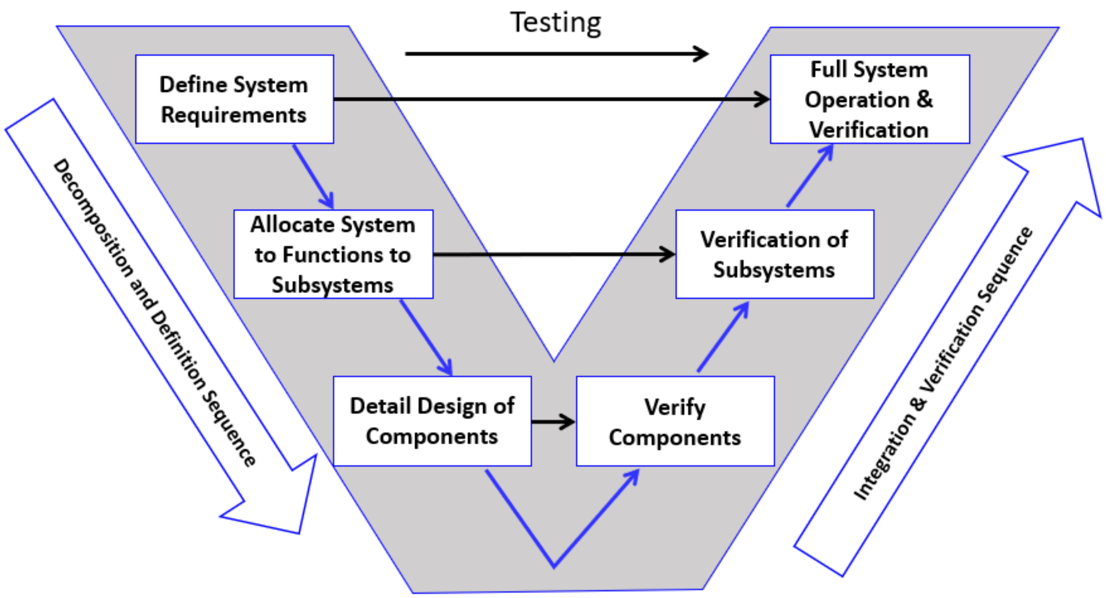

Figure 4. "Vee" Process Model. Adapted from Blanchard and Fabrycky (2011, 37).

B. MISSION ENGINEERING PROCESS

After utilizing the left side of the "Vee" model to define the system requirements outlined in the tasking statement, it was determined that the model did not contain enough detail to solve the problem. Therefore, to further guide the project team and complement the "Vee" model (left portion), the team utilized the Mission Engineering (ME) approach as shown in Figure 5.

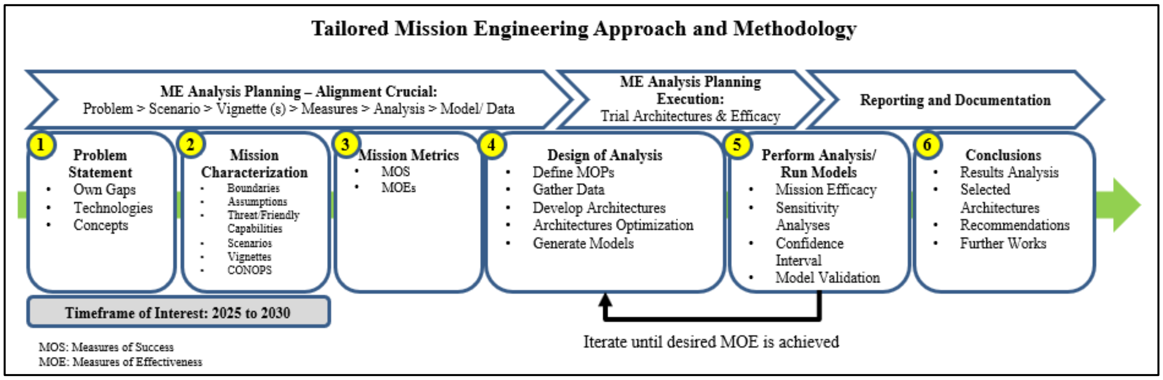

Figure 5. Tailored Mission Engineering Approach and Methodology. Adapted from Office of the Deputy Director for Engineering (2020).

The mission engineering approach and methodology outlined in the *Mission Engineering Guide*, was tailored to meet the needs of the SEA 31 team. Within the ME process, the ME analysis planning phase, encompassing the problem statement, mission characterization and mission metrics definition relate directly to the first phase of the "Vee" model on systems requirements. The second half of the "Vee" model is encompassed by the ME analysis, planning and execution phase and the reporting and documentation phase. The tailored ME process was complete, laid the framework for the execution of tasks, and satisfied the role of the basic components of the "Vee" model.

C. WORKPLAN AND MILESTONE CONTROL

The project team then tailored a workload and milestone process that would guide the team through the ME process. The workplan and milestone control plan is shown in Figure 6. This workplan encompassed elements from both the "Vee" model and the tailored ME process. Milestone dates, along with an assigned SEA team member, were incorporated into a work breakdown structure (WBS) to keep the project on track.

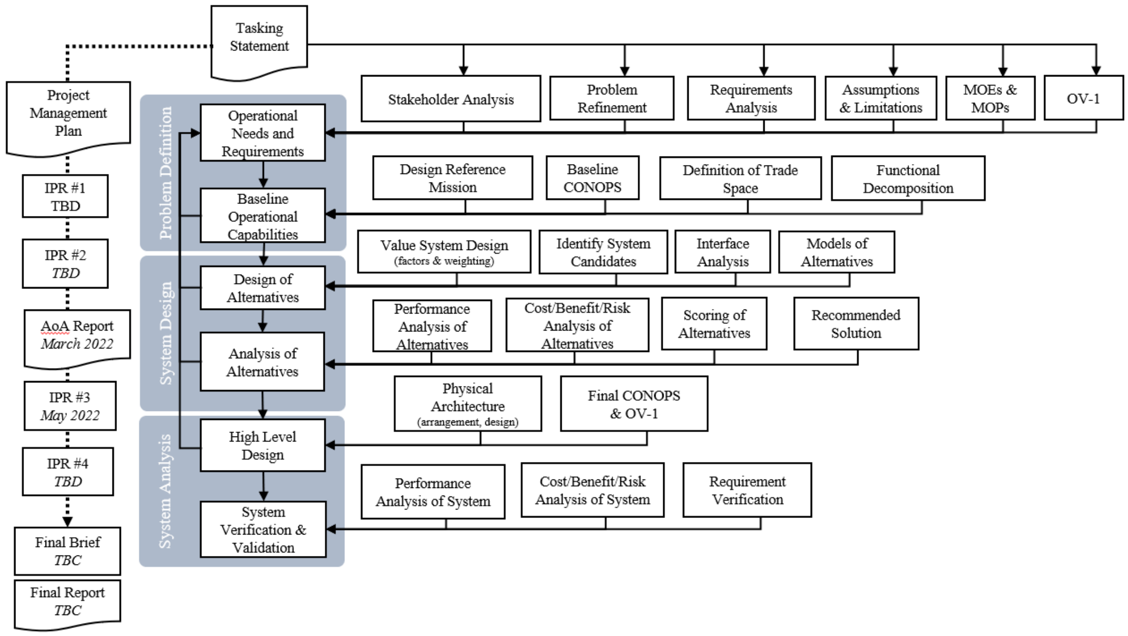

Figure 6. Workplan and Milestone Control. Adapted from Hust and Kavall (2021).

The workplan and milestone process for SEA31 utilized the "Vee" as milestones which serve as multiple checkpoints for stakeholder inputs while the ME process provides the team with guiding framework from deriving the requirements to ensuring the identified metric would allow for meaningful analysis. Each milestone also provides clear feedback loops to the operational needs and requirements which help ensure that the project is on track and able to fulfill stakeholders' requirements.

IV. MISSION ENGINEERING FOR HYBRID FORCE 2025

A. PROBLEM STATEMENT

The tailored mission engineering method begins with defining a specific problem that will be used to generate an overall scenario and subsequent vignettes within the scenario (Office of the Deputy Director for Engineering 2020). The problem statement was generated by analyzing current warfighting capability, technological, and doctrinal gaps. Utilizing the initial SEA 31 tasking statement, revised OPNAV N9I guidance, and the documents listed in the literature review section of this report, focus was placed upon developing a scenario for analysis to evaluate the expanding capability gap between the PRC and U.S. Navy. The A2/AD scenario in the South China Sea places the current USN force structure at great risk. Freedom of the seas would be denied in the A2/AD scenario and would put the Navy's CSGs at risk of ASCM attack if operating within the 2^{nd} island chain. The time sensitive nature of the tasking also creates a schedule problem for finding a solution. The problem statement and capabilities need were developed by the project team based on the tasking guidance and documents provided.

(1) Statement

How might we counter the anti-access and area denial capabilities of near peer adversaries cost effectively by the year 2025?

(2) Capabilities Need

Cost effectively adapt current capabilities and create a future architecture to enhance USN warfighting capabilities including presence, deception, ISR, defensive, and offensive capabilities in anti-access and area denied environments.

B. MISSION CHARACTERIZATION

1. Operational Environment

The South China Sea is a contested area in the United States Indo-Pacific Command area of responsibility and is the focus for this mission. The South China Sea contains major shipping lanes, multiple economic exclusion zones for different countries and has the potential to be an area that is denied to the United States due to the claimed significance to China. Figure 7 depicts the nine-dash line contested area and surrounding countries where China claims these waters and associated islands belong to mainland China. With China's rapid development and growth in military capabilities the need exists to improve the tactics and procedures utilized by the U.S. in this type of environment and specifically within the South China Sea. The following scenario was developed considering current events as well as these claims to create an anti-access, area denial environment.

Figure 7. South China Sea. Source: Dominguez (2015).

2. Scenario

U.S. Forces are planning to conduct freedom of navigation operations in the South China Sea in vicinity of PRC surface vessels and within range of land-based threats. The U.S. is utilizing one Flight IIA, Arleigh Burke Class Destroyer to conduct this mission. The PRC will attempt to deter and deny the U.S. from conducting these operations by operating UAVs and having the capability and intent to launch anti-ship missiles from their man-made islands, mainland China, and at sea. China utilizes a robust maritime militia for surveillance and reconnaissance. The following sections describe the boundaries, assumptions, as well as a baseline concept of operations used to analyze this mission in an anti-access, area denial environment.

3. Design Reference Mission

The design reference mission for the system of systems is to enhance the friendly force's kill chain and/or disrupt the enemy's kill chain by deploying unmanned systems from USN platforms at sea or from shore locations.

4. Boundaries

Bounding the problem within the South China Sea, the project team identified China as the main threat to the United States within this theater. Due to the timeline of implementation and integration the candidate systems and proposed solutions considered must be technological readiness level (TRL) 7 or above. This threshold ensures that the capabilities suggested could be implemented within the fleet by 2025. For this project, utilizing the described scenario, the system or system of systems must be organic to one DDG operating independently from other joint or allied systems. If the system exceeds the physical limits of a DDG, the system or system of systems must be capable of being on station within 24 hours.

5. Assumptions

After establishing the boundaries for the scenario, a list of assumptions was proposed based on the assumed capabilities of both U.S. and PRC forces. The current operating environment, allied partnerships, U.S. force structure, and budget allocation are assumed to remain relatively the same in 2025. It is assumed that the U.S. will not conduct the first offensive strike. The assumed capabilities of China include a large UXS inventory to conduct human in the loop targeting and attack, a possible underwater detection network in the South China Sea, GPS and communication denial and spoofing capabilities, and the ability to target electromagnetic emissions. China will utilize their militarized man-made islands and continue to use a maritime militia to conduct surveillance, reconnaissance, and attack. Furthermore, both China and the U.S. will have similar advanced satellite capabilities over the South China Sea. China is assumed to be capable of engaging any U.S. Forces within the nine-dash line.

6. USN/PRC Capabilities

a. USN Forces

The project team used the following assets as a baseline architecture for the defined scenario. Each of these assets will be further examine below. The summary of these assets below utilizes the Janes database as well as additional sources.

Table 4. Scenario Friendly Force Structure

Platform Type	Quantity
DDG Type 51 Flight IIA	1
Maritime Strike Tomahawk (MST) used as ASCM	8
Standard Missiles for Integrated Air & Missile Defense (IAMD)	8
Point defense capability	-

DDG Type 51 Flight IIA

According to Janes, the Arleigh Burke class (DDG Type 51 Flight IIA) is a warship in the United States Navy inventory (2022a). Utilizing the AEGIS Combat System, Flight IIA destroyers are capable of simultaneously conducting multiple warfare areas, such as strike, anti-air, anti-surface, and anti-submarine warfare. Additionally, this platform can carry up to two MH-60R helicopters and various quantities UAV depending on the size and weight of the UAV (Janes 2022a).

Figure 8. DDG Type 51 Flight IIA. Source: LaGrone (2015).

Maritime Strike Tomahawk (MST)

Janes describes the Maritime Strike Tomahawk as a long-range, subsonic cruise missile utilizing the body of the Tomahawk Block IV (RGM 109E) (Janes 2021a). The MST added many improvements to the capabilities of the Block IV, such as the ability to engage moving targets, multi-mode seekers, Joint Multiple Effects Warhead System, and upgraded software and sensor suite. The missile propulsion system consists of a solid propellent booster with turbofan for sustaining flight which reaches speeds in excess 490 kts, and a range of 850 nautical miles (Janes 2021a).

Figure 9. Tomahawk Block IV Missile. Source: Janes (2021a).

Standard Missile 2 (SM-2)

The SM-2 is a medium range surface-to-air missile deployed on U.S. Navy Destroyers and Cruisers. They serve a secondary purpose as an anti-ship missile (Janes 2013). The SM-2 is launched from the MK-41 Vertical Launching System and utilizes a dual thrust, solid rocket booster to travel and detonates utilizing HE blast fragmentation. There are three variants currently fielded by the U.S. Navy: SM-2 Block III, IIIA, and IIIB. Depending on the variant used, the SM-2 can travel up to 90nm (Janes 2013). The Block III and IIIA utilize command guidance via its INS in the mid-course phase, and semi-active radar guidance in the terminal phase. The Block IIIB utilizes its INS, but notably uses a side-mounted IR seeker to improve performance against low-flying cruise missiles when electronic countermeasures are being used in defense. The block IIIA and IIIB have the capability to be used for over-the-horizon engagements via CEC (Janes 2013).

Standard Missile 6 (SM-6)

The SM-6 is an extended range surface-to-air missile deployed on U.S. Navy Destroyers and Cruisers (Janes 2021c). They serve a secondary purpose as an anti-ship missile. The SM-6 is launched from the MK-41 Vertical Launching System and utilizes a two-stage solid rocket booster to travel and detonates utilizing HE blast fragmentation. It can travel up to 200 nm and utilizes command guidance via its INS for the boost and mid-course phases. The SM-6 was designed to combat a wide variety of threats given its capability of utilizing active or semi-active seeking in the terminal phase. It has the capability to be used for over-the-horizon engagements via CEC. Figure 10 depicts the SM-2 and SM-6 side-by-side (Janes 2021c).

Figure 10. SM-2 and SM-6. Source: Janes (2021c).

Evolved Sea Sparrow Missile (ESSM)

The Evolved Sea Sparrow Missile (ESSM) is a point defense surface-to-air missile. It is launched from the MK-41 Vertical Launching System on U.S. Navy cruisers and destroyers and utilizes a solid rocket motor with an advanced laser-based ignition system, giving it the capability of traveling up to 29.7 nm (Janes 2022c). They are loaded as a quad-pack in the MK-41 Vertical Launching System, giving ships four ESSM per launcher cell. The ESSM utilizes command guidance in the mid-course phase and semi-active radar homing in the terminal phase. Uniquely, the ESSM can use home-all-the-way (HAW) to intercept a target. HAW allows the ESSM to travel from launch to intercept under semi-active radar guidance via illumination alone. Upon intercept, it uses HE blast fragmentation to destroy its target (Janes 2022c).

Figure 11. Evolved Sea Sparrow Missile. Source: Raytheon Missile & Defense (2022).

b. PRC Forces

Based on the scenario, the project team utilized the forces and threats in Table 5 to create an architecture for analysis. Each of these assets is further explored within the report.

Table 5. Scenario Threat Force Structure

Platform Type	Quantity
PRC TYPE 052D (Luyang III) Class DDG	1
PRC S-100 (Camcopter UAV)	1
PRC ASN-301 (Harpy)	12
YJ-18 Anti-Ship Cruise Missile (ASCM)	8
Anti-Air Missiles for IAMD	8
Point defense capability	-

PRC Type 052D (Luyang III) Class DDG

According to Janes, the Luyang III DDG is a ship carried in the PRC inventory used to conduct anti-access/area denial missions, notably against enemy aircraft carriers and strike groups (Janes 2022b). The Luyang III carries multiple variants of ASCM utilized to conduct anti-surface warfare. Like the U.S. Flight IIA DDG, the Luyang III is also capable of conducting anti-air and anti-submarine warfare (Janes 2022b).

Figure 12. Type 52D (Luyang III) Class DDG. Source: Janes (2022b).

PRC S-100 (Camcopter UAV)

The Schiebel Corporation describes the PRC S-100 Camcopter UAV as an autonomous VTOL aircraft capable of being outfitted with multiple payloads to facilitate the conduct of missions both at sea and ashore (Schiebel n.d.). The S-100 can be launched from the Luyang III DDG providing the PRC with over-the-horizon maritime surveillance capabilities. Due to its small size, the S-100 has a small RCS making it hard to detect. It also has an endurance of greater than 6 hours and a sprint speed of 100 kts (Schiebel n.d.).

Figure 13. PRC S-100 Camcopter. Source: Scheibel Corporation (2015).

PRC ASN-301 (Harpy)

According to Janes, the ASN-301 (Harpy) is an unmanned, fully autonomous loitering munition system employed by the PRC (Janes 2021b). The Harpy was developed to serve as both a UAV and a missile, providing the PRC with increased detection and engagement capability. It receives pre-programmed information on targets but can receive updates via data link on potential targets. The Harpy maintains a low RCS due its small size and can carry a 32 kg warhead. It has an endurance of nine hours, range of 108 nm, and maximum operating speed of 225 kts (Janes 2021b).

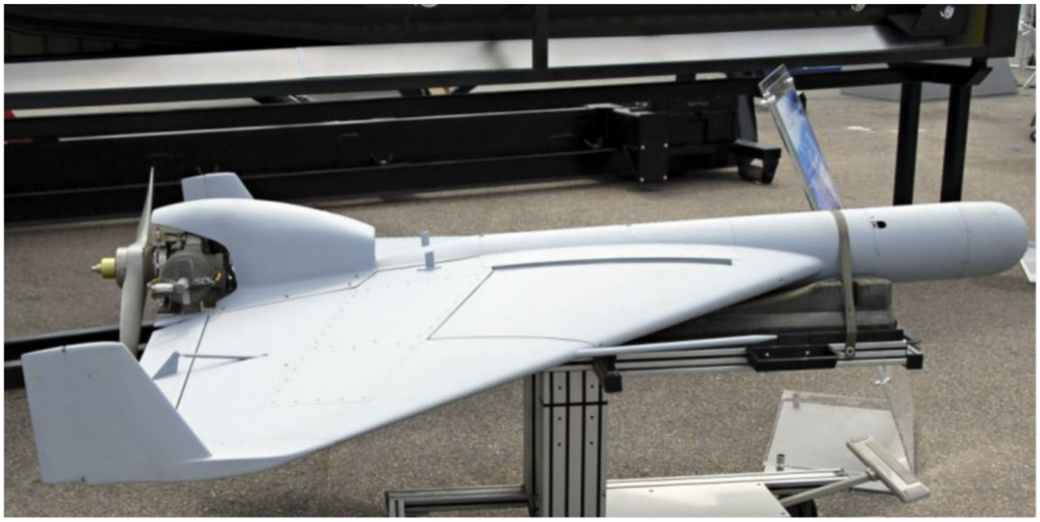

Figure 14. Harpy Weapon System. Source: Janes (2021b).

YJ-18 Anti-Ship Cruise Missile (ASCM)

YJ-18 is a vertically launched, anti-ship cruise missile. Its variant is also believed to be capable of land attack. YJ-18 operates with a subsonic cruise mode and a supersonic terminal attack (Missile Defense Project 2021). It has a range of 290 nm (330 mi; 540 km), with a threat ring of 264,200 sq nm (Janes 2021d). It utilizes its Inertial Navigation System (INS) and Global Navigation Satellite Systems (GNSS) for mid-course updates and an active radar seeker during the terminal phase. The YJ-18 was specifically designed to engage targets roughly the size of a destroyer (Missile Defense Project 2021).

Figure 15. YJ-18 Anti-ship Cruise Missile. Source: Missile Defense Project (2021).

PRC Anti-Air Missile (HQ-9/HHQ-9)

The HQ-9 is a medium- to long-range air defense missile, ground-launched missile with a track-via-missile (TVM) terminal guidance system like the Patriot missile system used by the United States (Kumar 2021). The aerodynamic design, rocket motor, and launching mechanism of the missile are likely based on Russian S-300 technology. There are several upgraded variants of HQ-9 varying in both technology and maximum range. The HHQ-9 is a naval version of the HQ-9, surface-launched missile. The Chinese Navy is progressively deploying contemporary ships equipped with powerful SAMs, notably a class of at least eight 055 guided missile cruisers, each with 112 vertical launch tubes for HHQ-9s. Furthermore, the Chinese are mass-producing Type 052D air defense destroyers, which can carry up to 88 HHQ-9 missiles in vertical launch (Kumar 2021).

Figure 16. PRC HQ-9. Source: Kumar (2021).

7. Baseline Concept of Operations (CONOPS)

To conduct an analysis of this scenario, a baseline concept of operations was developed by the project team. This concept focused on an Arleigh Burke Class Flight IIA Guided Missile Destroyer operating in the vicinity of the nine-dash line with the mission of conducting freedom of navigation operations in the contested area. In conjunction with the freedom of navigation operations, additional assets will be utilized to search over-the-horizon to provide improved situational awareness, reduce uncertainty, increase defense in depth, and increase the survivability of the DDG. The search time for these assets was set to 24 hours. This period includes the transit to the search area as well the time it takes to conduct the search. Theater assets are not suitable for this scenario due to the high costs and increased risk to both the theater asset and DDG due to the C2 structure required for operations. The DDG will utilize small scale semi-autonomous unmanned systems to enhance the operational commander's situational awareness, enhance the friendly kill chain process and degrade the enemy's kill chain process.

8. Vignettes

The next step in the mission engineering process involves creating specific vignettes within the overall scenario (Office of the Deputy Director for Engineering 2020). This process allows the proposed solution systems to be tested in multiple mission areas under the same architecture. The vignettes, depicted in Figure 17, are specific cases within the scenario developed to provide insight into the capabilities of the baseline, then further be analyzed when supplemented with unmanned systems.

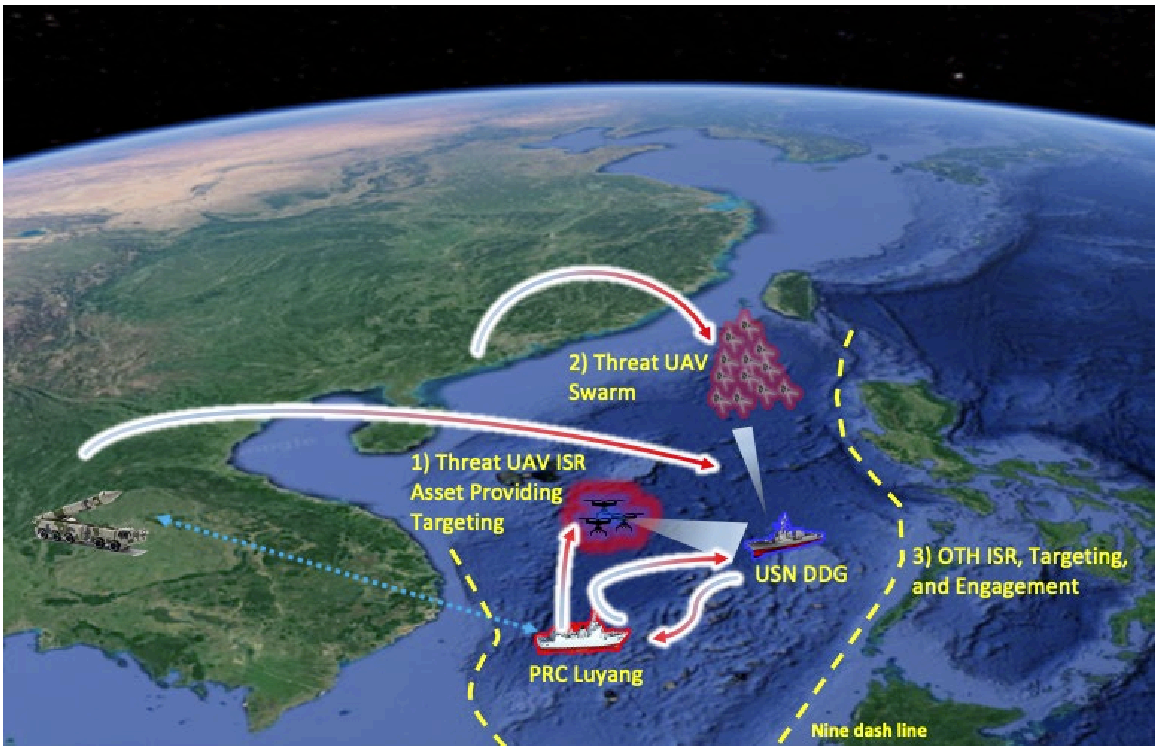

Figure 17. Scenario Overview with all Vignettes

- Over-the-horizon (OTH) ISR, targeting, and engagement – A PRC Type 052D (Luyang III) Class DDG is reporting the position of a USN DDG via electronic signature (ES) sensor to coordinate ASCM attack. To counter this act, the USN DDG needs an over-the-horizon search and strike capability. This asset needs to be capable of deploying 80 nm down the threat axis and searching within 40 nm x 40 nm search area, depicted in Figure 18, with a communication relay capability to coordinate attack. If an individual asset is not capable of completing this mission, then a system of systems will be needed to fulfill delivery, relay, and strike. The challenge within this vignette is the physical limitations associated with over-the-horizon communication and system endurance for delivery.

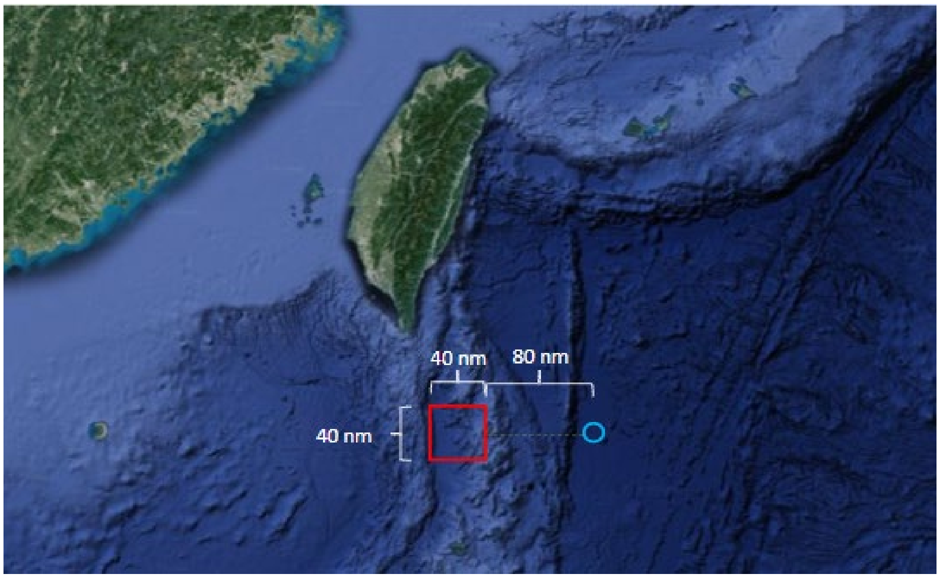

Figure 18. OTH Search Area

- Threat unmanned aerial vehicle swarm – A swarm of 12 PRC ASN-301 Harpy are attacking a USN DDG to reduce, degrade, and/or destroy the DDG's IAMD capability and capacity in support of follow on ASCM attacks. To counter a Harpy swarm, the USN DDG needs early detection and engagement capability. The assets for this vignette need to be capable of conducting high fidelity search and detection for subsequent high-speed maneuver and intercept. The challenges associated with this vignette are the detection capability, quantity of threats, and engageability of Harpy. The term engageability includes the engagement window, quantity, and variety of available assets to counter the threat.

- Threat UAV ISR asset providing targeting – A PRC Type 052D (Luyang III) Class DDG launches a PRC S-100 (Camcopter UAV) that is reporting the position of a USN DDG to coordinate ASCM attacks. To counter this threat, the USN DDG requires a system capable of detecting and engaging the Camcopter. If an individual asset is not capable of completing this mission, then a system of systems is needed to fulfill the search, relay, and strike requirements. The challenges within this vignette are the detection and engagement of the Camcopter. The defensive systems onboard USN DDGs are misaligned to this threat and do not match when engaging a small, inexpensive, UAV platform. A more economical solution is needed to counter the Camcopter threat.

C. MISSION METRICS

Mission metrics are used to evaluate the success and effectiveness of the operations conducted within the operating environment/scenario. Table 6 presents the measure of success as well as the measures of effectiveness to assess the U.S. capability to operate in the given environment against the defined PRC forces.

Table 6. Metrics of Analysis

Metric	**Justification**
Measure of Success (MOS)	
USN forces can operate in near peer A2/AD environment	This metric would determine if the proposed fleets could operate in the A2/AD environment.
Measure of Effectiveness (MOE)	
Number of hits on enemy platforms	The survivability of the fleet is dependent of the number of enemy platforms that could be defeated. This metric highlights the effectiveness of the fleet's ability to defend against any threat. Hence, a larger number of hits on enemy forces is better.
Number of hits on U.S. ships	The destruction of any platforms results in mission failure and implies the ineffectiveness of the defense suite. Therefore, fewer hits on U.S. ships are better.
Cost of system	The amount of munitions impacts the readiness and sustainability of the proposed fleet. The amount of munitions also consumes resources, such as budget and estate space. Hence, a lower cost is better.

D. DESIGN OF ANALYSIS

To quantify the predicted effectiveness of the proposed systems of systems, a value system was designed. Utilizing the Universal Naval Task list, the project team identified three tier-two tasks that the proposed solution system of systems would be required to complete to accomplish the mission. The Universal Naval Task List provides a specific task, brief description of the task, and standardized measures to evaluate how well that task is performed. The selected tasks are listed in Table 7 (Department of the Navy 2008).

Table 7. Selected Naval Tasks

NTA 2.2	Perform collection operations and management
NTA 3.2	Attack targets
NTA 5.1	Acquire, process, communicate information, and maintain status

Evaluation of subsequent tasks under the three selected tasks was conducted to identify specific functions the proposed system would be required to complete. A cursory review of current unmanned systems was conducted to identify the capabilities and limitations of these technologies in accomplishing these specific functions. The Socratic method was used to gain consensus within the project team regarding what would be feasible within the time constraint of 2025. From this review four high level functions the candidate unmanned system would need to accomplish were identified. These functions are delivery, search, communication relay, and attack.

The delivery function was selected to overcome the limited endurance and range of available anti-surface warfare (ASUW) UAV. The purpose of the delivery function is to position munitions over-the-horizon in the search area. The search function was selected to augment the over-the-horizon surface search capability of the manned surface platforms. In the described A2/AD environment, shipborne helicopters, manned MPRA, and unmanned MPRA cannot accomplish this function due to the increased risk to the assets and their relatively high associated costs. The communication relay function was selected to provide an alternate communication method if satellite communications between the surface unit and the unmanned system are degraded or denied. The attack function was selected to cost effectively increase the lethality and survivability of the manned surface units. For each of the functions measures of performance were selected to be used in Multi-attribute Value Analysis.

Multi-attribute Value Analysis was used to compare candidate systems that accomplish one or more of the four functions. The value of a system was derived by assigning a weight to each of the measures of performance (MOP) based on the project team's assessment of an attributes importance towards accomplishing a specific function. Weights ranged from 1 to 5, with 5 indicating the most important MOP. The product of the MOP and weight was calculated, and each of the products were summed to attain the value of the system. The measure of performance associated weights and units for each function are listed in the tables below. Size is the amount of space the unit occupies onboard the surface ship. Systems that do not occupy space onboard the ship have a size of zero.

Table 8. Search Measures of Performance

Search		
Weight	**System**	**Unit**
N/A	Unit Cost	US Dollars (USD)
3	Random Search Probability of Detection	Numerical
3	Time on Station	Hours (hrs.)
5	Susceptibility	Scale (1-5) 5 Least Susceptible
3	Recoverability	Scale (1-5) 5 Most Recoverable
3	Comms Range	Nautical Miles (nm.)
3	Payload	Pounds (lbs.)
1	Size	Cubic meters (m^3)

Table 9. Delivery Measures of Performance

Delivery		
Weight	**System**	**Unit**
N/A	Unit Cost	US Dollars (USD)
3	Time on Station	Hours (hrs.)
5	Susceptibility	Scale (1-5) 5 Least Susceptible
3	Recoverability	Scale (1-5) 5 Most Recoverable
3	Comms Range	Nautical Miles (nm.)
3	Payload	Pounds (lbs.)
1	Size	Cubic meters (m^3)

Table 10. Communications Measures of Performance

Communications		
Weight	**System**	**Unit**
N/A	Unit Cost	US Dollars (USD)
3	Time on Station	Hours (hrs.)
5	Susceptibility	Scale (1-5) 5 Least Susceptible
3	Recoverability	Scale (1-5) 5 Most Recoverable
3	Comms Range	Nautical Miles (nm.)
3	Payload	Pounds (lbs.)
1	Size	Cubic meters (m^3)

Table 11. Attack Measures of Performance

Attack		
Weight	**System**	**Unit**
N/A	Unit Cost	US Dollars (USD)
3	Transit Range	Nautical Miles (nm.)
4	Time on Station	Hours (hrs.)
5	Susceptibility	Scale (1-5) 5 Least Susceptible
3	Recoverability	Scale (1-5) 5 Most Recoverable
2	Comms Range	Nautical Miles (nm.)
3	Payload	Pounds (lbs.)
4	Engagement Speed	Knots (kts.)
5	Networking	Scale (1-5) 5 Best
5	Prob K	Numerical
3	Severity of K	Scale (1-5) 5 Best
1	Size	Cubic meters (m^3)

To identify candidate systems, members of the project team each researched and collected technical data for various unmanned systems. If the value for a specific unmanned system's MOP was not known, the value was inferred to be the same as an analogous system. If no such analogous system existed, the value was estimated using heuristics. Each individual system was presented to the entire team. Using the Socratic method, the system engineering "ilities" of each of the systems in relation to the described concept of operations were attained. Detailed descriptions of the selected candidate systems and other non-selected systems are included in Appendix A. For each of the functions, at least one system was identified that met the technological maturity to be considered for the hybrid force of 2025. For functions with more than one system, a gradient is applied to the MOP values to illustrate the differences among the systems. The following discussion describes the employment and measures of performance for each of the candidate systems.

1. Candidate Systems

a. Search Platform

In every SoS alternative, one VBAT 128 is utilized to search the operational area. The system is launched and recovered from the manned surface ship's flight deck (Shield AI 2021). The VBAT 128 transits to the search area to find, fix, track, and target enemy platforms, as well as to assess battle damage post engagement. The VBAT 128 employs an EO/IR sensor as well as an AIS capability. The manufacturer advertises a wide area search (WAS) algorithm capability that allows it to conduct maritime searches (Shield AI 2021). The VBAT 128 has a demonstrated capability in search execution, therefore other systems were not considered as search platforms for this analysis. This demonstration occurred when it was employed by the 11th Marine Expeditionary Unit onboard USS PORTLAND (LPD 19) (Naval Technologies 2021a). The V-BAT 128 system was also chosen by the U.S. Navy for a vertical take-off and landing (VTOL) UAS prototyping and development effort in 2021 (Naval Technologies 2021b).

Table 12. VBAT 128 Measures of Performance

Search	
System	VBAT 128 Search
Unit Cost	$500,000
Random Search Pd	1
Time on Station	10
Susceptibility	4
Recoverability	5
Comms Range	50
Payload	25
Size	6.75
Value	300

b. Delivery Platform

Jump 20 VTOL UAV

The Jump 20 is a VTOL UAV with the demonstrated capability of air launching UAV (Aerovironment 2022). The system is launched and recovered from the manned surface ship's flight deck. Four Jump 20 are launched, carrying two Coyote UAS each, from a manned surface ship to position in the search area where cueing suggests a specific enemy unit is operating. The range of Jump 20 allows it to engage the target, regardless of the position of the launch platform relative to the target, if the target is in the search area. The speed of the Jump 20 requires an hour and 30-minute transit to the target search area, where it can loiter for 15 hours to decrease the time between locating the target and engagement (Aerovironment 2022).

Aerotriton UUV/USV

Aerotriton is an unmanned system that is capable of both operating on the surface of the water and submerged (Oceanaero n.d.). When on the surface, propulsion can be provided via a sail and/or a propeller. Three Aerotriton, each carrying two Coyote UAV, are launched, and recovered from the over-the-side davit of the manned surface unit. The low speed of the Aerotriton requires it be launched 8 hours prior to the required on-station time. Once on station it can operate for 16 hours (Oceanaero n.d.).

Dive Large Diameter (LD) UUV

Dive LD UUV is a 3D printed unmanned underwater vehicle. Two Dive-LD UUV, each carrying five Coyote UAV, are launched, and recovered from the over-the-side davit of the manned surface unit (Anduril 2021). The low speed of the Dive-LD UUV requires it to be launched eight hours prior to the required on-station time. Once on station it can operate for 16 hours.

Medium Displacement Unmanned Surface Vessel (MDUSV)

MDUSV is the subsequent system to the Seahunter USV. The MDUSV follows the manned surface unit, allowing it to conserve space aboard the manned surface vessel during low-risk situations (Casola 2017). MDUSV's payload is 32 Hero-900 loitering munition

(LM) contained in four eight-pack canisters. The speed of the MDUSV requires it be deployed two hours prior to its required on-station time. Once on station it can operate for ten days (Casola 2017).

Table 13. Delivery Platforms Measures of Performance

Delivery				
System	**Jump 20**	**Dive-LD**	**Aerotriton**	**MDUSV**
Unit Cost	$750,000	$300,000	$1,200,000	$30,750,000
Time on Station	14	240	24	280
Susceptibility	3	4.5	4	2
Recoverability	3	4	4.5	5
Comms Range	115	10	25	30
Payload	30	100	50	14460
Size	12	14	5	0
Value	513	1098	336	44335

c. Communication Relay Platform

VBAT 128 UAV

The VBAT 128 was chosen again as a candidate system to provide the communication relay between the manned surface unit and the unmanned systems that are over-the-horizon, beyond line-of-sight communications. The speed and on station time of the VBAT 128 system allows it to remain on station for 10 hours (Shield AI 2021).

Sunglider UAV

Sunglider is a solar-powered high-altitude platform-station (HAPS) developed to operate at an altitude of 20 km within an area of 200 km^2 (Hapsmobile 2022). With a wingspan of 262 feet and a payload capacity of up to 150 pounds, it is propelled by 10 solar powered electric motors. The Sunglider will launch from shore and maintain position outside of enemy airspace to provide a wide area communications relay.

Table 14. Communication Relay Platform Measures of Performance

Communication Relay		
System	**VBAT 128 Comms**	**Sunglider**
Unit Cost	$500,000	$6,700,000
Time on Station	10	24
Susceptibility	3	4
Recoverability	3	5
Comms Range	50	200
Payload	25	150
Size	6.75	0.00
Value	286	1157

d. Attack Platform

Coyote UAV

Coyote UAV is a canister launched UAV that employs a passive sensor (Raytheon 2021). Guidance is accomplished via homing on ES, either from illumination or produced by the target. As part of a proposed architecture, three six-pack Coyote UAV canisters are installed onboard the manned surface unit. The system can be used to counter a single UAS conducting ISR, or to engage the swarm of loitering munition UAS (Raytheon 2021). The systems onboard the delivery vehicles will be used against surface targets. Individual Coyotes network together to conduct weapon and target pairing. Detonation of the fragmenting warhead is executed by an onboard proximity sensor. Guidance and detonation incorporate a human-on-the-loop interface to reassign weapons to different targets or abort the engagement (Raytheon 2021).

Switchblade 600 UAV

Switchblade 600 UAV is a canister launched UAV that employs an EO/IR sensor (Aerovironment n.d.). As part of a proposed architecture, three six pack Switchblade 600 UAV canisters are installed onboard the manned surface unit. The system can be used to counter a single UAS conducting ISR, or to engage the swarm of loitering munition UAS. The systems onboard the delivery vehicles will be used against surface targets. Individual Switchblade 600s network together to conduct weapon and target pairing. Terminal guidance is provided via an onboard electrooptical sensor. Detonation of the fragmenting warhead is executed by an onboard proximity sensor. Guidance and detonation incorporate a human-on-the-loop interface to reassign weapons to different targets or to abort the engagement (Aerovironment n.d.).

Hero 900 UAV

Hero 900 is a canister launched UAV loitering munition (Uvision 2018). The range of Hero 900 allows it to engage the target, regardless of the relative position of the MDUSV to the target, if the target is in the search area. The systems onboard the delivery vehicles will be used against surface targets. Hero 900 conducts engagements using an electrical optical sensor. Hero 900s network together to attack antennae with proximity fragmenting warheads (the system can also be equipped with impact or delay fuse warheads). Hero-900 LMs can also be utilized for limited area search assuming high confidence if enemy is in the area of operations (Uvision 2018).

Table 15. Attack Platform Measures of Performance

Attack			
System	**uVision Hero 900**	**Coyote**	**Switchblade**
Unit cost	$250,000.00	$15,000.00	$70,000.00
Transit range	135	70	24
Time on Station	5	1	0.6
Susceptibility	3	4	3
Recoverability	2	2	3
Comms range	135	50	30
Payload	44	2.2	101
Engagement speed	140	70	65
Networking	3	3	2.5
Prob of Kill	4	2	3
Severity of Kill	5	1	5
Size	0	0.21	0.05
Value	1458	654	763

2. Proposed System of Systems (SoS)

To accomplish all four functions, the combinations of candidate systems were permutated to create sixteen systems of systems. The attack function was decomposed into either offense (over-the-horizon engagements) or defense (interception of inbound targets). Across all SoS permutations the search function is performed by the VBAT 128. The Coyote is the sole munition that the delivery vehicles can transport, except for the MDUSV. The weight and size of the Switchblade and HERO 900 excluded them from being carried on any of the other three delivery platforms. Similarly, the cost and size of HERO 900 excluded it from being carried on a manned surface unit and being used as a counter UAS system.

Table 16. Proposed SoS Architectures

Search	Offense	Delivery	Comms	Defense	Architectures
VBAT	Coyote	Jump 20 (A)	VBAT (E)	Switchblade (G)	AEG
			Sunglider (F)		AFG
			VBAT (E)	Coyote (H)	AEH
			Sunglider (F)		AFH
		Dive-LD (B)	VBAT (E)	Switchblade (G)	BEG
			Sunglider (F)		BFG
			VBAT (E)	Coyote (H)	BEH
			Sunglider (F)		BFH
		Aerotriton (E)	VBAT (E)	Switchblade (G)	CEG
			Sunglider (F)		CFG
			VBAT (E)	Coyote (H)	CEH
			Sunglider (F)		CFH
	Hero	MDUSV (D)	VBAT (E)	Switchblade (G)	DEG
			Sunglider (F)		DFG
			VBAT (E)	Coyote (H)	DEH
			Sunglider (F)		DFH

3. Generation of Alternatives

To generate alternate designs for comparison against the proposed systems of systems, an optimization model was created to attempt to maximize the performance of a possible system of systems. The intent of the model was to independently generate architectures designed to meet the constraints to which the system must adhere. A value model was created to accomplish this task by first analyzing the five critical mission functions that must be achieved by the system of systems to attain success: search, delivery, communications relay, attack, and counter-swarm. For each of these functions, five critical technical aspects of a candidate system were identified to contribute to analysis. The selected technical aspects for each critical mission function are shown in Table 17.

Table 17. Critical Technical Aspects

Search	**Delivery**	**Comms Relay**	**Attack**	**Counter-swarm**
Sweep Width	Speed	Endurance	Speed	Speed
Speed	Endurance	Susceptibility	Susceptibility	Loitering Capability
Endurance	Susceptibility	Recoverability	Probability of Kill	Range
Range	Recoverability	Communications Distance	Severity of Kill	Probability of Kill
Susceptibility	Range	Speed	Networking Capability	Networking Capability

Next, the mission set was categorized into two distinct categories: offensive projection of force and defensive counter-swarm. The offensive category receives contributions from the search, delivery, communications relay, and attack platforms, whereas the defensive counter-swarm is the sole result of the effectiveness of the counter-swarm platform. Each category provides equal weight to the final calculation of the system of systems' effectiveness to ensure that the optimization model approximates reality in architecture design. The manufacturer data for each platform was then gathered for each technical aspect. To ensure no system skewed the data set due to overmatched performance, the technical data was normalized and then weighted into each category's overall score using the SMARTER method.

a. *Optimization Model Formulation*

Using Python's Pyomo optimization package, a linear integer program was constructed to determine the optimal SoS. The model is depicted in Figure 19. For example, set A, represents all action platforms, whereas set C represents the two c-swarm platforms. The set of all platforms is the union of all platform types. The parameters displayed in Figure 20 represent the coefficients and constants that are used in the linear program.

Indices and Sets

$a \in A$	Action Platforms
$c \in C$	C-Swarm Platforms
$d \in D$	Delivery Platforms
$r \in R$	Relay Platforms
$s \in S$	Search Platforms
$p \in P$	All Platforms ($P = A \cup D \cup C \cup R \cup S$)
$t \in T$	Type of platform (A, C, D, R, S)

Figure 19. Model Indices and Sets

Data

ψ_p	$p \in P$	cost for platform p for search platform s
β_p	$p \in P$	size of platform p
α_p	$p \in P$	contribution to mission effectiveness of platform p
n_p	$p \in P$	number of platform p in set
γ_p	$p \in P$	capacity of platform p
k_r	$r \in R$	Communications range of platform r
w_t	$t \in T$	Weight of platform type t
budget		Available budget
maxSize		Available storage space
minComm		Minimum communications range required

Figure 20. Coefficients and Constraints in Linear Program

There are two decision variables for each platform in consideration. The second decision variable listed X_p, however, informs the first Q_p. That is, after determining the number of platforms to include in the system, the number of sets of each platform to include can be derived.

Decision Variables

Q_p	$p \in P$	number of sets of platform p in system
X_p	$p \in P$	number of platform p in system

Formulation

$$\max \quad w_A \sum_{a \in A} \alpha_a X_a + w_C \sum_{c \in C} \alpha_c X_c + w_D \sum_{d \in D} \alpha_d X_d + w_r \sum_{r \in R} \alpha_r X_r + w_s \sum_{s \in S} \alpha_s X_s$$

Figure 21. Model Decision Variables and Objective Function

The objective function, Figure 21, seeks to maximize the performance of the system of systems. Included in the objective are the weights for each platform type, as well as their contribution to overall system performance.

$$\text{subject to} \sum_{a\in A}\beta_a X_a + \sum_{c\in C}\beta_c X_c + \sum_{d\in D}\beta_d X_d + \sum_{r\in R}\beta_r X_r + \sum_{s\in S}\beta_s X_s \le maxSize \quad (1)$$

$$\sum_{a\in A}\psi_a X_a + \sum_{c\in C}\psi_c X_c + \sum_{d\in D}\psi_d X_d + \sum_{r\in R}\psi_r X_r + \sum_{s\in S}\psi_s X_s \le budget \quad (2)$$

$$\sum_{r\in R} k_r X_r \ge minComm \quad (3)$$

$$X_{Coyote} + X_{Switchblade} + 0.5625 X_{Hero900} \le 18 X_{MDUSV} \quad (4)$$

$$X_{Coyote_{Any}} \le 6 \sum_{d\in D} X_d \quad (5)$$

$$n_a Q_a = X_a \quad \forall a \in A \quad (6)$$

$$n_c Q_c = X_c \quad \forall c \in C \quad (7)$$

$$n_{Vbat} Q_{Vbat} = X_{Vbat} \quad (8)$$

$$\sum_{p\in A} X_a \ge 1 \quad (9)$$

$$\sum_{c\in C} X_c \ge 1 \quad (10)$$

$$\sum_{d\in D} X_d \ge 1 \quad (11)$$

$$\sum_{r\in R} X_r \ge 1 \quad (12)$$

$$\sum_{s\in S} X_s \ge 1 \quad (13)$$

$$X_a \le \gamma_a \quad \forall a \in A \quad (14)$$

$$X_d \le \gamma_d \quad \forall d \in D \quad (15)$$

$$X_r \le \gamma_r \quad \forall r \in R \quad (16)$$

$$X_s \le \gamma_s \quad \forall s \in S \quad (17)$$

$$\sum_{c\in C} X_c \le 48 \quad (18)$$

Figure 22. Model Constraints

The integer linear program is heavily constrained to attempt to replicate the realities of architecture generation. For example, since the proposed system of systems is intended to be deployable from and independently operating DDG, a single helicopter hangar has been allocated for storage of the platforms and associated maintenance equipment. This will allow the DDG to gain the capabilities associated with the system of systems while only losing a redundant helicopter. This was translated into constraint (1) for the optimization model by constricting the total size of all included platforms to 42 m^3. Additionally, the total cost of the system of systems was constrained (constraint (2)) to the cost of an MH-60R, $47M. This value was chosen because the problem statement indicated that the chosen system shall be affordable. It was, therefore, a reasonable conclusion to assume that the generated architectures should cost no more than the system they are physically displacing. Furthermore, the minimum communications requirement for the relay platforms is represented by constraint (3). One of the major constraints for our problem was the issue of platform capacity and compatibility. For example, not all action platforms could fit on every delivery platform, and some action platforms had to be employed in sets of six. Constraints (4 – 8) and (14 – 18) shape the feasible region in a manner that satisfies these requirements. Constraints (9 – 13) ensure that at least one of each type of platform is included in the system of systems.

b. Optimization Results

The optimization model generated three alternative architectures, each optimized to highlight specific possibilities. The first architecture is performance optimized, selecting platforms to achieve the highest capability score possible. The second architecture, dubbed the "budget" architecture, is selected to achieve the highest capability score for approximately one quarter the cost of the original system, \$12M. The final architecture was selected to observe the capabilities that could be achieved from the lesser chosen platforms. The reason this architecture is included is to provide an alternate design if contracting for a selected system proves infeasible. The composition and capability score for each of the three generated alternate architectures is shown below in Table 18. Tables 19 through 23 summarize the number of systems in each system of systems generated by the team and the optimization model.

Table 18. Alternate SoS

System	Performance optimized	Budget	Alternate platforms
Hero 900	32	0	8
Coyote	48	54	12
Switchblade	0	0	0
Jump 20	0	0	54
Aerotriton	0	3	0
Dive LD	0	0	1
MDUSV	1	0	1
VBAT	4	2	2
Sunglider	0	1	1
Cost	$42.5M	$12M	$46.9M
Capability score	50.6	40.9	47.3

Table 19. Jump 20 SoS Alternatives

Architectures	AEG	AFG	AEH	AFH
VBAT search	1	1	1	1
Jump 20	4	4	4	4
VBAT comms	2	0	2	0
Sunglider	0	1	0	1
Switchblade	18	18	0	0
Coyote	8	8	26	26

Table 20. Dive LD SoS Alternatives

Architectures	BEG	BFG	BEH	BFH
VBAT search	1	1	1	1
Dive LD	2	2	2	2
VBAT comms	2	0	2	0
Sunglider	0	1	0	1
Switchblade	18	18	0	0
Coyote	10	10	28	28

Table 21. Aerotriton SoS Alternatives

Architectures	CEG	CFG	CEH	CFH
VBAT search	1	1	1	1
Aerotriton	3	3	3	3
VBAT comms	2	0	2	0
Sunglider	0	1	0	1
Switchblade	18	18	0	0
Coyote	6	6	24	24

Table 22. MDUSV SoS Alternatives

Architectures	DEG	DFG	DEH	DFH
VBAT search	1	1	1	1
MDUSV	1	1	1	1
VBAT comms	2	0	2	0
Sunglider	0	1	0	1
Switchblade	18	18	0	0
Coyote	0	0	18	18
Hero	32	32	32	32

Table 23. Optimized SoS Alternatives

Architectures	Budget	Performance	Alternate Platform
VBAT search	2	2	2
Dive LD	0	0	1
Aerotriton	3	0	0
MDUSV	0	1	1
VBAT comms	0	2	0
Sunglider	1	0	1
Coyote	54	48	60
Hero	0	32	8

The system of systems value and cost was calculated for each of the alternatives. The system value was calculated by summing the value of each of the systems in each alternative. Displayed in Table 24 is the cost of each architecture, system value, total number of units, number of offensive UAV and number of defensive UAV. Color gradient is applied to illustrate the differences between the systems. To determine effectiveness the alternatives, each one was evaluated using combat modeling.

Table 24. SoS Characteristics

Architectures	System Cost	System Value	System Size	Total Units	ASUW	C-UAS/ C-Swarm
AEG	$5,880,000	21915	73	33	8	18
AFG	$11,580,000	22500	59	32	8	18
AEH	$4,890,000	19951	76	33	8	18
AFH	$10,590,000	20536	62	32	8	18
BEG	$3,510,000	23368	52	33	10	18
BFG	$9,210,000	23953	38	32	10	18
BEH	$2,520,000	21403	55	33	10	18
BFH	$8,220,000	21989	41	32	10	18
CEG	$6,450,000	19559	39	30	6	18
CFG	$12,150,000	20145	25	29	6	18
CEH	$5,460,000	17595	42	30	6	18
CFH	$11,160,000	18180	28	29	6	18
DEG	$41,510,000	105614	22	54	32	18
DFG	$47,210,000	106199	8	53	32	18
DEH	$40,520,000	103649	25	54	32	18
DFH	$46,220,000	104235	11	53	32	18
Budget	$12,110,000	38125	42	60	6	48
Performance	$41,470,000	123594	38	85	32	48
Alternate platform	$41,650,000	98144	41	73	26	48

E. COMBAT SIMULATION

Modern missile warfare can be evaluated using the salvo combat model (Hughes 2000). The model is explained using the equations in Figure 23. This model was used to calculate the effectiveness of each of the SoS alternatives in each of the vignettes.

$$\Delta B = \frac{\sigma_A a_2 A - \tau_b b_3 B}{b_1} \qquad \Delta A = \frac{\sigma_B b_2 B - \tau_a a_3 A}{a_1}$$

Figure 23. Salvo Combat Model Equations. Source: Hughes (2000).

The salvo combat model's dependent variables are ΔA and ΔB. These are the number of units of a given force rendered out of action from an enemy salvo. There cannot be more units put out of action than there are number of units. If the dependent variables ΔA and ΔB are greater than the number of units, it signifies excess hits. This value is represented with *A and *B. The independent variables of the model are listed in the table below followed by the analytical assumptions.

Table 25. Salvo Combat Model Variables. Source: Hughes (2000).

Variable	**Description**
A, B	Number of units in force A and B
a_1, b_1(Staying power)	Number of hits to put one of A and B ship out of action
a_2, b_2(Offensive power)	Well aimed missiles launched by each A and each B ship
a_3, b_3(Defensive power)	Number of missiles each unit in A and B can intercept
σ_a,σ_b (Scouting)	Capability to find and target an adversary
τ_a,τ_b (Readiness)	Readiness of a defender

- firing of precision missiles is distributed uniformly
- all ships are homogenous on each side
- the firing side is within missile range, is well trained, and there are no decision errors
- there are no undetected targets
- missiles fired will hit

Accounting for these assumptions, the model was run through fourteen different iterations. The baseline iteration does not include an over-the-horizon search and targeting asset for either unit. To focus on the impact of over-the-horizon targeting, both units were assigned the same staying power, offensive power, defensive power, scouting and readiness. USN assets are represented by A, and PLAN assets are represented by B. The first four iterations established a baseline for performance. Next, the benefits of a USN over-the-horizon UAV and a Counter-UAV system, independent of current IAMD combat systems, were investigated. The second iteration included a PLAN UAV. The addition of this capability increased the variable scouting and readiness to the value of one. USN's offensive power was reduced to zero indicating the position of the PLAN unit is unknown and cannot be engaged. The third iteration signifies both units as having the over-the-horizon capability. The fourth iteration signifies only the USN having the over-the-horizon capability after the PLAN UAV is attrited, a weapon system that is independent of its IAMD defensive power. The USN UAV increased both scouting and readiness of the USN unit.

Table 26. Baseline Salvo Combat Model Results

Variable	**Baseline**	
A, B	1	1
a_1, b_1(Staying power)	1	1
a_2, b_2(Offensive power)	8	8
a_3, b_3(Defensive power)	8	8
σ_a,σ_b (Scouting)	0.7	0.7
τ_a,τ_b (Readiness)	0.7	0.7
ΔA, ΔB (Units killed)	0	0

Table 27. UAV Salvo Combat Model Results

Variable	**PLAN UAV**		**PLAN UAV & USN UAV**		**USN UAV**	
A, B	1	1	1	1	1	1
a_1, b_1(Staying power)	1	1	1	1	1	1
a_2, b_2(Offensive power)	0	8	8	8	8	0
a_3, b_3(Defensive power)	8	8	8	8	8	8
σ_a,σ_b (Scouting)	0.7	1	1	1	1	0.7
τ_a,τ_b (Readiness)	0.7	1	1	1	1	0.7
ΔA, ΔB (Units killed)	1	0	0	0	0	1

The results demonstrate the importance of an over-the-horizon ISR platform and an independent weapons system to engage enemy UAV. If defensive power is expended on an enemy UAV there is insufficient defensive power to engage the enemy's offensive power.

The next three iterations examined the effect that the inclusion of PLAN anti-surface warfare (ASUW) UAV would have on the model. The first iteration models the PLAN simultaneously engaging the USN with 8 ASCM and 12 UAV. This was accomplished by increasing the defensive power. The next two iterations model the inclusion of USN counter-swarm (C-SWARM) at the two different quantities from the SoS alternatives.

Table 28. Swarm Salvo Combat Model Results

Variable	**PLAN SWARM**		**PLAN SWARM & USN C-SWARM (12)**		**PLAN SWARM & USN C-SWARM (42)**	
A, B	1	1	1	1	1	1
a_1, b_1(Staying power)	1	1	1	1	1	1
a_2, b_2(Offensive power)	8	20	8	20	8	20
a_3, b_3(Defensive power)	8	8	20	8	50	8
σ_a, σ_b (Scouting)	0.7	0.7	0.7	0.7	0.7	0.7
τ_a, τ_b (Readiness)	0.7	0.7	0.7	0.7	0.7	0.7
ΔA, ΔB (Units killed)	1	0	0	0	0	0

The results demonstrate how the limited defensive power of current IAMD combat systems can be overwhelmed by cost effective ASUW UAV. The capacity of AEGIS cannot easily or cost effectively be increased to meet this threat. An independent system is required to increase the defensive power.

The final seven iterations model the inclusion of ASUW UAV delivered over-the-horizon and conducting a simultaneous attack with the USN's ASCM. The offensive power was increased to match the capacity of the system of system described previously.

Table 29. ASUW UAV Salvo Combat Model Results 1

Variable	Jump 20 (4) Coyote (8)		Dive-LD (2) Coyote (10)	
A, B	1	1	1	1
a_1, b_1(Staying power)	1	1	1	1
a_2, b_2(Offensive power)	16	8	18	8
a_3, b_3(Defensive power)	8	8	8	8
σ_a, σ_b (Scouting)	0.7	0.7	0.7	0.7
τ_a, τ_b (Readiness)	0.7	0.7	0.7	0.7
ΔA, ΔB (Units killed)	0	1	0	1

Table 30. ASUW UAV Salvo Combat Model Results 2

Variable	Aerotriton (3) Coyote (6)		MDUSV (1) Hero 900 (32)	
A, B	1	1	1	1
a_1, b_1(Staying power)	1	1	1	1
a_2, b_2(Offensive power)	14	8	40	0
a_3, b_3(Defensive power)	8	8	8	8
σ_a, σ_b (Scouting)	0.7	0.7	0.7	0.7
τ_a, τ_b (Readiness)	0.7	0.7	0.7	0.7
ΔA, ΔB (Units killed)	0	1	0	1

Table 31. ASUW UAV Salvo Combat Model Results 3

Variable	Budget		Performance		Alternate platform	
A, B	1	1	1	1	1	1
a_1, b_1(Staying power)	1	1	1	1	1	1
a_2, b_2(Offensive power)	14	8	40	8	34	8
a_3, b_3(Defensive power)	8	8	8	8	8	8
σ_a, σ_b (Scouting)	0.7	0.7	0.7	0.7	0.7	0.7
τ_a, τ_b (Readiness)	0.7	0.7	0.7	0.7	0.7	0.7
ΔA, ΔB (Units killed)	0	1	0	1	0	1

The results demonstrate the benefit of adding over-the-horizon search and targeting capability. To increase the USN unit's lethality require the capability to deliver additional over-the-horizon firepower. Using theses insights developed a combat model to simulate each vignette in greater detail.

1. Spreadsheet Combat Model

Both units possess integrated air and missile defense in depth. To model this interaction, the different engagements were modeled in Microsoft Excel using an Inverse Binomial function, shown below. To attain stochastic results the number of trials was set to 300 and each probability was given a range of possible values.

BINOM.INV (ASCM, Probability of K, Random Number)

The independent variables in the model can be categorized as either defensive or offensive. The defensive variables are the number and probability of kill of integrated air and missile defense weapons on each unit. The offensive variables for the PLAN are the YJ-18 ASCM and Harpy UAV. The offensive variables for the USN are the Maritime Strike Tomahawk ASCM and purposed ASUW UAV. Defensive probability of kill and limits of current weapon systems are listed in Table 32. The values apply to the weapons effectiveness against both the ASCM and ASUW UAV threat.

Table 32. IAMD Probability of Kill and Limits

USN	PLAN	PK High	PK Low	Limit
SM-2	HQ-9	90	63	4
ESSM	HQ-10	90	63	1
5 in	130 mm	37	25	1
NULKA	Chaff	50	35	1
CIWS	Goalkeeper	90	63	1

The two proposed defensive systems have different probabilities of killing enemy threats. Because the Switchblade system has an EO/IR sensor onboard it was assigned a higher probability of kill than the Coyote system, which lacks an EO/IR sensor.

Table 33. C-Swarm Probability of Kill

System	PK High	PK Low
Coyote	70	49
Switchblade	90	63

Table 34. PLAN Weapon Limits

Threats to USN	Quantity	
Weapon	**High**	**Low**
YJ-18	8	6
ASN-301 Harpy	12	8

The three ASUW UAV alternatives were treated the same by the PLAN defensive systems. The different systems were modeled by an increase in the quantity of ASUW UAV.

Table 35. USN Weapon Limits

Threats to PLAN	Quantity	
Weapon	**High**	**Low**
MST	8	6
ASUW UAV 1	6	4
ASUW UAV 2	8	6
ASUW UAV 3	10	7
ASUW UAV 4	26	18
ASUW UAV 5	32	22

The result of the simulations indicates the number of hits either on the enemy surface platform or on the USN surface unit. The number of hits is characterized by mean, standard deviation, standard error, 0.95 confidence interval high and low. By comparing the number of hits with the proposed system to the baseline, a percentage of change was attained. This is presented in the equation below.

Measure of Effectiveness = (Baseline # Hits – SoS # Hits) / Baseline # Hits

Using the 0.95 confidence interval, the estimated range of number of hits were used to calculate the percentage change for both defense and offense for each of the SoS. This result allows for the following statement to be made regarding each SoS: Based on the model, one can expect with 0.95 confidence that the addition of the SoS will increase the effectiveness of the surface unit between the two values. The four measures of effectiveness are listed below.

Defensive Percentage Change High = (Baseline # Hits on USN DDG – SoS # Hits on USN DDG High) / Baseline # Hits

Defensive Percentage Change Low = (Baseline # Hits on USN DDG – SoS # Hits on USN DDG Low) / Baseline # Hits

Offensive Percentage Change High = (Baseline # Hits on PLAN DDG – SoS # Hits on USN PLAN High) / Baseline # Hits

Offensive Percentage Change Low = (Baseline # Hits on PLAN DDG – SoS # Hits on USN PLAN Low) / Baseline # Hits

The effectiveness of both offense and defense were weighted equally for our analysis allowing the high values for offensive and defensive percentage change to be summed to calculate a total percentage of change high and low. Equations for the final two measures of effectiveness are listed below. The results of the model will be discussed in subsequent chapter.

Total Percentage Change High = Defensive Percentage Change High + Offensive Percentage Change High

Total Percentage Change Low = Defensive Percentage Change Low + Offensive Percentage Change Low

2. Model Validation Using Agent-Based Modeling and Simulations (ABMS)

The last part of the Mission Engineering framework requires our model to be validated (Office of the Deputy Director of Engineering 2020). To accomplish this, an agent-based modeling and simulation (ABMS) methodology was utilized. The following is a description of the objectives, components, and methodology of ABMS used to validate the results of the previous model.

ABMS was used to validate each of the envisaged system architectures against the desired MOEs. ABMS aims to capture the stochastic, yet complex, nature of warfare engagement by modeling the interactions between agents. Repeated computational simulations were conducted to gather individual-level data on the performance of each system. Subsequent statistical analysis allowed us to ascertain and quantify the improvement each proposed system architecture achieves, providing decision-makers a means to conduct cost-benefit analysis on the architectures. Similar studies using ABMS were conducted by the RAND corporation on network centric operations to study the networking capability factors affecting warfighter effectiveness (Porche and Wilson 2006). Further studies showcased the emergence of population-level dynamics and behaviors from micro-level social influence (Nowak et al. 2017).

There are three components to an ABMS: agents, environment, and interactions. Agents are the respective warfighting platforms and weapons. Each agent has its own internal state for attributes such as damage points or physical dimensions. Agents also possess a set of actions to interact with the environment or other agents. The behaviors of agents are governed by rules crafted by the scenario designer.

The environment provides the setting in which agents interact with each other or with the environment. For instance, the ability for an agent's sensor to detect a flying aircraft is a function of the property of the sensor, the aircraft, and the environment. In some sense, the environment adjudicates the interactions between agents; the outcome of interaction between two missiles is determined probabilistically depending on the dynamics and characteristics of interacting agents.

The interactions between agents at an individual level allows ABMS to produce a large amount of data for analysis. The interactions with the environment are modeled using physics-based engineering models, such as the trajectory of a naval ship movement in different sea states, the flight of a guided weapon, or the degradation of communication range between communication nodes with distances. The interactions between agents utilize engagement models. For example, the propagation of a radar wave across space to detect an aircraft is governed by the radar equation and the properties of the environment, the characteristics of the search radar, and the target at a specific time. The interactions between these agents coupled with rule-based doctrines allow us to understand the outcomes of each scenario and to provide quantitative comparison between each of the force architectures proposed in Table 23.

Command Modern Operations (CMO) was selected as the simulation engine for this project. CMO is a "cross-domain modern wargaming" computer software that aims to simulate tactical to operational level operations (Matrix Games 2022). The game software features an extensible open-sourced database engine, and a game simulation engine that models interactions using physics and effects-based kinematics for platforms, sensors, weapons and warheads. CMO was selected for its database of existing open-source data of USN and PRC naval platforms and weapon systems. CMO also provided the flexibility to custom-make additional platforms required for our proposed architectures. The individual level physics based ABSM allows the scenario designer to statistically analyze force-on-force engagements within the scenario. Importantly, CMO includes a Monte Carlo Analysis function which allows a given scenario to be run multiple times to generate statistics on the interaction between forces. The output from the Monte Carlo function provided a dataset to quantitatively compare the efficacy of each force architectures.

a. ABMS Assumptions

We assumed that the models used in CMO to adjudicate the engagement effects and movement of the agents in the simulation are within expectations of reality. In other words, using CMO reduces the need to introduce additional engagement models while limiting the scenario editor to creating scenarios for each set of force structures and designing new platforms and weapons for the purpose of force structure. In addition, since the study is limited to the force structure, the different means of organizing the delivery platforms for each scenario were not explored. For example, we assumed that by placing the delivery platforms at least 40 nm ahead of the USN DDG, these platforms would deliver their intended offensive munition on the target before the USN DDG could conduct offensive actions against the target.

Simulation of OTH sense and strike capability by the delivery platforms was reduced to organic sense-and-strike in CMO. The intended functionality of communications relay was not directly available in our simulation and hence limited the ability to model and simulate the communications relay between forward deployed ISR assets and delivery platforms to conduct OTH sense and strike on the enemy's surface vessel. Thus, we assumed and modeled each delivery platform's ability to conduct sense and strike organically by mounting an organic sensor suite to provide the agent with the ability to sense and interact with the environment and other agents. To compensate for the electronic emission from the sensor suite on the USV, we reduced the RCS of the delivery platform to make it less susceptible to an enemy's direct action.

It was assumed that the default loadout provided from CMO's database of the surface DDG was accurate and sufficient for our simulation purpose. In addition, to elicit the comparative differences afforded by each force architecture for USN, we reduced the default loadout of the USN DDG to a quarter. This would be useful to study the offensive and defensive MOEs as it allows the additional capabilities to be utilized before the end condition of the simulation was met. Table 36 illustrates the reduced weapon loadout for USN DDG and default loadout for PRC DDG in CMO database.

Table 36. Weapons Loadout in CMO for USN and PRC DDG

USN DDG 51 Arleigh Burke	**PRC DDG Type 052D (Luyang III) Class**
08 x RGM-84G Harpoon ICR 08 x RIM-66M-2 SM-2MR Blk IIIA 08 x RIM-66M-5 SM-2MR Blk IIIB 340 x 12.7mm/50 MG Burst [10 rounds] 280 x 127mm/54 HE-CVT [HiFrag] 260 x 127mm/54 HE-PD [HiCap] 80x 127mm/54 WP 30 x 30mm Goalkeeper Burst [240 rnds] 120 x Mk214 Sea Gnat Chaff 24 x Mk234 Nulka 36 x Mk245 GIANT Flare 4 x Mk59 Mod 0 Floating Decoy 2 x AN/SLQ-25A Nixie 14 x Mk54 LHT Mod 0	48 x HHQ-9 24 x HQ-10 [FL-3000N] 16 x YJ-18 12 x Harpy 440 x 130mm China H/PJ-38 HE 15 x 30mm China H/PJ-12 128 x Generic Chaff Rocket 64 x Generic Flare Rocket 2 x China Towed Acoustic Decoy 6 x Yu-7

b. ABMS Limitations

CMO had limitations that affected how each of the architectures and scenarios were modeled. An agent in CMO executes its actions based on the mission profile it is given and the doctrines and ROE pre-determined in the scenario. These rules-based actions would thus determine the properties and actions of the agents in the simulation. CMO provides a set of doctrines that determine the behaviors of the agent; while the scenario editor is allowed to activate or deactivate the doctrines for each agent, CMO's proprietary algorithms are not publicly available for validation. The description and observation of the doctrines available in the game's manual are the best reference to understand the intended actions of the agents.

Doctrine and rules of engagement (ROE) within CMO were preset and specific to the class of targets. CMO currently does not have a weapon to target matching rules of engagement module. The ROE settings are limited to create rules for agents to fire specific weapon systems against categories of targets. For instance, CMO does not allow the editor to dictate an agent to fire the modeled Coyote against guided weapons such as Harpy only. Coyotes would be fired by the agent if a guided weapon was sensed by the agent, independent of if it is a Harpy or YJ-18 inbound for the DDG. This is a reasonable tradeoff as the DDG may not have the high-fidelity resolution of the exact guided weapon that is targeting the DDG, but only a coarse awareness of an inbound enemy weapon. Engagement models and physics-based and effects-based models in CMO are proprietary, and scenario editors are not given full view of the inner workings. In general, these physics-based and effects-based models do not deviate from our expectation of how a weapon or platform would realistically perform.

c. Design of Experiment in CMO

The vignettes described in previous chapter were modelled in totality and consistently across all proposed SoS alternatives for the USN assets. This was to maintain a coherent adversary force, illustrated in Figure 24, while different optimized SoS configurations for USN were assessed. Table 37 states that all optimized SoS alternatives identified earlier, including the baseline configuration, that were modelled in CMO for subsequent analysis. USN assets emphasized in bold are the significant differences in delivery and offense platforms across the SoS alternatives; search and defense platforms remained the same throughout all configurations.

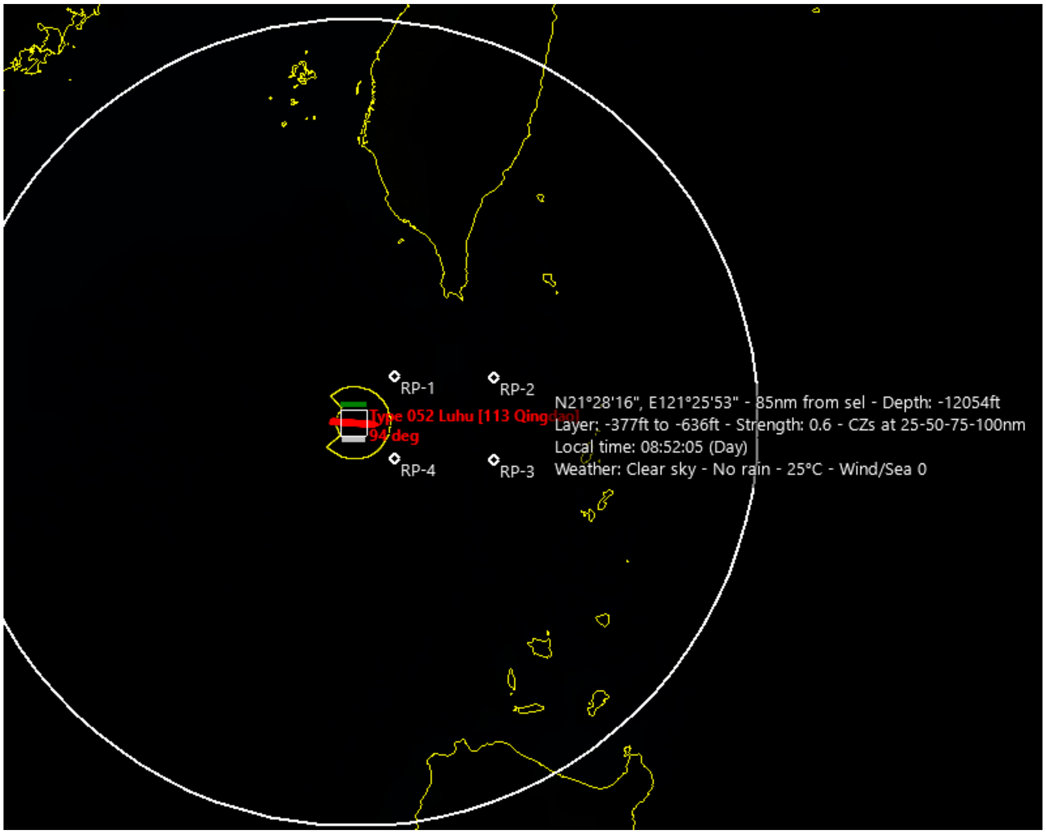

Figure 24. CMO model of PRC DDG with A2/AD box of 40 nm

Table 37. Optimized SoS Configurations Modelled in CMO

Configuration	USN	PRC
Baseline	01 x DDG 51 Arleigh Burke	01 x PRC TYPE 052D (Luyang III) Class 12 x ASN-301 Harpy 01 x Camcopter
Budget	48 x Coyote LM onboard DDG 02 x VBAT UAV 03 x Aerotriton, each with 02 x Coyote LM	
Performance	48 x Coyote LM onboard DDG 02 x VBAT UAV 01 x MDUSV, with 32 x Hero900 LM	
Alternate Performance	48 x Coyote LM onboard DDG 02 x VBAT UAV 01 x MDUSV, with 08 x Hero900 LM & 12 x Coyote LM 01 x Dive-LD, with 06 x Coyote LM	

Graphical illustrations of the various delivery and offensive platforms can be found in Figures 25 to 28. In the figures, it can be observed that CMO simulation was initialized with USN commencing 80 nm east of A2/AD box. Although both PRC and USN force units are initialized at the same locations, their behavior corresponds to the built-in ASUW mission settings in CMO and are stochastic in nature. For instance, the approach path taken by each agent towards the A2/AD area was dynamically determined and updated during runtime. Consequently, the sequence of sense and strike events between the agents differs between each iteration.

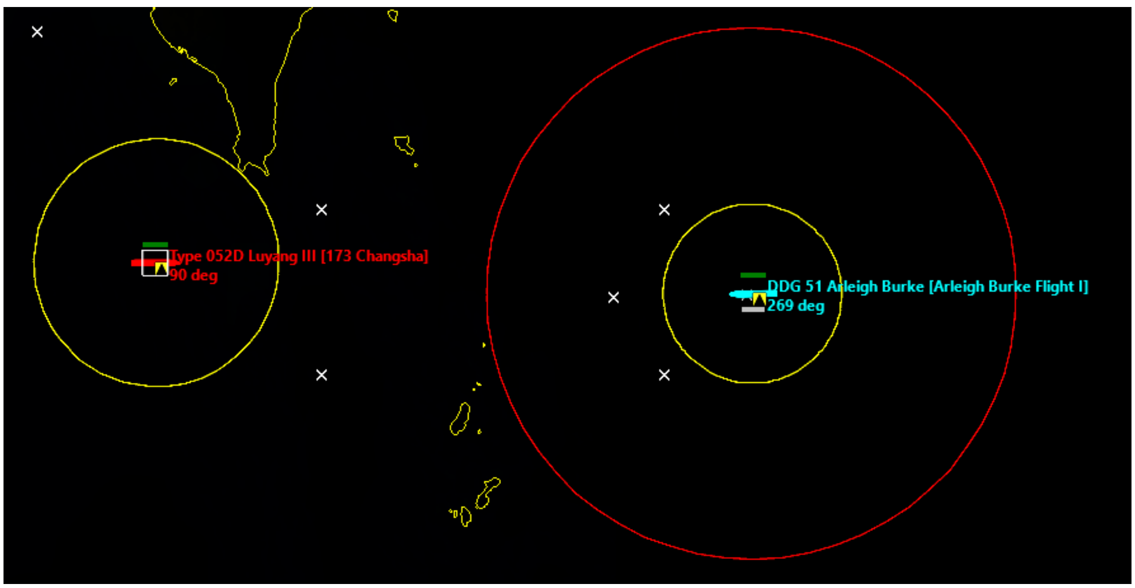

Figure 25. Start State of the Baseline in CMO

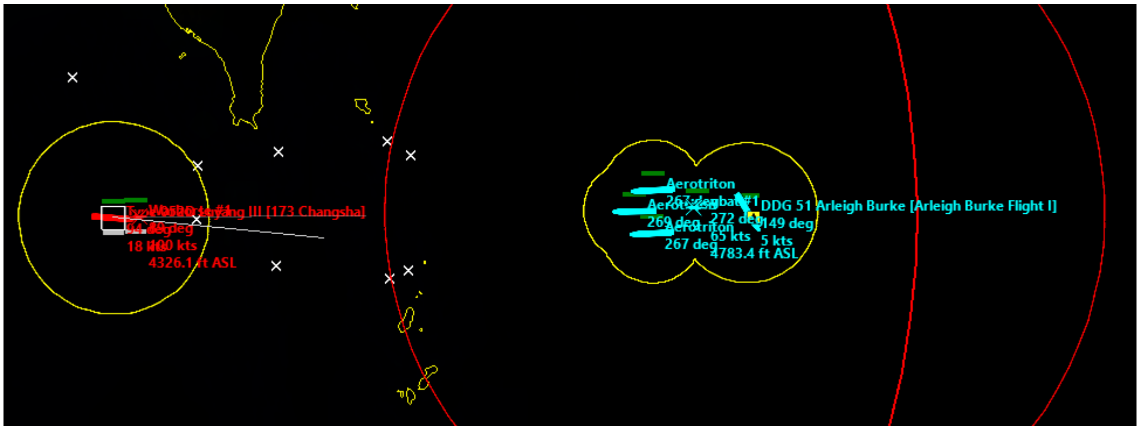

Figure 26. Start State of Budget Configuration in CMO

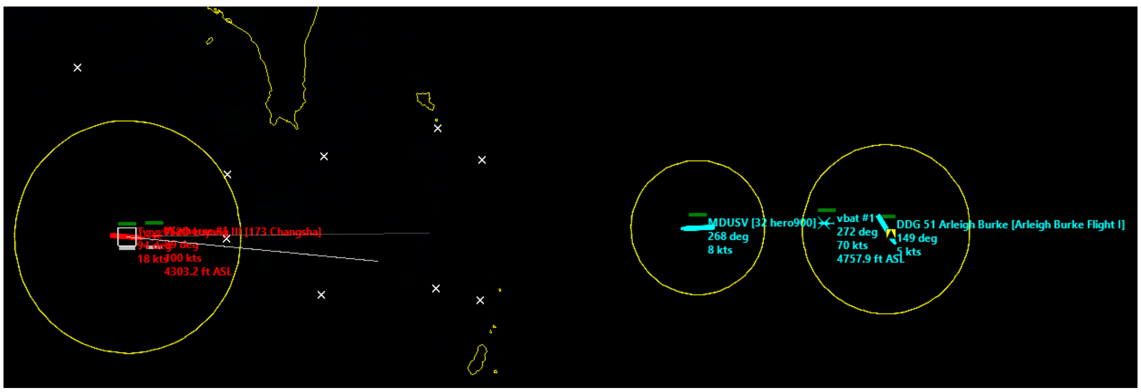

Figure 27. Start State of Performance Configuration in CMO

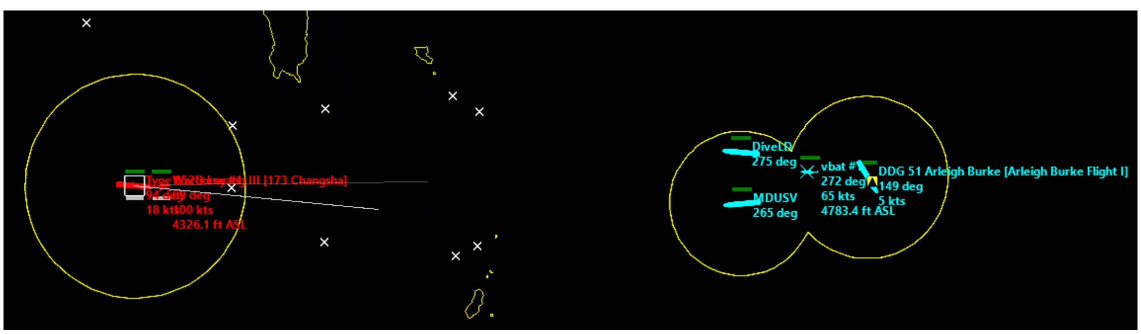

Figure 28. Start State of Alternate Performance Configuration in CMO

Nominal environmental conditions were modelled in CMO, to reduce the effects of weather on the emergent behaviors of the SoS alternatives. For all configurations, the environmental conditions are:

- weather: Clear sky, no rain
- temperature: 25˚C
- wind state: 0
- sea state: 2

An end condition is required to bound the time required to complete each scenario. Each iteration of the scenario terminates when either of these two conditions were met:

- the simulation time exceeded 48 hours
- either of the surface vessels were at least 40% damaged

As compared to multi-attribute value analysis approach, CMO allows for quantitative system MOPs to be modelled, and their relative differences to be observable in simulation outcomes. Each platform was modelled in accordance with publicly available information, with the following critical differences highlighted:

Delivery Platform

- Aerotriton. Long endurance but slow speed (2 kts subsurface, 5 kts surface) with lowest payload capacity, restricting the number of Coyote UAV equipped to two.
- MDUSV. Large payload capacity equivalent to a 40 ft container and cruise speed of 16 kts.
- Dive LD. Slow platform with maximum speed of 7 kts, with mid-range endurance. It has stealth advantage with an operating depth of 6000 m.

Offensive Weapon

- Coyote UAV. Small platform (0.91 m length by 1.5 m wingspan), giving it advantage in RCS compared to other offense candidates. It has a max speed of 70 kts, and low range of 80 km and 2 hr endurance.

- Hero 900 UAV. Relatively larger platform (2.5 m length by 1.8 m wingspan), resulting in relatively higher RCS. It operates at a max speed of 140 kts, with high range of 250 km and 7 hr endurance.

Defensive Weapon

- The MOP of defensive Coyote UAV used onboard DDG is like that of the offensive weapon above except for the defensive behavior allowing the Coyote UAV onboard the DDG to only target incoming guided weapons instead of hostile surface vessel.

d. Metrics from CMO

Data generated by CMO simulations were categorized into five groups: Sensor Detection Attempt, Unit Position, Weapon Fired, Weapon Endgame, Unit Status, Unit Destroyed. While all categories provided informative descriptions and statistics of the events occurring in each simulation run, only metrics under Weapon Fired and Weapon Endgame were of interest to the purpose statistical analysis. Data dictionaries for the two categories of interest are presented in Table 38 and 39 respectively, providing a summary of description for each field logged. The fields that are useful for our MOE calculation are boldface for awareness.

Table 38. Weapon Fired Data Dictionary Summary from CMO

Field	Description
TimelineID	The unique ID of the simulation run under which the event occurred
Time	The scenario time at which the event occurred
FiringUnitID	Firing Unit ID
FiringUnitDBID	Firing Unit ID in the database
FiringUnitName	Firing Unit Name
FiringUnitType	Firing Unit Type
FiringUnitClass	Firing Unit Class
FiringUnitSide	Firing Unit Side
FiringUnitLongitude	The longitude of the firing unit
FiringUnitLatitude	The latitude of the firing unit
FiringUnitCourse	The firing unit's course (heading) in degrees
FiringUnitSpeed_kts	The firing unit's speed (true airspeed in the case of aircraft) in knots
FiringUnitAltitude_m	The firing unit's barometric (above mean surface level) altitude, in meters
FiringUnitAGL_m	The firing unit's actual above-ground altitude, in meters
WeaponID	The unique ID of the weapon being fired
WeaponDBID	The database ID of the weapon being fired
WeaponName	The actual name of the weapon being fired
WeaponType	The type-description string (e.g., 'Guided Weapon') of the weapon being fired
WeaponClass	The unit-class description (e.g., 'AGM-154C-1 JSOW, 2012') of the weapon being fired
TargetContactID	The unique ID of the contact being fired upon
TargetContactLongitude	The current / last-known longitude of the contact being fired upon
TargetContactLatitude	The current / last-known latitude of the contact being fired upon
TargetContactHeading	The current / last-known heading of the contact being fired upon
TargetContactSpeed	The current / last-known speed of the contact being fired upon
TargetContactAltitude	The current / last-known barometric altitude of the contact being fired upon
TargetContactRangeHoriz_nm	The horizontal ranges from the firing unit to the engaged contact's last known location, in nautical miles
TargetContactRangeSlant_nm	The slant ranges from the firing unit to the engaged contact's last known location, in nautical miles
TargetContactActualUnitID	The unique ID of the actual unit correlated with the engaged contact
TargetContactActualUnitName	The actual name of the unit correlated with the engaged contact
TargetContactActualUnitClass	The unit-class description of the unit correlated with the engaged contact

Field	Description
TargetContactActualUnitSide	The name of the side to which the unit correlated with the engaged contact belongs
SalvoID	Salvo ID
CountermeasuresRemaining	Counter measures remaining

Table 39. Weapon Endgame Data Dictionary Summary from CMO

Field	Description
TimelineID	The unique ID of the simulation run under which the event occurred
Time	The scenario time at which the event occurred
WeaponID	Weapon ID
WeaponName	Weapon Name
WeaponSide	Weapon Side
ParentFiringUnitID	The unique ID of the unit that fired the weapon
ParentFiringUnitName	The actual name of the unit that fired the weapon
TargetID	The unique ID of the target unit at which the weapon is attacking
TargetName	The actual name of the target unit which the weapon is attacking
TargetSide	The name of the side to which the attacked unit belongs
TargetLongitude	The longitude of the target unit
TargetLatitude	The latitude of the target unit
TargetAltitude_ASL_m	The barometric (above mean surface level) altitude of the attacked unit, in meters
TargetAltitude_AGL_m	The actual above-ground altitude, in meters, of the attacked unit
DistanceFromFiringUnit_Horiz	The horizontal range from the weapon's firing unit to the endgame location, in nautical miles
Result	The result of the endgame sequence: Direct hit, miss or defeated by point defences
EndgameMessage	The generated logged message that describes the endgame sequence

MOEs defined in Table 6 in the earlier Mission Metrics chapter were adapted to collate the average number of hits across the simulation runs for each scenario. Using the *Result* field from Weapon Endgame and tracing each *WeaponID* and *WeaponSide* to respective *TargetID*, the firing and target units were identified, and the results of the weapons were collated. The pseudocode for determining the offensive MOE and defensive MOE is presented in Figures 29 and 30 respectively. Equations used to calculate the MOEs are presented in Table 40.

```
SET offensive MOE = 0
SET offensiveWeapons = list of WeaponID that are used to target Surface Vessels by USN
FOR each row in the Table WeaponEndGame
  IF row.TargetID is PRC DDG and row.WeaponSide is USN and row.WeaponID is in
offensiveWeapons THEN:
     IF row.Result is either 'HIT' or 'KILL' THEN add 1 to offensiveMOE
END
```

Figure 29. Calculation of Offensive MOE in CMO

```
SET defensiveMOE = 0
SET offensiveWeapons = list of WeaponID that are used to target Surface Vessels by PRC
FOR each row in the Table WeaponEndGame
  IF row.TargetID is USN DDG and row.WeaponSide is PRC and row.WeaponID is in
offensiveWeapons THEN:
     IF row.Result is either 'HIT' or 'KILL' THEN add 1 to defensiveMOE
END
```

Figure 30. Calculation of Defensive MOE in CMO.

Table 40. Equations Used to Calculate MOE

Offensive MOE	$Number\ of\ USN\ Weapon\ Hits\ on\ PRC\ DDG$
Defensive MOE	$Number\ of\ PRC\ Weapon\ Hits\ on\ USN\ DDG$
Offensive MOE (% of PRC fired)	$\frac{Offensive\ MOE}{Number\ of\ PRC\ Weapons\ Fired} \times 100\%$
Defensive MOE (% of PRC fired)	$\frac{Defensive\ MOE}{Number\ of\ USN\ Weapons\ Fired} \times 100\%$

F. COMBAT MODEL RESULTS

1. Spreadsheet Combat Simulation Results

The first results from the spreadsheet combat model were the simulated number of hits on the USN DDG by the PLAN DDG over three different iterations. The simulated results for a PLAN DDG attacking with only YJ-18, attacking with only Harpy, and a simultaneous YJ-18 and Harpy attack are listed in Table 41. The results from the simultaneous YJ-18 and Harpy attack were used as the baseline value in the defensive MOE.

Table 41. Baseline Hits on USN DDG

	YJ-18	Harpy	ASCM & Harpy
Number of hits on USN DDG	1	3	9

Next, the two different defensive UAV systems were separately added to the combat model. The simulation for a Harpy-only attack and simultaneous YJ-18 and Harpy attack were repeated with the added platforms. The defensive percentage change for each system was calculated using the previously described equation. The results for both systems are listed in Tables 42 and 43.

Table 42. C-Swarm Hits on USN DDG

	Switchblade	Coyote
Harpy	0	1
ASCM & Harpy (low)	3	4
ASCM & Harpy (high)	0	1

Table 43. Percentage of Defensive Change

System	Defensive change high	Defensive change low
Switchblade	100%	67%
Coyote	89%	56%

The next simulation returned the number of hits on the PLAN DDG by the USN DDG over three different iterations. The results for a USN DDG attacking with only MST, attacking with only the ASUW UAV, and a simultaneous MST and ASUW attack were generated. The number of hits resulting from an MST-only attack was used as the baseline value in the offensive MOE. Next, the seven different delivery systems were separately added to the combat model. The simulation was repeated for an ASUW UAV-only attack and simultaneous MST and ASUW UAV attack. The offensive percentage change for each delivery system was calculated using the previously described equation. The results for both systems are listed Tables 44 through 47.

Table 44. Baseline Hits on PLAN DDG

	Number of hits on PLAN DDG
MST attack only	1

Table 45. Only ASUW UAV Hits on PLAN DDG

Delivery platforms	**ASUW Only**
Jump 20	1
Dive LD	2
Aerotriton	1
MDUSV	19
Budget	1
Performance	19
Alternate platform	14

Table 46. MST/ASUW UAV Hits on PLAN DDG

	MST & ASUW UAV	
Delivery platforms	**HIGH**	**LOW**
Jump 20	7	6
Dive LD	8	7
Aerotriton	5	3
MDUSV	26	25
Budget	5	3
Performance	26	25
Alternate platform	22	21

Table 47. Percentage of Offensive Change

Delivery System	Offensive change high	Offensive change low
Jump 20	600%	500%
Dive LD	700%	600%
Aerotriton	400%	200%
MDUSV	2500%	2400%
Budget	400%	200%
Performance	2500%	2400%
Alternate platform	2100%	2000%

The final MOE for each of the alternative SoS is displayed in Tables 48 and 49. The equally weighted offensive and defensive percentage change are summed to calculate a total percentage of change for both high and low confidence. Based on the model, it can be expected with 0.95 confidence that the addition of the SoS will increase the effectiveness of the surface unit by a percentage between the high and low value.

Table 48. Percentage of Total Change

Offensive delivery	Defensive system	Total change high	Total change low
Jump 20	Switchblade	700%	567%
	Coyote	689%	556%
Dive-LD	Switchblade	800%	667%
	Coyote	789%	656%
Aerotriton	Switchblade	500%	267%
	Coyote	489%	256%
MDUSV	Switchblade	2600%	2467%
	Coyote	2589%	2456%
Budget	Coyote	489%	256%
Performance	Coyote	2589%	2456%
Alternate platform	Coyote	2189%	2056%

Table 49. Measures of Success

Search	ASUW UAV	Delivery	Comms	C-Swarm	Cost	MOE total change	MOE total change
VBAT	Coyote	Jump 20	VBAT	Switchblade	$5,880,000	700%	567%
			Sunglider		$11,580,000	689%	556%
			VBAT	Coyote	$4,890,000	700%	567%
			Sunglider		$10,590,000	689%	556%
		DIVE-LD	VBAT	Switchblade	$3,510,000	800%	667%
			Sunglider		$9,210,000	789%	656%
			VBAT	Coyote	$2,520,000	800%	667%
			Sunglider		$8,220,000	789%	656%
		AeroTriton	VBAT	Switchblade	$6,450,000	500%	267%
			Sunglider		$12,150,000	489%	256%
			VBAT	Coyote	$5,460,000	500%	267%
			Sunglider		$11,160,000	489%	256%
	Hero	MDUSV	VBAT	Switchblade	$41,510,000	2600%	2467%
			Sunglider		$47,210,000	2589%	2456%
			VBAT	Coyote	$40,520,000	2600%	2467%
			Sunglider		$46,220,000	2589%	2456%
	Budget	$12,110,000	489%	256%			
	Performance	$41,470,000	2589%	2456%			
	Alternate Platform	$41,650,000	2189%	2056%			

2. Results from Agent-Based Model

For the agent-based model, four scenarios (baseline, A1, A2 and A3) were created and run through 100 iterations. The recorded metrics from CMO are listed in Table 48 and 49. Following this, the agent-based model results were compared to the results from the spreadsheet combat simulation model. Table 50 presents the defensive and offensive MOEs derived from ABMS using CMO.

Table 50. Results of the ABMS Compared to Baseline

Design	Defensive MOE (Hits on USN DDG)	Offensive MOE (Hits on PRC DDG)	Defensive MOE (% of PRC fired)	Offensive MOE (% of USN fired)
Baseline	3.46 ± 1.201	0 ± 0	0.152 ± 0.079	0 ± 0
Budget	2.43 ± 1.578	0.06 ± 0.239	4.293 ± 2.994	0.145 ± 0.621
Performance	1.94 ± 1.462	0.56 ± 1.166	4.644 ± 3.828	1.346 ± 2.903
Alternate Performance	2.43 ± 1.565	0.05 ± 0.261	4.975 ± 3.45	0.125 ± 0.65

Pairwise hypothesis testing was conducted to assess the statistical improvement introducing the proposed SoS alternatives created when compared to the baseline, with p-values illustrated in Table 51 and Table 52 for offensive and defensive MOEs, respectively. It was concluded that each of the three proposed SoS outperforms the baseline with 95% confidence for both offensive and defensive MOEs.

Table 51. P-values from Offensive and Defensive MOEs Pairwise Hypothesis Testing

Offensive MOE (Hits on PRC DDG)

	Budget	Performance	Alternate Performance
Baseline	0.0068	0.0001	0.0292
Budget		0.0001	0.6111
Performance			0.0001

Offensive MOE (% of USN fired)

	Budget	Performance	Alternate Performance
Baseline	0.0106	0.0001	0.0285
Budget		0.0001	0.5887
Performance			0.0001

Defensive MOE (Hits on USN DDG)

	Budget	Performance	Alternate Performance
Baseline	0.0001	0.0001	0.0001
Budget		0.0119	0.5000
Performance			0.0116

Defensive MOE (% of PRC fired)

	Budget	Performance	Alternate Performance
Baseline	0.0001	0.0001	0.0001
Budget		0.7641	0.9312
Performance			0.261

Further testing was conducted to determine if the SoS alternatives performed similarly, or if any SoS alternative significantly outperformed the others with respect to each MOE. With respect to the offensive MOEs (Table 51), the performance optimized SoS alternative statistically significantly outperforms the budget and alternate performance alternatives. Comparing the budget and alternate performance alternatives, no statistically significant difference in offensive MOEs was observed. It is recommended that further study on the contributing factors (e.g., type and number of LMs and surface vessel performance) for offensive MOEs be conducted.

From Table 52, we observed that there are no statistical differences in the defensive MOEs between SoS alternatives. This was expected, since the additional defensive systems were relatively similar, and the change in offensive sub-systems in each SoS alternatives does not affect the performance of the defensive sub-system and defensive MOEs.

From the ABMS methodology, all three proposed architectures resulted in significant improvement for both offensive and defensive MOEs when compared to the baseline. This was expected, because the addition of defensive weapon systems on the DDG will reduce the number of direct hits that DDG sustains. Similarly, adding offensive weapon systems will enhance OTH sensor capability and increase the number of weapons for direct action on the target. Broadly, we can conclude that the performance observed from the ABMS correlates to the expected performance observed from the spreadsheet model.

Analysis of the offensive and defensive MOEs compared to the average number of weapons expended by each unit provides the following:

- The defensive MOE was a broad-based improvement, and none of the proposed architectures perform significantly better than the others. This is expected, since all three proposed architectures provide generally the same additional capabilities to the DDG. Thus, regardless of the number of shots fired by the PRC DDG, the improvement in defensive MOE remains similar across the three architectures.

- The largest differences between the three architectures are in the combination of delivery platforms and the offensive payload delivered. In this category the performance optimized architecture significantly outperformed the remaining architectures. In general, it is expected that a better performing system would fire fewer weapons at a target while dealing more hits. This property was only observed with the performance optimized architecture.
- While the conclusion on defensive MOE agrees with that of the spreadsheet model, the ABMS model departs in the analysis of offensive MOE, as both the budget and alternate performance architectures perform on par with the performance optimized architecture.

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V. CONCLUSIONS

A. ANALYSIS

The development and proliferation of low-cost unmanned systems presents a new and dangerous paradigm of threats to USN assets across the globe. Furthermore, without a capable counterthreat, commanders have no choice but to increase the standoff range to these threats unless they are willing to engage them using expensive weapons designed for higher end threats. Logically, most commanders would be unwilling to take such an action unless there is an eminent danger that risks the loss of the ship. Nominally, increasing standoff range is the more prudent decision, however, this conclusion will embolden adversaries to establish A2/AD environments to improve their own sea control.

The project results show that the acquisition of low-cost unmanned systems can both improve over-the-horizon targeting and add vital point defense to counter UAS capabilities with minimal modification to the legacy fleet. Additionally, these capabilities are essential to challenging and defeating adversarial A2/AD capabilities. Even the addition of lower performance counter-UAS platform, like Coyote, can improve survivability against adversarial UAS swarms. With the addition of any of the analyzed systems of systems a significant improvement was achieved over the baseline system.

Our analysis shows that success is largely driven by the number of kinetic strike platforms that can be deployed per engagement. This fact remains regardless of which kinetic strike platform is chosen. Furthermore, the efficacy of those kinetic strike platforms increases when equipped with multiple passive sensors to enhance the ability to find and identify targets. The kinetic strike platforms are mainly limited by their launch platforms, which have limited capacity to equip and deploy them.

However, the most critical factor that these types of systems of systems need to function effectively is the ability to communicate. These systems cannot meet the functional requirements without protected, high bandwidth communication capabilities. For our system designs, we require man on the loop style of command and control which would be ineffective without protected, high bandwidth communication. Therefore, the system that is providing communications is a vital lynch pin in our system of systems design. Furthermore, with additional time and resources, our agent-based modelling could have provided further insights into our designs and demonstrated the value of the communication platforms.

B. SELECTED ARCHITECTURES

This work shows the value that unmanned systems can bring to the current fleet architecture even in the most modest configuration. Based on the team's analysis, the best performing systems of systems configurations featured the use of the MDUSV and Switchblade, also known as the student generated DEG architecture as well as the performance optimization architecture. These were the two configurations that produced the highest percentage of total change and provided the greatest benefit to the commanders and crew. Of note, these represent the most expensive architectures.

When considering cost limitations, the most optimal system of systems is the student generated BEH architecture featuring the Dive-LD with the VBAT and Coyote. This option provides the largest total percentage change per dollar of system cost. The additional cost flexibility provided would allow for the deployment of additional Dive-LD based systems of systems. This could enable the possibility of a networked chain of Dive-LDs which would provide a persistent long-range strike or ASUW capability. The feasibility of such a distributed architecture would require additional analysis.

C. RECOMMENDATIONS

This project highlights the dangers faced by the U.S. Navy when facing a near peer competitor armed with commercial off the shelf (COTS) based unmanned systems enforcing an A2/AD environment. Furthermore, this project highlights the need for the acquisition of over-the-horizon targeting capabilities to support long range engagements. The results have outlined the functions needed as well as full sets of systems of systems that can provide the legacy fleet with this additional capability. Weather effects are of significant concern and would heavily effect both the search and communications capabilities of these systems. This concern could be somewhat mitigated if the search platforms were equipped with multiple passive sensors, increasing the probability of detection of adversary units regardless of weather conditions and even emissions controls techniques. Moreover, the recovery of these platforms is also of concern, specifically for the communications and search platforms. This limitation lends more credence to the selection of unmanned undersea assets, like the Dive-LD, which should face fewer issues during recovery.

The tasking required that the team constrain the cost of the systems chosen for analysis, not allowing for a strictly purpose-built system. Furthermore, the costs used for our analysis are the manufacturer's determined cost, which do not represent the life cycle cost for acquisition. The analysis shows that as the number of kinetic strike platforms increases, so does the quality of the resulting outcome. Therefore, should a large-scale unmanned platform with the ability to deliver a high number of kinetic strike vehicles be developed, even greater success would be achievable. However, the modularity and flexibility of such a system would be of concern as these systems were specifically designed to organically deploy from a DDG. There would also be a tradeoff to consider in the design of a purpose-based system as the size and carrying capacity would have to be balanced with the susceptibility.

Our work could be further enhanced and refined with the support of robust stakeholder feedback. Our stated stakeholders were primarily made up of academic resources available here at NPS. If we expand our stakeholder membership to include industry partners, we could further refine the systems that we developed as well as the analysis that we conducted. Furthermore, if we added additional warfare development staff, we could further refine our system design requirements

D. FURTHER WORKS

The focus of this work was primarily on the interdiction of an adversary in the A2AD environment, specifically, the South China Sea. The application of the proposed solution system should not be dependent on operations in only this region. The offensive capabilities should be applicable to a variety of different operational theaters and many kinds of operations. Moreover, these capabilities could enhance friendly A2AD scenarios to improve and enhance sea control. One specific application that our system would be well suited to is port defense and opposed egress. The benefit of these systems is clear; however, the full impact of their implementation is not known. How these systems could integrate into new advanced concepts such as Distributed Maritime Operations or Expeditionary Advanced Base Operation would need to be investigated. Furthermore, the team did not fully weigh the impact of human factors on these systems nor their impact on the hosting ship and crew. Additionally, the quality attributes of these systems were only marginally considered while the training requirements for them were not considered for our design or analysis. To analyze the training aspect of these systems, extensive development on how these systems would integrate into the AEGIS combat system. Finally, the critical operational issues for the selected system need to be analyzed to prove that the system will be both suitable and effective.

APPENDIX. MEMORANDUM FOR SYSTEMS ENGINEERING ANALYSIS COHORT 31 (SEA 31)

NAVAL
POSTGRADUATE
SCHOOL

30 June 2021

Memorandum for Systems Engineering Analysis Cohort 31 (SEA31)

Subj: FY2021 SEA31 Capstone Project: Tasking and Timelines

Enclosures:

Tab A: Mission Engineering for Hybrid Force 2045
Tab B: NPS Warfare Innovation Continuum "Hybrid Force 2045"

1. This memorandum provides the FY2021-22 guidance for the conduct of the Systems Engineering Analysis (SEA) integrated project, which is required as partial fulfillment for the SEA degree. SEA students will deliver completed project reports and final briefing materials to faculty advisors in accordance with the following plan and milestones. SEA 31 will:

a. Develop project proposals and management plans during the Fall Quarter AY2022. These proposals and plans will serve to focus initial research and analysis. These plans will be reviewed and updated frequently as research progresses.

b. Conduct project reviews approximately every six weeks, finishing with a final brief to interested stakeholders on and off campus.

c. Assign a report lead. Work closely with faculty advisors to prepare the final reports for faculty advisor signature by six workweeks before graduation. The final reports are then due to the SEA chair one week later; and to the Operations Research and Systems Engineering department chairs two weeks before graduation.

d. Develop and deliver an annotated briefing and report to OPNAV N9I that considers performance, costs, and design alternatives to better inform DoDs POM process.

2. SEA students will identify and integrate students and faculty from across the campus – and from outside NPS – to participate directly in the project or to provide source documents, technical knowledge and insights, and knowledge of evolving requirements, capabilities, and systems. This participation could include students who would join project groups like MSSE distant learning and MSA distant learning; students doing related individual thesis topics from TSSE, TDSI, OR, IS or SE; faculty inside or outside NPS who have expertise related to the project; and appropriately engaged government agencies

and industry developers. It is the students' responsibility to integrate the efforts of outside participants in the projects. Faculty advisors and the SEA Chair will significantly assist in these efforts.

3. Prior to commencing the formalized systems engineering and analysis process including stakeholder analysis, the SEA team will consult with Chairman of the NPS Institutional Review Board and submit a general description of the team's systems and analytical approach to address the tasking and a list of candidate questions for stakeholders for review. The intent is to ensure questions are oriented about the "what" of the systems and not about the "who" of the stakeholder.

4. The analysis will employ the systems engineering and operations analysis methodologies presented in class work and from the project advisors. The role of the SEA students is that of the lead project systems engineering team, working closely with other members of the project engineering teams from TDSI and other campus curricula. SEA students will be expected to define the functions and performance of systems, develop alternative architectures to meet those functions, and evaluate the alternative architectures for performance and cost. In executing these tasks, students will be defining and understanding the overall project requirements, recognizing that the definition process is iterative and will evolve as the project progresses.

5. Grades are assigned to the participants in these projects. Although work is performed as part of a team, individual performance will be the basis for this evaluation. Successful completion and documentation of the project is a degree requirement.

6. The SEA 31 project will build on, possibly challenge, but not replicate, other DOD, Navy, Naval War College, FFRDC, MSSE and SEA projects. SEA 31 will coordinate their study efforts, participate, and occupy leadership roles in other FY21/22 efforts at NPS aimed at contributing to developing the concepts and designs for preparing for war in the era of Great Power Competition and unmanned systems warfare. These activities, coordinated within the Warfare Innovation Continuum are described in Tab B.

Matthew G. Boensel
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Distribution: SEA 31 students; NPS Warfare Chairs; NWSI participants; Profs. Huang, Papoulias, Carlyle, Giachetti, Yakimenko, Pollman, Porter; President Rondeau; Provost Gartner; Deans Wirtz, Scandrett, Dell, Paduan, and Snider; CDR Arledge; LCDR Shutt; CDR Geiser, Dr. L. Shattuck, RADM Pitts (OPNAV N9I), Mr. Michael Stewart (OPNAV N9IB), Ms. Virginia Beall (N81B), Mr. Paul Lluy (OPNAV N9B), Mr. Charles Werchado (USMC ADC, P&R) and Ms. Kathie Cain

TAB A

Mission Engineering for Hybrid Force 2045

Reaping lessons learned from the all WIC activities, SEA 31 will focus on "Mission Engineering for Hybrid Force 2045." The SEA team will analyze selected architectures for various missions, for instance: Full Spectrum ASW; Littoral Warfare (Strike); War at Sea Strike (Long Range Fires); Port/Base Security; Integrated Air and Missile Defense; Maritime Interdiction Operations (Grey Zone activities); Protection of Underwater Infrastructures.

Overarching concepts described in the CNO NAVPLAN, NWP-3, Unmanned Campaign Plan, and other guidance direct the basis of force development and deployment. SEA 31 may use the NSWC Mission Engineering approach to describe the functional requirements, networks, and platforms. SEA 31 also will use principles from systems engineering to identify future force requirements, capability gaps, and an architecture to meet those requirements. SEA 31 will then synthesize mission-by-mission approach into larger-scope fleet requirements.

SEA 31 should anticipate an evolving threat; therefore, it is reasonable to envision that China and Russia employ many more Unmanned Systems in 2045. The above-mentioned mission areas may fit under the general concept of "Swarm vs. Swarm for Sea Control," but SEA 31 should seek to identify areas of synergy across proposed mission-area solutions.

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TAB B

NPS Warfare Innovation Continuum
A Coordinated Naval Postgraduate School Cross-Campus Project FY 21–22
"Hybrid Force 2045"

Purpose: This paper's purpose is to the FY21-FY22 NPS NWSI Warfare Innovation Continuum (WIC) theme to be "Hybrid Force 2045" to align with the CNO's NAVPLAN, the Tri-Service Maritime Strategy "Advantage at Sea," and the Navy's Analytic Master Plan.

Background: For the past 13 years the NPS has adopted a major theme of naval interest to align over 300 faculty and students' classroom, research, and capstone project work with emerging technologies, naval concepts, and operational issues. The Warfare Innovation Continuum (WIC) 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 in the littorals. Products from these efforts often precede and contribute to warfare development centers' concept development campaigns[i]. In this sense, NPS fulfills its mission to provide a graduate education experience to prepare our officers for uncertain conflict environments as technological leaders.

Discussion: Emerging technologies in unmanned systems; directed energy; autonomy; missile systems; undersea systems; long-range, netted, quantum and multi-domain sensors; additive manufacturing; artificial intelligence, and networks create a new environment for operations in the littorals, on, under and over the sea. This changing technology environment both challenges traditional fleet operations and provides opportunities for new fleet design; innovative tactics, techniques, and procedures to achieve maritime domain objectives in sea control, power projection and distributed maritime operations. Unmanned systems technologies; joint, combined and coalition forces contributions; and multi-domain C2 provide opportunities to support integrated offensive operations, and further develop a hybrid naval force to operate in the range from competition to conflict. As a graduate education and research center committed to gaining technological advantage, NPS is a fertile ground for exploring opportunities to advance force design.

Proposal: Designate "Hybrid Force Design 2045" as the NPS WIC theme for FY21-FY22. The WIC efforts can contribute, and be informed by, the Navy's AMP events and studies as it progresses. For example, issues from NWC wargaming on the Future Force Design 2045 may shape the WIC while in progress.

The larger research questions for this continuum are: **"How might emerging technologies, new operational concepts, and alternative fleet designs contribute to a more effective naval force across the spectrum from competition to conflict? How do the alternative**

fleet designs enhance the effectiveness and resilience of joint, combined and coalition forces across all domains?"

In alignment with the Tri-Service Maritime Strategy and CNO's NAVOPLAN and to support the Navy's Analytical Master Plan and Marine Corp's Force Design, the following WIC activities are proposed:

- NWSI research group Task Force Overmatch supports NAVWAR's efforts on Naval Operational Architecture Development
- Faculty submitting IREPs to the NPS Naval Research Program align their proposals to the CNOG's key operational problems (with no reference) and/or hybrid force development.
- Capstone Courses like the Wargaming, Joint Campaign Analysis, Joint C4I, Tactical Oceanography, Naval Tactical Analysis, and others adopt a common unclassified world-wide conflict scenario and address topics related to a "Hybrid Fleet," and those emerging technologies which may enable it. Specific technical or tactical/operational topics maybe subjects for sponsored wargames.
- The NPS NWSI September Warfare Innovation Continuum Workshop brings together naval systems commands and navy lab engineers; fleet representatives; warfare center and warfare development center representatives; warfare development squadrons, NEE faculty, and students; and industry engineers to consider emerging technology opportunities on hybrid fleet design
- Incoming students within the Master of Science in Strategy program will be directed to focus their applied research thesis towards topics related to a "Hybrid Fleet" and those emerging technologies may enable it.
- The NPS Total Ship Systems Engineering design some portion of an unmanned-manned platform system in a three-course engineering design sequence.
- The three-quarter NPS Systems Engineering Analysis interdisciplinary cross campus capstone project adopts "Hybrid Force 2045" to explore force architecture design alternatives.
- CRUSER, CISER, JIFX, and the various research centers on campus are made aware of the broad WIC topic and contribute to the final executive report

[i]2013-2014 WIC theme is "Distributing Air and Future Naval Forces" In January 2015 Surface Force proposes "Distributed Lethality" which USFF modifies in 2016 as the concept "Distributed Maritime Operations" Capstone projects (TSSE, JCA, and J4CI classes) and theses produced preceding these concepts and later in support of developing these concepts.

2014-2015 WIC theme is "Littoral Warfare in the Contested Environments" In 2015 the concept of "Littoral Operations in the Contested Environments" is proposed by NWDC and MWCL. NPS work fed directly into that proposal

2019-2020 WIC theme is "Logistics in Contested Environments," now a major study project by OPNAV N4, NWDC, and MCWL. NPS work includes analysis starting in FY18, the TSSE group design for a robust logistics carrier, and the SEA group interdisciplinary project with the same title. All provided to OPNAV N4, NWDC, and MCWL

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