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**SYSTEMS ENGINEERING
CAPSTONE REPORT**

**LONG RANGE FIRES JOINT FORCE OPERATIONS
IN GPS-DENIED AND DEGRADED ENVIRONMENTS**

by

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AND DEGRADED ENVIRONMENTS**

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ABSTRACT

The employment of Long-Range Fires is a high priority for the U.S. Navy, addressing the capability of forces to coordinate an emerging arsenal of deep strike weapons that can be launched from an array of joint assets against critical enemy assets at sea or hardened facilities on land. Additionally, the Long-Range Fires process must be resilient in a degraded or denied environment. However, coordinating Long-Range Fires encompasses a complex set of actions, to include target prioritization and development, command and control, tasking, kinetic and non-kinetic fires, battle damage assessment, rearming and contested logistics. Our approach leverages recent Navy-sponsored MBSE research, simulation, and analysis to include projects involving joint fires within Distributed Maritime Operations and feasibility of deploying hypersonic missiles on U.S. surface ships. We apply a similar approach here but augment it with a system of systems analysis of Long-Range Fires in a degraded and denied environment as part of a timely and relevant joint operational scenario. We examine significant design decisions and operational parameters, as well as appropriate measures of effectiveness, in generating successful Long-Range Fires through systems architecture development and simulation analysis.

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LIST OF ACRONYMS AND ABBREVIATIONS

3PS	Prosecution, Protection, and Prevention
A2/AD	Anti-Access and Area Denial
AC2	Assured Command and Control
AHE	Advanced Hawkeye
AOI	Area of Interest
ASAT	Anti-Satellite Weapon
BA	Battlespace Awareness
BDA	Battle Damage Assessment
BIT	Built in Test
C2	Command and Control
C4ISRT	Command, Control, Computers, Communications, Intelligence, Surveillance, Reconnaissance, and Targeting
C5ISRT	Command, Control, Computers, Communications, Cyber, Intelligence, Surveillance, Reconnaissance, and Targeting
CDCM	Coastal Defense Cruise Missile
CL	China Lake
COI	Contact of Interest
CONOPS	Concept of Operations
D3SOE	Denied, Degraded, and Disrupted Space Operational Environment
DARPA	Defense Advanced Research Projects Agency
DCNO	Deputy Chief of Naval Operations
DOE	Design of Experiments
EFFBD	Extended Functional Flow Block Diagram
EMI	Electromagnetic Interference
EMP	Electromagnetic Pulse
EMS	Electromagnetic Spectrum
ESSM	Evolved Sea Sparrow Missile
EW	Electromagnetic Warfare
FCO	Fire Control Officer
FoS	Family of Systems

GPS	Global Positioning System
GUI	Graphical User Interface
HAWC	Hypersonic Air-breathing Weapon Concept
HCM	Hypersonic Cruise Missiles
HGV	Hypersonic Glide Vehicles
HIMARS	High Mobility Artillery Rocket System
HVP	Hyper-Velocity Projectiles
ICAM	Integrated Computer Aided Manufacturing
IDC	Information Dominance Corps
IDEF0	ICAM Definition for Function Modeling
IF	Integrated Fires
IFTU	In-Flight Trajectory Update
INCOSE	International Council on Systems Engineering
IPR	In Progress Review
IPT	Integrated Product Team
ISR	Intelligence, Surveillance, and Reconnaissance
ISRT	Intelligence, Surveillance, Reconnaissance, and Targeting
JCID	Joint Capability Integrated Development
JCIDS	Joint Capability Integrated Development System
JCS	Joint Chief of Staff
LPD	Landing Platform Dock / Amphibious Transport Dock
MALD	Miniature Air-Launched Decoy
MBSE	Model Based Systems Engineering
MHA	Missile Hit Assessment
MIP	Military Intelligence Program
MOE	Measure of Effectiveness
MOP	Measure of Performance
NATO	North Atlantic Treaty Organization
NAVAIR	Naval Air Systems Command
NAVSEA	Naval Sea Systems Command
NAWCWD	Naval Air Warfare Center Weapons Division
NIP	National Intelligence Program

NOLH	Nearly Orthogonal Latin Hypercubes
NPS	Naval Postgraduate School
OASuW	Offensive Anti-Surface Warfare
ONR	Office of Naval Research
OPNAV	Office of the Chief of Naval Operations
OV-1	High-Level Operational Concept Graphic
R&M	Reliability and Maintainability
RF	Radio Frequency
SAM	Surface-to-Air Missile
SAR	Synthetic Aperture Radar
SATCOM	Satellite Communications
SMDC	Space and Missile Defense Command
SoS	System of Systems
TPO	Technical Project Office
UAV	Unmanned Aerial Vehicle
WDL	Weapons Data Link

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EXECUTIVE SUMMARY

This capstone project examines the capability of U.S. forces to coordinate an emerging arsenal of deep strike weapons against enemy targets that can be launched from an array of joint assets, to include submarines, surface ships, land platforms, and aircraft. The emerging arsenal of deep strike weapons includes ballistic missiles, surface and air launched cruise missiles, and hypersonic missiles. Other systems used in the capstone excursion scenarios include decoys with jamming capabilities and flares to obscure and offset enemy sensing capabilities. This combination of weapons is launched against targets composed of critical enemy assets located at sea or hardened, land-based facilities.

A notional scenario has been developed for simulation purposes to examine the success rate of various combinations of long-range fire weapons for striking targets within degraded or denied Command, Control, Computers, Communications, Intelligence, Surveillance, Reconnaissance, and Targeting (C4ISRT) environments. Four scenario excursions were developed to expand on the notional scenario to assess further variability in weapon combinations. For simulation purposes, the degraded environment means C4ISRT capabilities for the deep strike weapons are reduced by up to 40% and 60% for denied environments.

The notional excursion scenario involves Country Blue's national Intelligence Surveillance, and Reconnaissance (ISR) assets revealing that Country Red is installing a long-range hypersonic missile launcher on disputed Country Red controlled territory. This site has the capability to launch an attack on Country Blue, partner nation naval or land targets including major cities, military locations, or on Country White shipping in the Azure Sea. Country Red has sophisticated ISR, Anti-satellite (ASAT) weapons, and offensive cyber capabilities that could be used to disrupt or disable Country Blue C4ISRT and can be expected to employ these should Country Blue attempt a strike. Country Red's hypersonic missile launch site is not yet completed, but it is protected by Anti-Access and Area Denial (A2/AD) weapons and has anti-air, and medium range defense missiles. Country Blue's joint forces, led by the Navy, has been directed to eliminate the proposed

Country Red launch site before it becomes operational and a threat to Country Blue's strategic interests.

The top-level system functions are: 1) executing command and control (C2), 2) conducting intelligence, surveillance, and reconnaissance (ISR), and 3) employing weapons. Each of these functions are decomposed further to lower-level functions. This report focuses its efforts on assessing battle damage under executing C2 and the two lower-level functions, selecting weapons and fire weapons under engage contact of interest (COI) which is decomposed from the employ weapons function.

In our study, the MOE of probability of kill determines the percent chance the Blue Force long-range fire weapon renders the Red Force target destroyed so it cannot be used to launch any weapons. The MOE of probability of damage is the percentage reduction of capability for the Red Force target to launch a weapon after being hit by a Blue Force weapon. The MOPs include the probability of intercept and probability of hit. Probability of intercept is the percent chance the Red Force is able to intercept the incoming Blue Force weapon preventing it from hitting the Red Force target. Probability of hit is the percent chance the Blue Force weapon strikes the Red Force target resulting in damage to the target.

There are several system design variables that affect the success of Blue Force long-range fire weapons such as probability of hit or kill but most are set by the weapon manufacturer. For our simulation, we therefore focused on the operational variables that can be adjusted by the mission commander including the number of weapons per salvo or the number of decoys used along with the weapon salvo. The percentage of C4ISRT available to the Blue Forces (the objective is to make that percentage as high as possible) is a variable used in the simulation which is reduced due to the Red Force target located within a degraded or denied environment, but that reduction can be mitigated with the addition of decoys.

Based on the functional hierarchy and the primary variables, our simulation results show that the addition of decoys along with the long-range fire weapon salvo is more effective at successfully destroying the Red Force target compared to adding more weapons to the salvo. The decoys can reduce the amount of C4ISRT degradation caused by the Red

Force which results in a higher probability of hit and kill for the Blue Force weapons. Additionally, considering the cost of decoys versus weapons used, including cruise missiles, Sea-skimming missiles, and hypersonic missiles, it can be more cost effective to use more decoys with the weapons salvo than adding more long-range fire weapons to the salvo.

Possible future research may use our simulation with real world data for weapon probability of kill, probability of detection, or C4ISRT capabilities. The addition of these real-world variables would require the investigation team to follow proper classification guidelines.

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This capstone team would like to extend our gratitude to Professors Paulo, Beery, MacKinnon, and Porter for their direction and support in undertaking the study of Long-Range Fires. We would also like to extend our appreciation to Professor Gehris for her guidance and insight in developing the simulation models. Additionally, we would like to recognize our individual commands for sponsoring this opportunity at the Naval Postgraduate School and for coworkers providing their expertise and insight. We would like to thank Mr. Robert Swain from NAWCWD for sharing his expertise. Finally, we would like to thank our friends and family for their encouragement and tolerance of the many hours spent as we progressed through this adventure.

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I. INTRODUCTION

A. BACKGROUND

Long range fires address the capability of U.S. forces to coordinate an emerging arsenal of deep strike weapons against enemy targets that can be launched from an array of joint assets, to include submarines and surface ships, land platforms, and aircraft. This concept involves launching ballistic missiles, cruise missiles, hypersonic missiles, decoys, flares, and electronic warfare weapons from multiple, extremely dispersed locations, against critical enemy assets at sea or hardened facilities on land. The long-range fires process must also be resilient in a degraded or denied environment. The integration of long-range fires into our joint forces clearly meets the Navy's priority of All Domain Fires, and when including the need to apply these fires in a degraded environment, it also directly addresses the Navy priority of Command, Control, Computers, Communications, Intelligence, Surveillance, Reconnaissance, and Targeting (C4ISRT).

Coordinating long range fires encompasses a complex set of actions, to include intelligence, surveillance, and reconnaissance; target identification, prioritization, and development; communications; command and control; precision targeting and navigation; kinetic fires; battle damage assessment; and rearming and resupply in a contested logistics environment. Understanding the most significant operational parameters, which may involve material system development or tactical/organizational adjustments, regarding successful employment of long-range fires in a concept of operations (CONOPS) which would likely take place within a degraded or denied environment would lead joint and maritime commanders to increased situational awareness (Magnuson 2021; U.S. Fleet Cyber Command n.d.).

B. PROJECT PURPOSE

Long-Range Fires represents a family of systems (FoS) that can increase the striking capability and survivability of joint forces tasked to enter denied maritime battlespaces and engage high-value targets with limited targeting data and target cueing.

The Long-Range Fires FoS will be capable of sea, land, and air launch and net-enabled, but not net dependent.

All long-range fires will be capable of in-flight targeting updates (IFTU) via Global Positioning System (GPS), link 16, and weapons data link (WDL). All weapons variants will be capable of autonomous target identification and aim point selection in a networked C4ISRT-denied environment.

The flight of Long-Range Fires weapons is updated with targeting information for track corrections. As shown in Figure 1, In Flight Track Updates (IFTU) are provided by components composed of Intelligence, Surveillance, and Reconnaissance (ISR) and Prosecution, Protection, and Prevention (3PS) in concert with the missile launcher and controller.

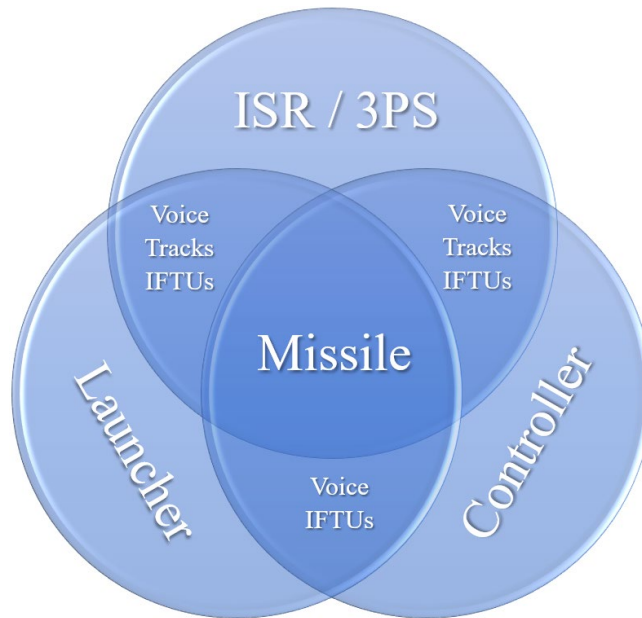


Figure 1. Long-Range Fire System. Adapted from NAVAIR (2013).

C. PROBLEM STATEMENT

Due to advancements made by our adversaries in weapons technology, the U.S. needs to effectively penetrate a denied territory under degraded C4ISRT conditions (NAVAIR 2013). New weapons technologies developed by adversaries include

Hypersonic Cruise Missiles (HCM), Hypersonic Glide Vehicles (HGV), and Hypervelocity Projectiles (HVP). It can be assumed that an adversary will use these types of weapons to counterattack U.S. attempts to penetrate denied battlespaces. The adversary may also be capable of degrading U.S. communications by means of cyberattacks, Electromagnetic Pulse (EMP) weapons, attacks on U.S. satellites, etc. Degraded communications can negatively impact the effectiveness of the weapons being used by the U.S. and jeopardize mission success. It is therefore necessary to assess how the U.S. can launch a combination of legacy and newly developed weapons to penetrate a denied territory within a degraded communications environment. Computer models can explore multiple scenarios to inform recommendations based on the results obtained.

D. RESEARCH OBJECTIVE

The technological edge and military superiority of the U.S. Navy is being jeopardized by the technological advances achieved by strategic competitors such as Russia and China. The U.S. Navy and the Joint Force is already investing in developing hypersonic/hypervelocity technology to maintain its military superiority while countering that of strategic adversaries.

Our group sought to determine significant design decisions and operational parameters necessary to generate successful Joint Long-Range Fires in a degraded or denied environment against critical enemy assets at sea or hardened facilities on land. We utilized a complex, relevant, and timely operational scenario and developed system models and an operational simulation to allow for a thorough systems analysis. The integration of long-range fires in degraded environments into our joint forces meets the Navy's priorities of All Domain Fires and Counter C4ISR. We sought to determine the potential increase in probability of kill by adding more long-range fire weapons to an attacking salvo compared to the potential increase in probability of kill using decoys along with the weapon salvo.

E. SYSTEMS ENGINEERING METHOD

The systems engineering methodology used in this project consists of five phases as depicted in Figure 2. The study begins by defining the problem being covered throughout

the capstone project. Initial research is performed to determine current capabilities associated with the defined problem and which areas of current knowledge can be expanded. The second step in the systems engineering methodology involves establishing a concept of operations (CONOPS) and narrowing the scope of the problem definition to maintain research focus. The next phase involves developing the system architecture and associated system models. This includes establishing project parameters by developing the project overview models that include OV-1, IDEF0, and system hierarchies. The fourth phase involves analyzing the system of interest through modeling and simulation. Project parameters are used to develop simulation models in Innoslate, Excel, Minitab, and ExtendSIM. These models are further developed and refined for comparing scenario outcomes. The final phase involves reviewing the analysis and simulation results to develop capstone project conclusions and recommendations and to identify areas for future research. All this effort culminates with the collection of results to form the final report and presentation (Van Bossuyt et al. 2019; Blanchard and Fabrycky 2011).

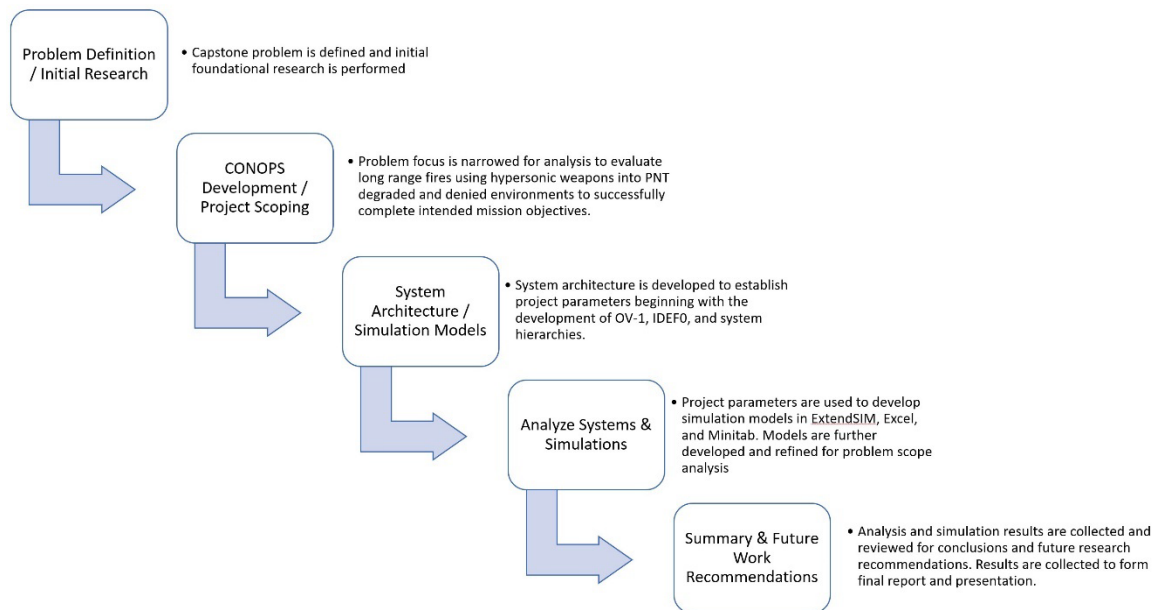


Figure 2. Systems Engineering Method

II. LITERATURE REVIEW

A. OVERVIEW

Prior literature was reviewed including previous capstone projects to better understand current capabilities related to Long-Range Fires in degraded and denied environments. The previous study, *Bringing Hypersonic Capability to the Fleet* (Banuchi, et al. 2021), provides insights on which current Navy platforms are the most effective to implement launching hypersonic missiles. This information can help to narrow down which platforms will launch hypersonic missiles in modeling for analysis.

The previous study, *Increased Effectiveness of the Joint Fires Kill Chain via Improvements in Command-and-Control Responsiveness for Better Cooperative Engagement Capability* (Haycock, et al. 2020), gives insights on kill chain effectiveness using three different network configurations (centralized, de-centralized, and distributed). This study also provides metrics on decision-making time and the type of distribution (uniform, normal, lognormal, or Binomial) that should be used for modeling. This study also provided quantifiable data for modeling and simulation showing how effective the kill chain was using various network configurations. The resulting data can be useful for developing new models for analysis.

The *Joint Concept for Command and Control of the Joint Aerial Layer Network* (Senate Armed Services Committee sub committee on Seapower 2020) document aids in understanding how the U.S. command can maintain communications in degraded environments. A notional Command and Control (C2) process for Joint Aerial Layer Networks is provided which can be used as a tailored framework for analysis. “C2 in a degraded environment requires a layered approach with the ability to adapt the changing electromagnetic environments beyond line of sight. This layered network approach, coupled with a command philosophy that allows commanders in all echelons the freedom to make decisions while operating within their higher commander’s intent, provides a resilient dynamic C2 structure that harnesses new and emerging technology to support decision superiority” (Geurts and Smith 2020, 4).

B. DEGRADED / DENIED ENVIRONMENT DEFINITION

Command and control signals can be affected by active interference from an adversary or natural environmental conditions (Center for Army Lessons Learned 2018). The composite of conditions, circumstances, and influences constitutes the Denied, Degraded, and Disrupted Space Operational Environment (D3SOE). “D3SOE applies to both actions taken within the electromagnetic spectrum and actions taken against physical assets that facilitate our use of space” (Francis n.d., 1). Some unintended or natural causes for D3SOE may be electromagnetic interference from space weather, terrain and vegetation effects, and allocation of satellite frequencies. Examples of adversary-induced threats to D3SOE “include signal jamming, signal spoofing, physically or virtually disabling or destroying space assets such as ground control stations and satellites and disabling or deceiving user equipment” (Francis n.d., 1). Figure 3 depicts the 14 major factors which may degrade or deny C2 capabilities.

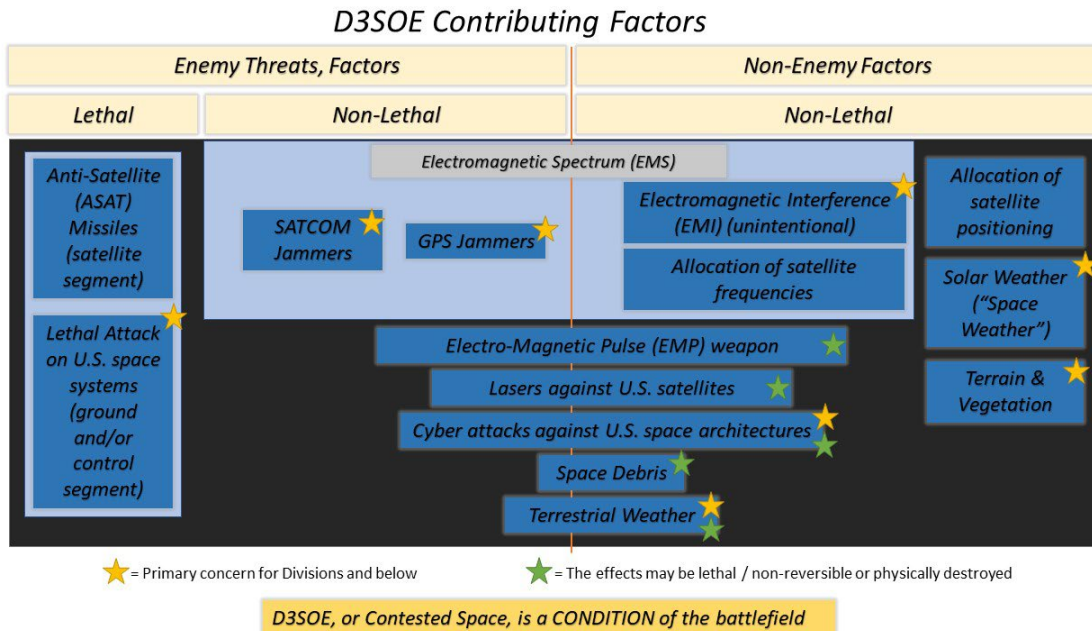


Figure 3. D3SOE Contributing Factors. Adapted from Center for Army Lessons Learned (2018).

For the purposes of modeling, this capstone refers to an adversary-induced *degraded* environment resulting in command-and-control signals reduced by at least 40% and a *denied* environment resulting in C2 signals reduced by at least 60%.

C. CAPABILITY GAP ANALYSIS

With new technologies becoming more available worldwide, the ability for unfriendly powers to instigate Anti-Access and Area Denial (A2/AD) strategies is becoming increasingly available. Anti-access domains can be established in the maritime regime through the employment of submarines, mines, and the operational and strategic placement of Coastal Defense Cruise Missiles (CDCM). New and increasingly more capable Surface-to-Air Missiles (SAM) that extend the A2/AD environment to include the maritime air domain impede the efficient execution of maritime air operations. Additional factors affecting A2/AD environments include disrupting underwater communication cables or surface operations that utilize civilian merchant vessels to obstruct harbors and ports by laying mines or the use of civilian fishing vessels armed with SAMs to pose a threat in the air domain (Ernst 2016). These and other tactics can create a degraded environment by disrupting satellite navigation, limiting ISR missions by jamming all-weather Synthetic Aperture Radar (SAR), and degrading communications with Electromagnetic Warfare (EW) jamming (Daniels and Starling 2021); (MacKenzie 2021).

D. COMBAT SYSTEMS

Various aircraft platforms can be used to launch weapons considered in this capstone, including cruise missiles, ballistic missiles, hypersonic missiles, and decoys.

1. Aircraft Platforms

In developing the excursion scenarios used in this capstone, a variety of aircraft platforms are considered including the F/A-18E/F, F-35 for launching weapons from a relatively mid-to close range from a target. For longer range launching the B-52H is considered. The E-2D is used in the excursion scenarios to provide C4ISRT information.

The F/A-18 shown in Figure 4, is “highly capable across the full mission spectrum: air superiority, fighter escort, reconnaissance, aerial refueling, close air support, air defense suppression and day/night precision strike” (NAVAIR 2022, 1).



Figure 4. F/A-18E/F Super Hornet. Source: NAVAIR (2022).

The F-35 shown in Figure 5, is a fifth generation single-engine, all-weather stealth multirole combat aircraft. The advanced technology of the F-35 provides the capability for air superiority and strike missions. With the addition of an advanced suite of sensors, the F-35 can conduct electronic warfare, intelligence, surveillance, and reconnaissance operations.



Figure 5. F-35 Lightning II. Source: NAVAIR (2022).

Long-range fire weapons can be delivered by large bombers including the B-52H Stratofortress shown in Figure 6.



Figure 6. B-52H Stratofortress. Source: U.S. Air Force (2022).

“The B-52H Stratofortress is a long-range, heavy bomber that can perform a variety of missions. The bomber is capable of flying at high subsonic speeds at altitudes of up to 50,000 feet (15,166.6 meters). It can carry nuclear, or precision guided conventional ordnance with worldwide precision navigation capability” (U.S. Air Force 2022).

Additional C4ISR asset to provide situational awareness to the battle space commander includes systems such as the E-2D Advance Hawkeye aircraft shown in Figure 7.



Figure 7. E-2D Advance Hawkeye (AHE). Source NAVAIR (2022).

The Hawkeye’s command and control capability makes it a multi-mission platform through its ability to coordinate concurrent missions that may arise during a single flight, to include airborne strike, land force support, rescue operations, managing a reliable communications network between widely dispersed nodes and support for drug interdiction operations. The use of the new glass cockpit and tactical fourth operator display allows the five-person crew more flexibility in fulfilling these diverse missions. (NAVAIR 2022)

2. Unmanned Aerial Vehicles

Unmanned Aerial Vehicle (UAV) classes of aircraft have less size and weight than conventional aircraft since accommodations for pilot and crew is not required. They provide mission planners the ability to deploy UAV aircraft with extended dwell-time. The

UAV system is typically comprised of the aircraft, sensor payloads, ground control station, communication equipment, and ground support. The UAVs can carry a variety of sensor payloads to conduct Intelligence, Surveillance, Reconnaissance, and Targeting (ISRT) (Tice 1991).

The MQ-9 Reaper shown in Figure 8, is an example of a UAV that can perform ISRT while carrying ordnance to strike targets after confirmation (United States Air Force 2021).



Figure 8. MQ-9 Reaper. Source: U.S. Air Force (2021).

The MQ-4C Triton shown in Figure 9, is another type of UAV used for ISR. The Triton is the largest UAV in the U.S. inventory and is capable of long range, high altitude, and long duration operations providing mission planners detailed ISR while orbiting outside contested airspace (NAVAIR 2021).



Figure 9. MQ-4C Triton landing at Point Mugu. Source: NAVAIR (2021).

3. Sea-skimming Missiles

Sea-Skimming Missiles fly low to the sea surface to avoid radar, visual, and infrared detection. The Tomahawk cruise missile shown in Figure 10 is an example of a Sea-skimming missile. Sea-skimming lowers the chance of detection by utilizing the earth's curvature and various radar sources to reduce radar image clutter. Sea-skimming missiles are equipped with radar altimeters continuously measuring the missile height above the sea surface (z-position) maintaining safe clearance from sea spray and waves depending on sea state. The missile guidance and control loop use the radar altimeter input to continuously update the ideal altitude above the sea surface. Sea-skimming missiles have lower probabilities of detection compared to cruise or ballistic missiles (White 2021).



Figure 10. Tomahawk Cruise Missile. Source: Raytheon Missile & Defense (2021).

4. Hypersonic Weapons

A variety of hypersonic weapons are being developed for use by U.S. forces. In general, hypersonic missiles have an estimated range of 1,500 miles at speeds of more than Mach 5 (five times the speed of sound). Designs include the ability to launch from land-based facilities, air platforms, submarines, and surface ships (Freedberg Jr. 2021). Figure 11 shows the DARPA Hypersonic Air-breathing Weapon Concept (HAWC).

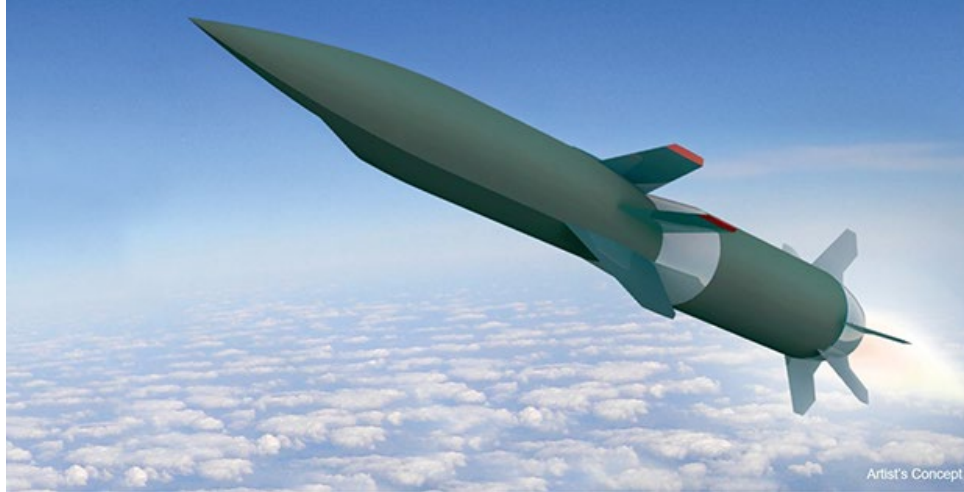


Figure 11. DARPA Hypersonic Air-breathing Weapon Concept (HAWC).
Source: DARPA (2022).

5. Air-Launched Decoy

Decoys are small air launched unmanned craft used to foil enemy radar. The decoys can fly into contested environments alone or in formation, duplicating combat flight profiles and signatures of blue force fighter aircraft. Decoys confuse the situational picture for the enemy while allowing Blue Forces to enter contested areas with reduced chance of intercept (Raytheon Missiles & Defense 2021). An example of a decoy which could be used is the MALD decoy shown in Figure 12.



Figure 12. MALD Decoy. Source: Raytheon Missiles & Defense (2021).

III. SYSTEM ARCHITECTURE DEVELOPMENT

A. STAKEHOLDERS

Table 1 includes the stakeholders associated with this Long-Range Fires capstone. More detail is included below.

Table 1. Stakeholders

Stakeholder	Priority	Needs & Wants	Goal	Concerns
N2/N6 OPNAV	1	Long Range Fires in GPS denied and Degraded Mode	Making sure that the hypersonic weapons can fill the capabilities gap to maintain operational success under various platform	GPS degraded mode, and denied environment and operational success via various platform for hypersonic weapons
NAWCWD-China Lake	1	Utilizing various operational scenario of Long Range Fires considering hypersonic missiles, & HVP by utilizing various platforms.	Succeed in completing amphibious missions Minimize force loss and risk under GPS Denied and degraded environments.	Enemy force and weapon capabilities. Disruption of established naval practices
Office of Naval Research & Development	2	Integration of the Long Range Fires on LPD ships. Operational evaluation under GPS denied and degraded environments	Fill weapon capability gaps in naval expeditionary operations	Load Capabilities. Size, weight, & engagements
Joint Chiefs Staff	2	Coverge/Coordinate Joint Capabilities Integration and Development System (JCIDS)/Acquisition efforts to efficiently support the Long Range Fires defined capability	implementation of requirements	Risk associated with GPS denied and degraded environment and operational success

1. Office of the Chief of Naval Operations N2/N6

The Long-Range Fires in degraded and denied environments capstone project is sponsored by the N2/N6 Office of the Chief of Naval Operations (OPNAV). “OPNAV N2/N6 is the U.S. Navy’s primary office for resourcing capabilities such as intelligence, cyber warfare, command and control, electronic warfare, battle management, oceanography, and meteorology amongst others” (Stiner 2022). “The Deputy Chief of Naval Operations (DCNO) for information dominance serves as the National Intelligence Program (NIP) resource sponsor and Military Intelligence Program (MIP) component manager for Naval intelligence capabilities. The DCNO is tasked with directing the efforts of military and civilian professionals making up the Information Dominance Corps (IDC) and with providing warfare commanders with Assured Command and Control (AC2), Battlespace Awareness (BA), and Integrated Fires (IF)” (Stiner 2022).

2. Naval Air Warfare Center Weapons Division China Lake

The Naval Air Warfare Center Weapons Division (NAWCWD) China Lake (CL) has many Technical Project Offices (TPO) support various weapons programs. The Offensive Anti-Surface Warfare (OASuW) TPO is responsible for providing project coordination, systems engineering, test support, overall planning, execution, and contractor testing support. NAWCWD is a stakeholder that provided relevant long-range fires information and may utilize the resulting capstone research in existing weapons programs.

3. Office of Naval Research and Development

The Office of Naval Research (ONR) is actively performing research in the areas covered by the Long-Range Fire capstone study. ONR works to improve logistics operations and mission planning. The capstone team will share the logistics approach studied to provide new insight into logistics support and mission planning capabilities.

4. Joint Chief of Staff

The office of the Joint Chief of Staff (JCS) coordinates Joint Capabilities Integration and Development System (JCIDS) and acquisition efforts to efficiently support capabilities of long-range fires. The efforts include, but are not limited to, data standardization, architecture, network environment road maps, capability alignment with long-range fires programs, and more.

B. OPERATIONAL CONCEPT

To aid with visualization when developing the simulation model, OV-1 diagrams (shown below) were developed for the top level CONOPS and each of the four excursion scenarios.

1. Top Level CONOPS



Figure 13. Top Level CONOPS

Country Blue's national ISR assets have revealed that Country Red is installing a long-range hypersonic missile launcher on disputed Country Red controlled territory. This site has the capability to launch an attack on Country Blue, partner nation naval or land targets including major cities, military locations, or on Country White shipping in the Azure Sea. Country Red has sophisticated ISR, ASAT, and offensive cyber capabilities that could be used to disrupt or disable Country Blue C4ISR and can be expected to employ these should Country Blue attempt a strike. Country Red's hypersonic missile launch site is not yet completed, but it is protected by anti-access and area denial weapons and has anti-air, and medium range defense missiles. Country Blue's joint forces, led by the Navy, has been directed to eliminate the proposed Country Red launch site before it becomes operational and a threat to Country Blue's strategic interests. The measures of effectiveness (MOEs) for this CONOPS include the probability of kill in either a degraded or denied environment.

2. CONOP Excursion Scenarios for Analysis

The top level CONOPS was further broken down into more detailed excursion scenarios.

a. *Excursion Scenario #1*

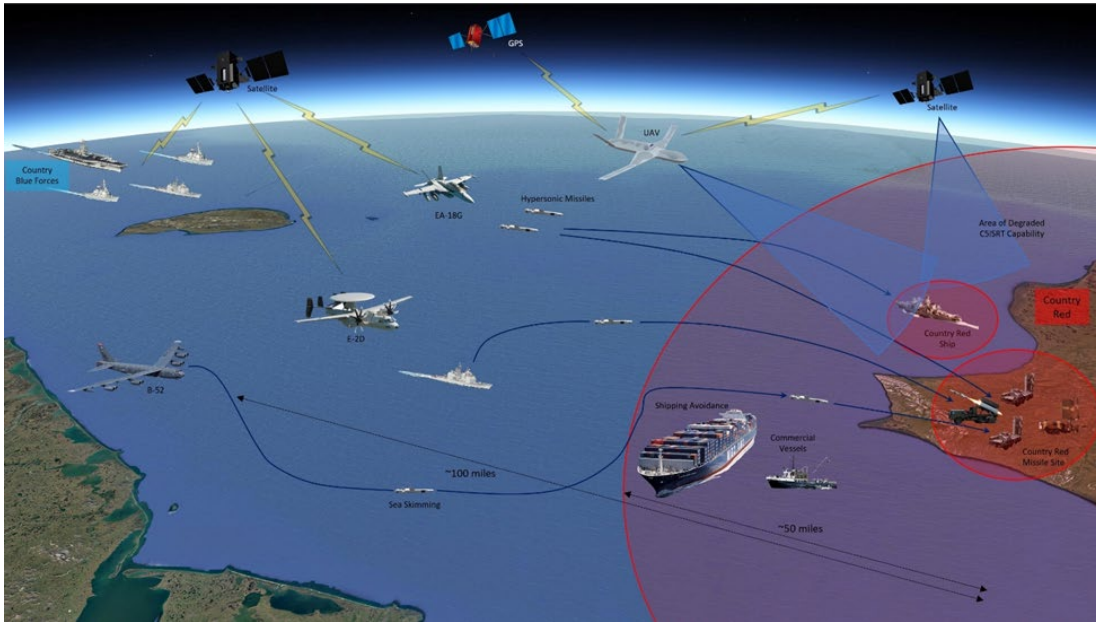


Figure 14. Excursion Scenario #1

Country Blue deploys an unmanned aerial vehicle (UAV) near disputed Country Red controlled territory. The UAV can detect and identify radio frequency (RF) transmissions from Country Red and communicate data via friendly aircraft and satellites for weapon orientation toward identified targets in the denied environment. Multiple weapons may be utilized by Country Blue's commander and deployed via aircraft (B-52, F-18, F-35) or sea surface platforms. Weapons can include air or surface launched hypersonic, cruise, or sea surface-skimming weapons.

b. *Excursion Scenario #2*

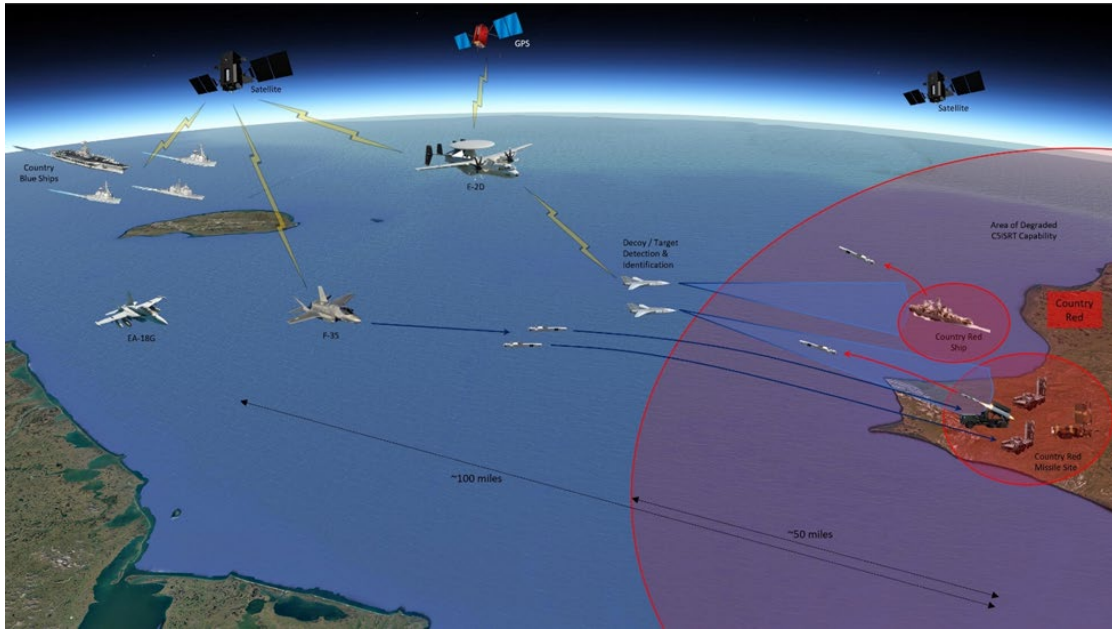
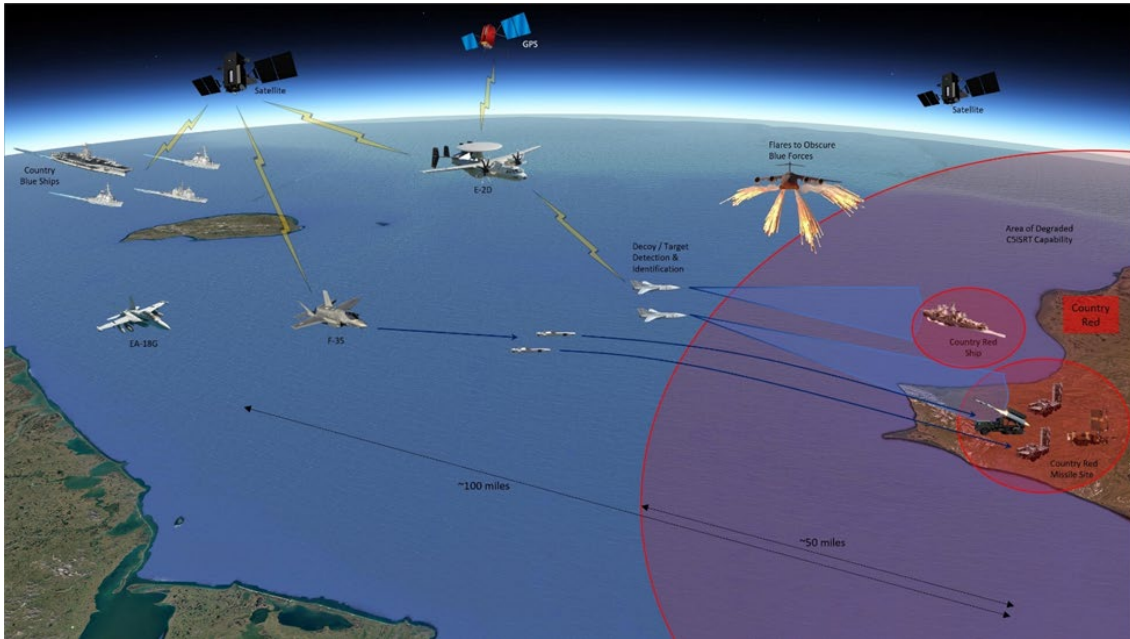


Figure 15. Excursion Scenario #2

A salvo of decoys is deployed into the denied environment of disputed Country Red controlled territory in preparation for a Long-Range Fire weapon strike on decoy-confirmed targets. When used in mass, decoys can overwhelm enemy sensor systems or exhaust enemy resources (e.g., anti-aircraft missiles). The assumption is that enemy resources in each region are finite and could be consumed before Blue Force assets enter conflicted airspace. Decoys detect radio frequency (RF) signals to identify target locations. Target information is communicated to Country Blue forces via satellite and friendly aircraft including F-18s, F-35s, and E2-Ds, or directly to Long-Range Fire weapons for guidance and target lock-on. It is expected that the utilization of weapon system combinations, that include decoys, would increase the probability of operational success in striking targets within degraded and denied environments.

c. *Excursion Scenario #3*



d. *Excursion Scenario #3*

Expanding on excursion scenario #2, a salvo of decoys detects enemy radio frequency (RF) signals to identify target locations. Target information is communicated to Country Blue forces via satellite and friendly aircraft including F-18s, F-35s, and E2-Ds, or directly to Long-Range Fire weapons for lock guidance to target location. Prior to long-range fire weapons entering denied environment, a flare attack is deployed to disrupt Country Red's intercept and jamming capabilities, allowing decoys to penetrate deeper into the denied environment for increased probability of target identification. It was expected that combined use of decoys and flares prior to a Long-Range Fire weapons attack would increase the probability of operational success while minimizing collateral damage and reducing Country Blue's cost and logistic footprint.

e. *Excursion Scenario #4*

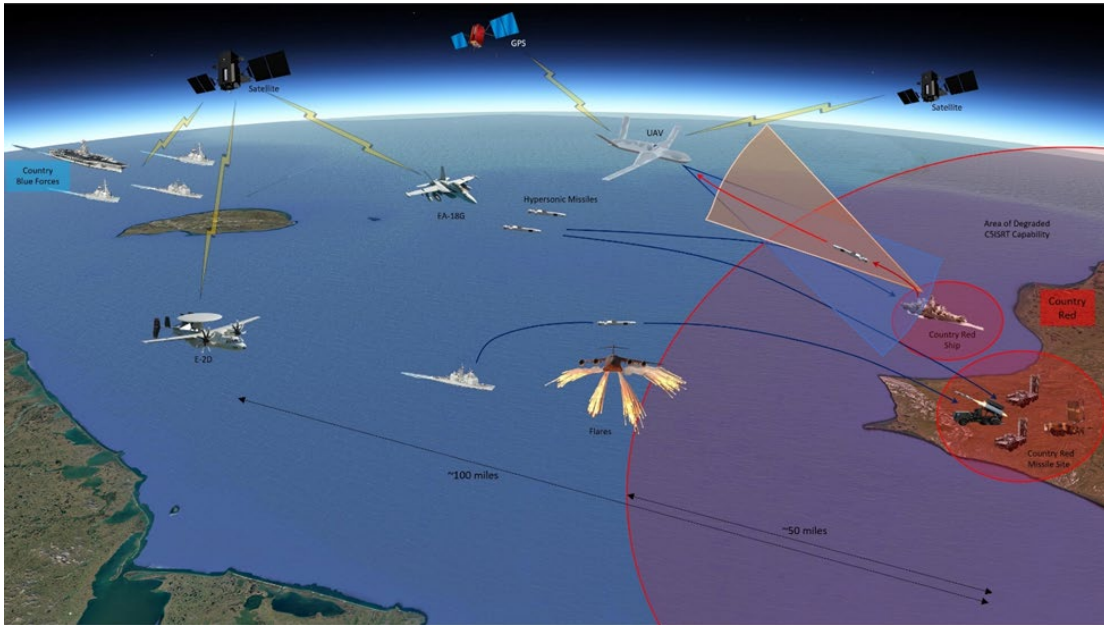


Figure 16. Excursion Scenario #4

Country Blue has an intelligence-gathering UAV loitering near Country Red’s disputed territory. Country Red detects and launches an attack against Country Blue’s UAV, thereby degrading C4ISR capabilities. In response, Country Blue deploys a combination of flares, decoys, and long-range fire weapons into the denied environment attacking previously known targets. Since Country Red may have changed the target locations, target data previously acquired by Country Blue’s UAV may be unreliable. Country Blue, therefore, resumes target data verification via satellite or other means which is communicated across Country Blue forces.

C. FUNCTIONAL ANALYSIS AND HIERARCHY

To gain a better understanding of how our team is modeling a Long-Range Fires attack in an A2/AD environment, we constructed a functional decomposition of the process based on the decomposition in “The Organic Over the Horizon Targeting for 2025 Surface Fleet” report written by Team Alpha Cohort in 2015. This functional decomposition is depicted in Figure 17. Due to limitations imposed by the A2/AD environment, it is difficult

for a ship's commanding officer to gather the necessary information to make real-time engagement decisions to employ weapon systems. Our model will give the commanding officer access to target data obtained by a combination of decoys, UAVs, and satellites allowing needed to conduct a Long-Range Fires strike (Newland and Tornatore 1984; Team Alpha Cohort 21 2015).

The overall goal for this team is to accurately model the kill chain enabling the commanding officer to launch Long-Range Fires successfully in an A2/AD environment. This is accomplished through three primary high-level functions:

1. Execute Command and Control
2. Conduct ISR
3. Employ Weapons

D. TOP-LEVEL FUNCTIONS AND THEIR DESCRIPTIONS

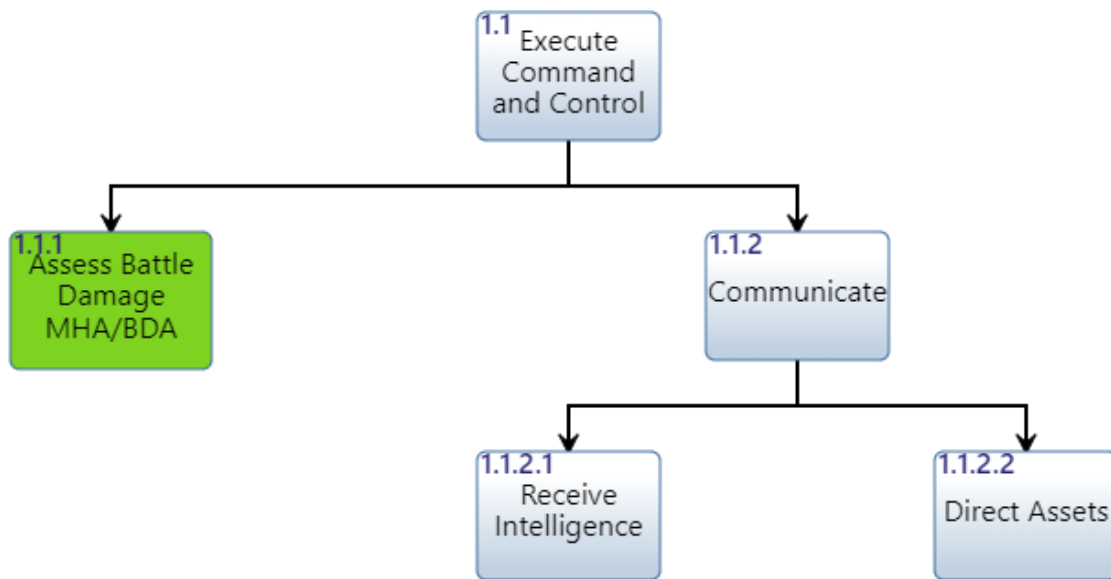


Figure 17. Execute Command and Control Hierarchy

1. Execute Command and Control

The U.S. Joint Chiefs of Staff defines C2 as the “exercise of authority and direction by a properly designated Commander over assigned forces in the accomplishment of their mission.” In general, C2 is the direction and control of general-purpose forces. The Joint Chiefs of Staff state that “C2 functions are performed through an arrangement of personnel, equipment, communications, facilities, and procedures which are employed by a commander in planning, directing, coordinating, and controlling forces in accomplishment of the mission” (Newland and Tornatore 1984, 3–8). In our model, the FoS will provide the commander the means to execute C2 by assessing the operating environment, conducting Missile Hit Assessment (MHA) and Battle Damage Assessment (BDA), and communicating effectively with employed direct assets. In Figure 17, the Assess Battle Damage MHA/BDA block is highlighted in green to show the focus of these functions for simulation modeling.

a. Assess Battle Damage

Our model implements national assets such as satellites, and commander-controlled decoys which will be able to detect radio frequency signals to identify Contacts of Interest (COI) locations. Since our model is set in A2/AD environment, the battle damage must be continuously and reliably monitored to provide decision-makers timely, accurate information on any COI. A missile hit assessment is simulated in the model to analyze the effectiveness of long-range missiles. In a real-world situation, this information would be provided to the decision-makers allowing them to determine whether follow-on actions are necessary. A battle damage assessment is simulated in the model to analyze the effectiveness of strikes in each excursion scenario. In a real-world situation, this information would be provided to the decision-makers allowing them to determine whether follow-on actions are necessary. The battle damage assessment information is continuously fed through the functional hierarchy components for up-to-date decision making.

b. Communicate

Since our model is set in an A2/AD environment, the FoS must have timely and reliable communication. To be successful, the FoS must be able to execute two-way

communications as needed to provide speedy relay and security of collected data and information. (Team Alpha Cohort 21 2015)

(1) Receive Intelligence

The FoS shall have access to national intelligence networks to receive ISR reports, and updates as required. It shall also be able to tailor own-sensor(s) ISR as necessary in the Area of Interest (AOI).

(2) Direct Assets

The FoS will have the knowledge needed to send its employable assets, such as nationally controlled satellite assets and UAVs, to the intended AOI once intelligence has been collected and processed. Once these assets reach the AOI(s), they can begin communicating and relaying information from the AOI(s). This will enable decision makers to allocate and account for intelligence collection distributed among available assets.

E. CONDUCT ISR

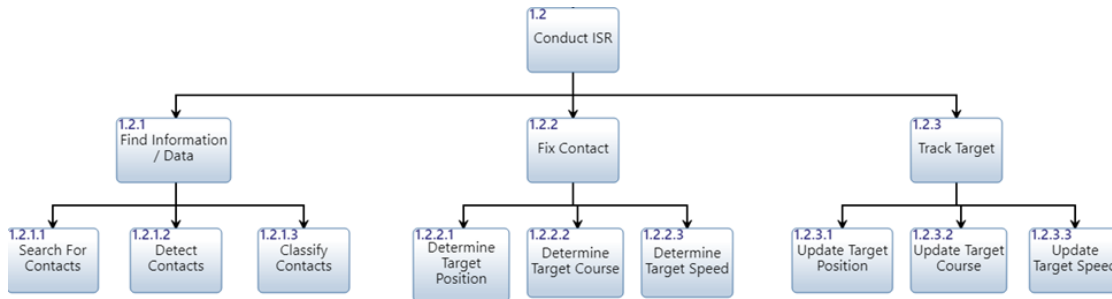


Figure 18. Conduct ISR Hierarchy

“The principal function of ISR is to find, fix, and track both friendly and hostile forces, as well as to assess damage to hostile targets in an area of interest” (Committee on C4ISR for Future Naval Strike Groups 2006, 175).

1. Find Information / Data

The FoS must be able to employ ISR effectively for timely battlespace awareness, target identification and tracking, BDA, and MHA. The system will do this within the A2/AD environment through radar signatures shared by UAVs, satellites, and decoys.

a. Search for Contacts

The FoS needs to be able to identify, locate, track required target COIs in all weather conditions and in an A2/AD battlespace.

b. Detect Contacts

COIs, whether below, on, or above the surface, need to be reliably detected using onboard sensors with a low false alarm rate and with limited latency. To improve the search and detection profile, the controlling platforms will cue the detection windows and broadcast them to the network or Blue Force commander-controlled sensors.

c. Classify Contacts

Using all available collection assets and sensors, the FoS will be able to accurately classify all COIs. Specific contact data collected by the available sensors will be documented and saved for future reference. Each COI will be designated with one of the following classifications: friendly, hostile, or unknown. The COI will then be entered into national databases for additional correlation and contact fidelity.

2. Fix Contact

The classified contacts will be processed by the FoS based on the threat level they pose. The threat level will either be pre-determined or determined on the fly as the situation unfolds. After every contact is classified, the FoS will be able to determine the COI position, location, and speed in an A2/AD environment to provide decision makers the ability to “Fix,” or target, the COI if necessary.

a. *Determine COI Position*

The FoS will be capable of “fixing” the COI in an A2/AD environment in all weather conditions.

b. *Determine COI Course*

Based on relative motion and GPS, the FOS will be able to Fix a COI’s current position to determine its anticipated course. This data will then be reported to the decision-makers.

c. *Determine COI Speed*

The FOS will be able to determine the speed of a COI allowing a profile to be created using position, course, and speed data. Once the profile is created, the FOS will prepare for possible encounter.

3. *Track COI*

The FoS will have the ability to track COIs in an A2/AD environment. The ability to track a COI is essential for future COI development and, if necessary, to generate a precise firing solution. By timely tracking and reporting of all COIs, the FOS will provide decision-makers with the greatest possible common operating picture of the battle damage assessment.

a. *Update COI Position*

The FOS will be able to generate the COI location at predetermined intervals to provide a reliable COI track in time for effective targeting. Individual Commanders will be able to choose which weapon to deploy as well as customize the delivery window of COI engagement based on changes to its track which were determined during the fixed or variable reporting intervals.

b. *Update COI Course*

After each new sweep or scan, the FoS will update a COI’s course and position, ensuring the most up-to-date COI location information.

c. Update COI Speed

The FoS will be able to update a COI’s speed information after each new sweep or scan. By updating the COI speed, the FOS will be able to create weapon intercept profiles and identify potential limitations in COI engagement.

F. EMPLOY WEAPONS

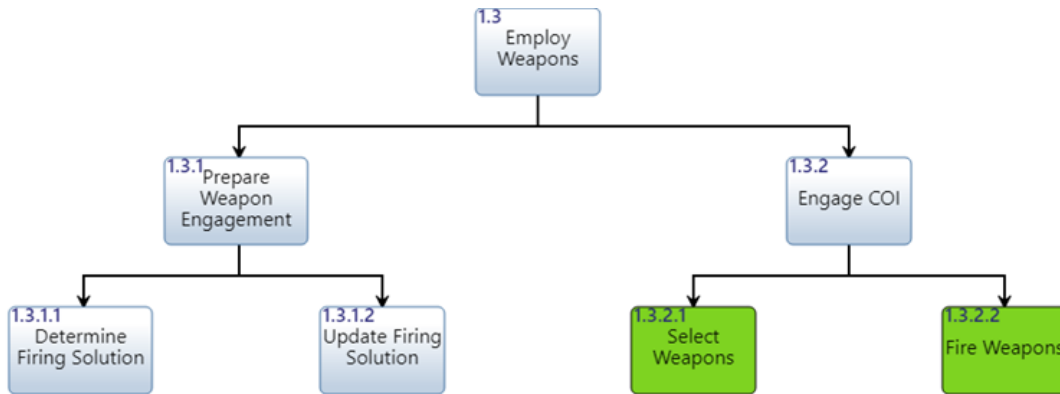


Figure 19. Employ Weapons Hierarchy

The FoS will allow a ship’s commanding officer to engage a COI beyond the radar horizon of the ship. Prior to and after the launch of weapons, the FoS will be able to determine, create, and update firing solutions (Team Alpha Cohort 21 2015). The Select Weapons and Fire Weapons block are highlighted in green in Figure 19 to show the focus of simulation modeling.

1. Prepare Weapon Engagement

The FoS will analyze the latest environmental conditions along with the latest COI characteristics to determine the firing solution. Updates to the firing solution will continue if the system is in active contact with the COI.

a. Determine Firing Solution

The FoS will determine a firing solution for multiple selected COIs and recommend to decision makers the optimal weapon to use. If active contact is maintained with the COI, the firing solution for each COI will be stored and updated in internal memory.

b. Update Firing Solution

While the system is in active contact with the COI, the FoS will be able to update the firing solution in real time.

2. Engage COI

Once a suitable firing solution has been determined, the FoS will be able to engage COIs. The FoS will use the COI characteristics data determined earlier to recommend the optimal weapon for employment to the decision makers. The decision to engage a COI will be given to the human in the loop along with the latest guidance on the COI.

a. Select Weapons

The FoS will be able to determine which weapon to select based on environmental conditions and COI characteristics data determined earlier (e.g., range, course, speed, altitude / depth).

b. Fire Weapons

Once the weapon has been selected, the human in the loop will be updated with the latest guidance by cuing sources to increase the weapon's probability of hit (P_{hit}). The human will order the firing of the weapon.

G. OBJECTIVES HIERARCHY

Measures of Effectiveness (MOE) are defined in the International Council on Systems Engineering (INCOSE) Systems Engineering Handbook as “measures that define the information needs of the decision makers with respect to systems effectiveness to meet operational expectations” (International Council on Systems Engineering (INCOSE) 2015). For this project, MOEs will be determined by the success of a hit leading to a kill

by the weapon systems employed to strike the target within a *degraded* or a *denied* environment.

Measures of Performance (MOP) are similarly defined in the INCOSE Systems Engineering Handbook as “measures that define the key performance characteristics the system should have when fielded and operated in its intended operating environment” (International Council on Systems Engineering (INCOSE) 2015). For this project the MOPs are measured based on the ability of the weapon systems to successfully reach the target within the degraded or the denied environment.

1. Measures of Effectiveness

Table 2. Measures of Effectiveness

Measure of Effectiveness	MOE Description	MOE Value
Probability of Kill	Measures the probability of kill for Blue Force weapons against Red Force target	Weapon probability of kill
Probability of Damage	Measures the probability the weapon will damage the Red Force target	Weapon probability of damage when striking the Red Force target

Table 2 shows the MOEs established for this capstone. Probability of hit is used to evaluate the chance the weapon hits the desired target while the probability of kill evaluates whether the weapon causes enough damage to render the target non-operational. There are two MOEs for both probability of hit and kill, one each for operations in a degraded environment and one each for operations in a denied environment.

2. Measures of Performance

Table 3. Measures of Performance

Measure of Performance	MOP Description	MOP Value
Probability of Intercept	Probability the weapon is intercepted by Red Force during attack	Probability the weapon is detected based on altitude, speed, and weapon characteristics
Probability of Hit	Measures the Blue Force weapon probability of hitting the Red Force target	Weapon probability of hit

Table 3 shows the MOPs established for this capstone to evaluate the ability of the weapon to reach the target before being intercepted by Country Red. Probability of Intercept evaluates the ability of the enemy to intercept Country Blue's incoming weapon with sufficient time and detail to intercept and eliminate it. Probability of hit represents the probability the Blue Force long-range fire weapon reaches and successfully hits the Red Force target.

IV. SYSTEM ARCHITECTURE MODEL DESIGN

A. MODEL APPROACH

To determine the effectiveness of long-range fires in an A2/ AD environment, our team implemented a combination of ExtendSIM and Excel modeling. ExtendSIM is a Graphical User Interface (GUI) – based tool with extensive pre-built modeling and simulation elements including flexible rapid model building and custom functions. We first created a Design of Experiments (DOE) consisting of 12 factors using the Nearly Orthogonal Latin Hypercubes (NOLH) method (Sanchez 2009). We discuss the factors and their values in detail in section C below.

Once we determined the DOE factors and values, they were then entered into the ExtendSIM model. The ExtendSIM model, using the DOE results and randomized weapon survivability, calculated how many times the target was destroyed out of a significant number of simulations runs. To verify the model, results from the ExtendSIM model were then compared to a stochastic model created in Excel. The target is considered destroyed if the probability of kill is greater than or equal to 85%. The 85% probability of kill value was provided by Mr. Robert Swain, data scientist at NAWCWD China Lake as an appropriate approximation while allowing this capstone to remain unclassified.

B. ASSUMPTIONS AND LIMITATIONS

For the excursion scenarios modeled in this report, we assumed a C4ISR effectiveness values of 40%–60% in the A2/AD degraded or denied environment of the battlespace. In this scenario, we assumed there is only a singular non-moving target which cannot be destroyed by one weapon alone. To engage this target, we assumed the Blue Force only has access to three types of long-range weapons (Hypersonic, Cruise, or Sea-skimming missiles). We also assumed that each decoy used improved the Blue Force C4ISR (effectiveness) by 5% and reduced the probability of Blue Country's weapon being intercepted by 10%. Values presented in this section were selected after discussions with the Evolved Sea Sparrow Missile (ESSM) Reliability and Maintainability (R&M)

Integrated Product Team (IPT) Lead James Hodgson and the Operational Research IPT Lead Mr. Derek Reusch at NAWCWD China Lake.

C. INPUT VARIABLES

As mentioned earlier in the report, our DOE consists of 12 factors. Each factor was assigned a high and a low value. A detailed description of each factor can be found in Table 4.

Table 4. Input Variables

Design Parameters	Low Value	High Value	Description
Weapon 1 (WEP1)	1	3	Weapon 1 is a long-range Blue Force fire modeled on a hypersonic missile. Due to the classification of these attributes, all values mentioned here are generic for simulation purposes. Maximum quantity per engagement cannot be more than three due to targeting only one non-moving target with various weapons per salvo attack.
Weapon 2 (WEP2)	1	4	Weapon 2 is a long-range Blue Force fire modeled on a cruise missile. Due to the classification of these attributes, all values mentioned here are generic for simulation purposes. Maximum quantity per engagement cannot be more than four due to targeting only one non-moving target with various weapons per salvo attack
Weapon 3 (WEP3)	1	4	Weapon 3 is a long-range Blue Force fire modeled on a Sea-skimming missile. Due to the classification of these attributes, all values mentioned here are generic for simulation purposes. Maximum quantity per engagement cannot be more than four due to targeting only one non-moving target with various weapons per salvo attack
Number of Decoys	4	8	In the second excursion scenario, model enhancements are needed to meet or exceed the defined probability of kill (0.85). Adding decoys with this engagement will provide a five to ten percent improvement in C4ISRT effectiveness for the Blue Forces and degrade the probability of intercept by the Red Force.
C4ISRT	0.4	0.6	C4ISRT (effectiveness) is assigned values defined in the capstone project. We used a 40 to 60 percent degraded or denied environment for our analyses and simulation purposes while performing battle engagement (offensive mode).

Design Parameters	Low Value	High Value	Description
Probability of Hit WEP1	0.5	0.7	Due to confidentiality concerns, we have assigned engineering estimates for low and high values. Probability of intercept per weapon type is embedded within the probability of hit for each weapon. In most cases, probability of intercept for long range fire weapons are ≥ 0.99 and confirmed with Mr. James Hodgson, NAVAR ESSM R&M IPT Lead, China Lake, CA.
Probability of Hit WEP2	0.4	0.6	Due to confidentiality concerns, we have assigned engineering estimates for low and high values. Probability of intercept per weapon type is embedded within the probability of hit for each weapon. In most cases, probability of intercept for long range fire weapons are ≥ 0.99 and confirmed with Mr. James Hodgson, NAVAR ESSM R&M IPT Lead, China Lake, CA.
Probability of Hit Wep3	0.3	0.5	Due to confidentiality concerns, we have assigned engineering estimates for low and high values. Probability of intercept per weapon type is embedded within the probability of hit for each weapon. In most cases, probability of intercept for long range fire weapons are ≥ 0.99 and confirmed with Mr. James Hodgson, NAVAR ESSM R&M IPT Lead, China Lake, CA.
Probability of Damage Wep1	0.45	0.55	Due to confidentiality concerns, we have assigned engineering estimates for low and high values Notional values were obtained from Mr. Robert Swain at NAWCWD, China Lake, CA.
Probability of Damage Wep2	0.4	0.5	Due to confidentiality concerns, we have assigned engineering estimates for low and high values Notional values were obtained from Mr. Robert Swain at NAWCWD, China Lake, CA.
Probability of Damage Wep3	0.35	0.45	Due to confidentiality concerns, we have assigned engineering estimates for low and high values Notional values were obtained from Mr. Robert Swain at NAWCWD, China Lake, CA.
Probability of Intercept (Red Force)	0.3	0.5	The probability of intercept of Red Forces is based on engineering estimates. Usually, Red Forces have a 50% probability of intercepting incoming missiles. However, for our simulation, we are using high and low values to evaluate the actual effect of the engagement.
* - Command, Control, Computers, Communications, Intelligence, Surveillance, Reconnaissance, and Targeting			

D. SIMULATION OUTPUT VARIABLES

Using the input factors from Table 4 and equations obtained from a stakeholder in the R&M division at NAWCWD China Lake, we were able to output the variables in Table 5. The associated equations in Table 5 are applied to calculate the cumulative probability of kill.

Table 5. Output Variables (Farris and Hunt 1981)

Output Variable	Equation
Number of Hits =	$\sum WEP_n - Prob_{Intercept} * \sum WEP_n$
Probability of Hit given C4ISRT =	$Prob_{Hit} * C4ISRT$
Probability of Damage (Weapon 1,2,3) in A2/AD battle damage =	$Prob_{Damage} * Prob_{Hit * C4ISRT}$
Probability of Kill (Weapon 1,2,3) in A2/AD battle damage =	$1 - (1 - Prob_{Damage_{WEP_n}})^{WEP_n}$
Probability of Damage (Salvo Attack) in A2/AD battle damage =	$1 - \prod(1 - WEP_n)$
Probability of Kill (Salvo Attack) in A2/AD battle damage =	$1 - (1 - Prob_{Salvo Damage})^{\# of Hits}$

E. DESCRIPTION OF VARIABLES

Multiple variables, described below, are used in the ExtendSIM simulation. By varying the input values for these variables as determined by the DOE, the effectiveness of long-range fire weapon salvo combinations, along with the additional employment of decoys, can be calculated.

1. Number of Weapons

As mentioned above, simulation results are based on salvo attacks. Three long-range fire weapons were used for the simulation. The maximum number of weapons per salvo attack for each weapon type is given below:

- Weapon-one: total quantity equals three

- Weapon-two: total quantity equals four
- Weapon-three: total quantity equals four

Thus, the maximum number of weapons per salvo attack was eleven combined. This is considered a fixed variable. Thus, increasing weapons quantities was not an option.

2. C4ISRT

C4ISRT values are assigned for the experiment design per capstone requirements (40 – 60) % degraded or GPS denied environments. Thus, our DOE C4ISRT values were defined as a minimum of 40% and a maximum of 60%. The addition of decoys increased the value used for C4ISRT (effectiveness) by 5% per decoy.

3. Number of Decoys

The addition of decoys was used in the second ExtendSIM model. Using decoys for this scenario improves the cumulative probability of target kill by the Blue Forces. The addition of decoys per salvo attack is an enhancement for the ExtendSIM model so that percentage improvements in killing Red Forces' target can be measured.

4. Probability of Hit by Blue Forces

Minimum and maximum values for the probability of a hit (per weapon) of Blue Forces were assigned for DOE purposes. Interception per weapon type by Red Force is embedded in the probability of hit number so that classification of these values cannot be compromised. Typically, Blue Force weapons may be intercepted by Red Forces up to 70% of the time.

5. Probability of Damage by Blue Forces

Probability of damage to a Red Force target because of a Blue Force weapon strike is expressed as a percentage. Minimum and maximum values for the probability of Blue Forces damage to the target (per weapon) were assigned for DOE purposes. These values are again entered as engineering estimates.

6. Probability of Intercept by Red Forces

Minimum and maximum probability of intercept by Red Forces were used for DOE purposes. These values were assigned per engineering estimates and confirmed by Chief Data Scientist of NAWCWD Mr. Robert Swain.

F. FUNCTION TO VARIABLE FLOW

The linkage from low level function through the set of MOEs and MOPs to the output variables used in the model can be found in Table 6. Each of the model input variables lead to the model output variables. The scope of the ExtendSIM simulation model includes the three colored functions from the functional hierarchy: Assess Battle Damage, Select Weapon, and Fire Weapon.

Table 6. Function to Variable Flow

Low level Function	MOEs selected for the Model	MOPs selected for the Model	Output Variables used in the Model
1.1.1 Assess Battle Damage MHA/BDA	Probability of Damage	Probability of Intercept	Probability of Damage (Weapon 1,2,3) in A2/AD battlespace, Probability of Kill (Weapon 1,2,3) in A2/AD battlespace, Probability of Damage (Salvo Attack) in A2/AD battlespace, Probability of Kill (Salvo Attack) in A2/AD battlespace
	Probability of Kill	Probability of Hit	Number of Hits, Probability of Hit given C4ISR
1.3.2.1 Select Weapons	Probability of Damage	Probability of Intercept	Probability of Damage (Weapon 1,2,3) in A2/AD battlespace, Probability of Kill (Weapon 1,2,3) in A2/AD battlespace, Probability of Damage (Salvo Attack) in A2/AD battlespace, Probability of Kill (Salvo Attack) in A2/AD battlespace
	Probability of Kill	Probability of Hit	Number of Hits, Probability of Hit given C4ISR
1.3.2.2 Fire Weapons	Probability of Damage	Probability of Intercept	Probability of Damage (Weapon 1,2,3) in A2/AD battlespace, Probability of Kill (Weapon 1,2,3) in A2/AD battlespace, Probability of Damage (Salvo Attack) in A2/AD battlespace, Probability of Kill (Salvo Attack) in A2/AD battlespace
	Probability of Kill	Probability of Hit	Number of Hits, Probability of Hit given C4ISR

G. DESIGN OF EXPERIMENTS

The DOE was developed by varying the 12 factors described earlier in Table 4. A total of 6500 data points were created from these factors. Since we wanted to keep this report unclassified, all probabilities were based on engineering estimates.

The DOE was designed based on excursion scenarios 1 and 2. These scenarios focus on long-range fire weapons (hypersonic, cruise, or Sea-skimming missiles) launched against a non-moving Red Forces target within C4ISRT denied or degraded A2/AD environments. The two scenarios differ with the addition of decoys used in excursion scenario 2 to reduce the degradation of Blue Force C4ISRT capabilities while in the degraded or denied environment and reducing the probability Red Force can intercept incoming weapons. Using input factors, we were able to determine the success of the long-range fires which we defined as the cumulative probability being greater than or equal to 0.85. These values result in the minimum probability of kill goal which yields the successful elimination of Red Force target.

H. EXTENDSIM MODEL

We created two models: one without decoys and one with decoys (see Figure 20). The baseline model starts by creating a stationary Red Forces target and three Blue Force attack salvos: each attack with its own type of weapon. Our team named these weapons: WEP1, WEP2, and WEP3. While each weapon was modeled according to the current Navy weapons, due to security concerns, the names of the weapons were omitted from this report. The quantities of each type of weapon are read from an input variables database which has been populated with DOE results obtained from an NOLH spreadsheet (Sanchez 2009). Engineer-estimated attributes for each weapon are also assigned from the input variables database. After these unclassified attributes are assigned to each weapon type, our team chose to randomize the weapon survivability attribute using a lognormal distribution for each weapon's probability of hit.

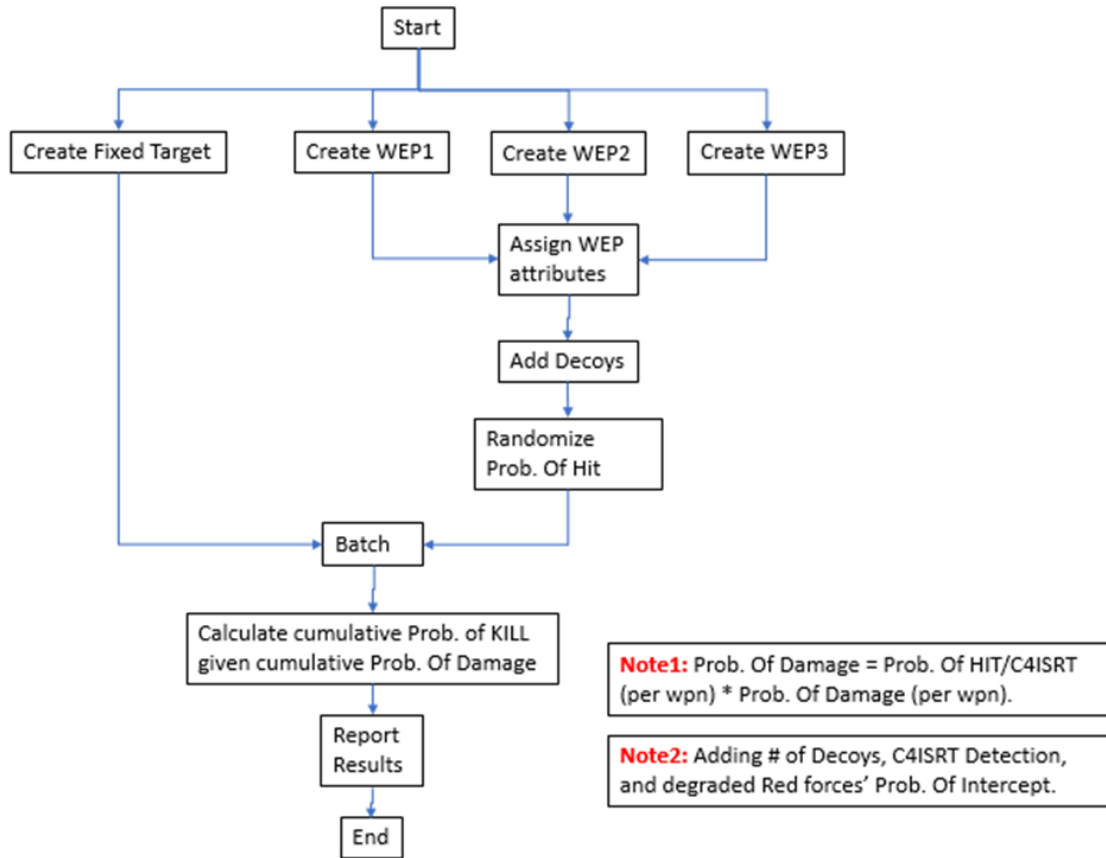


Figure 20. ExtendSIM Model Flowchart

After the model has randomized each weapon’s survivability attribute, the weapons and the target are grouped together using a “Batch” item block. After the weapons and the target have been batched, the cumulative probability of kill for each weapon type is calculated using equations from Table 5.

Our model reports the total number of targets killed by salvo attack on each run, as well as the number of targets killed by each weapon type. This completes our model for Excursion Scenario 1.

Our second model, based on excursion scenario #2, is almost identical to the baseline model used for Excursion Scenario #1, with the exception that this model adds the effects of using decoys during the attack. Our team assumed that each decoy reduces the

degradation of the Blue Force C4ISRT by 5% and reduced the probability of intercept by 10%. Snapshots of both ExtendSIM models can be found in Appendix A.

For both models, if the cumulative probability of kill was greater than or equal to 0.85 then our mission was considered successful.

I. STOCHASTIC MODEL

To verify the ExtendSIM model, we conducted a statistical analysis using Excel. Once again, each input variable was assigned a high and low value and then randomized within that range. Using the equations discussed in the output variable section, we were able to determine the probability of hit given C4ISRT effectiveness, probability of damage, and the probability of kill for each salvo attack. We then determined whether the salvo attack was able to successfully destroy the Red Force target. The statistical analysis was conducted for both excursion scenarios and then compared to the ExtendSIM model to verify the model validity.

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V. MODEL RESULTS AND ANALYSIS

A. MINITAB STATISTICAL POST ANALYSIS

The output results from the ExtendSIM model were entered into Minitab to perform a statistical analysis. The purpose of the post analysis is to validate whether the simulation results met, exceeded, or failed to meet the threshold objectives of weapon probability of kill against the Red Force target. Two simulation scenarios were evaluated to determine which yields more effectiveness. Simulation scenario #1 varies the number of weapons per salvo attacking the Red Force target. Simulation scenario #2 includes the addition of decoys paired with the weapon salvo. By comparing the effectiveness of each scenario, we can evaluate which results in higher probability of kill. Because some long-range fire weapons are orders of magnitude more expensive than decoys, adding more weapons to the salvo may be considered far too expensive by the decision makers to warrant their use. However, if the same or better results can be achieved with the use of decoys, the combination of long-range fire weapons and decoys may result in better cost per attack.

1. Simulation # 1 Scenario without Decoys - No Improvements

The first model created and analyzed for this project was based on excursion scenario #1. In this scenario, the Blue Force salvo attack consists of three types of long-range fire weapons striking the Red Force target without the aid of decoys. Using the variables and equations described in Chapter Four, we were able to run our ExtendSim model. From our model, we were able to calculate the average probability of kill to be 76%. For this mission to be successful, we were required to have a probability of kill to be greater than or equal to 85%. Therefore, we consider this excursion scenario to be unacceptable and realized improvements will need to be made to guarantee mission success. These results were then verified using the stochastic excel model. The descriptive statistics for both ExtendSim and Excel model can be viewed in the Figure 21.



Figure 21. Simulation # 1 Scenario without Decoys - No Improvements

2. Simulation # 2 Scenario with Decoys

The second model we created is based on excursion scenario #2. In this scenario, the Blue Force salvo attack consists of three types of long-range fire weapons striking the Red Force target with the aid of decoys. Using the variables and equations described in Chapter Four, we were able to run our ExtendSim model. From our model, we were able to calculate the average probability of kill to be 92%. Therefore, we considered the mission to be successful for this excursion scenario. These results were then verified using the stochastic excel model. The descriptive statistics for both ExtendSim and Excel model can be viewed in the Figure 22.

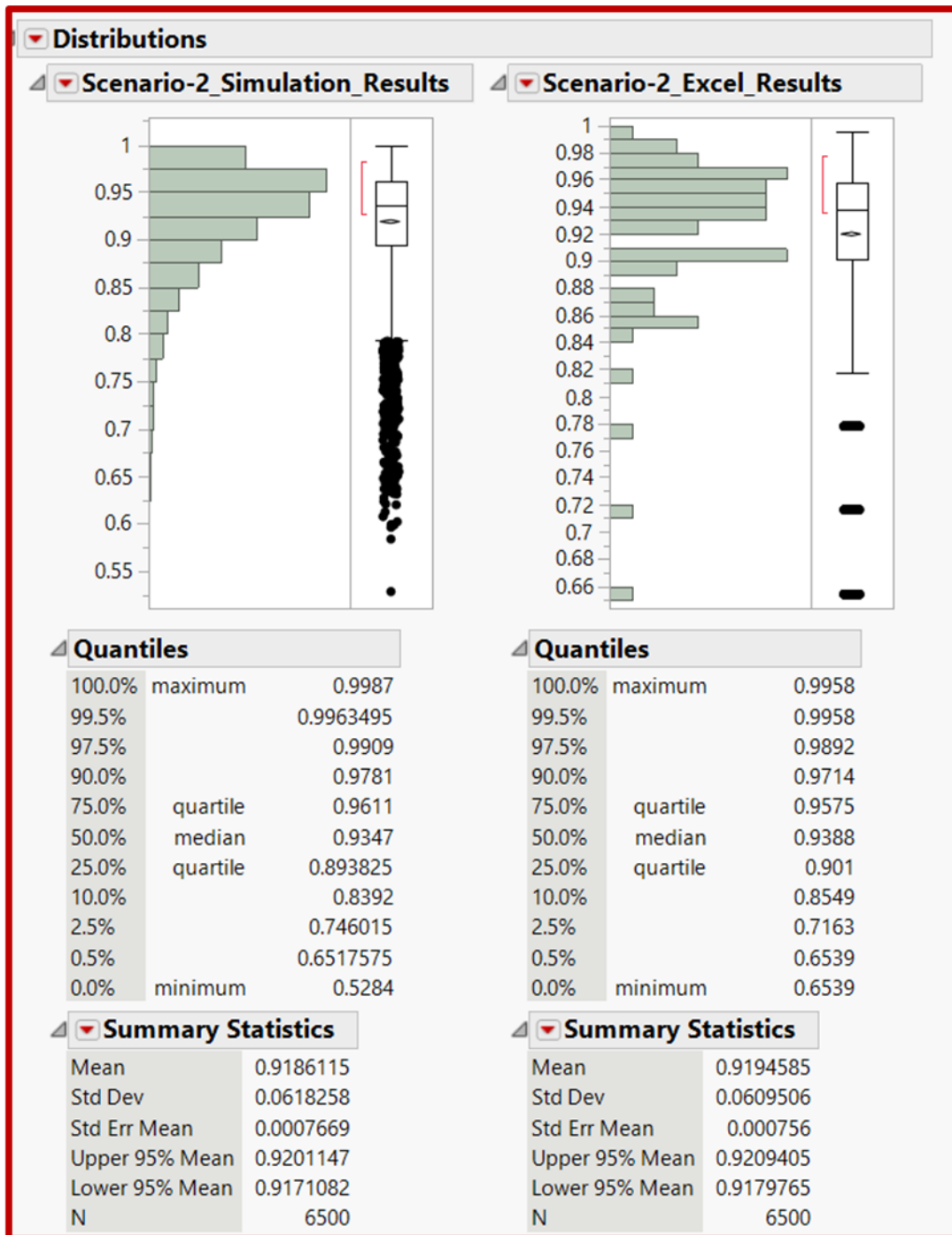


Figure 22. Simulation # 2 Scenario with Decoys

The addition of decoys clearly demonstrates the increase in likelihood of mission success. Similar improvements can be reached by adding more weapons to the long-range fire salvo. However, increasing the number of weapons will also increase the cost of a

strike. The addition of decoys to the long-range fire weapons salvo will reduce the degradation of Blue Force C4ISRT while also degrading Red Force's probability of intercepting the salvo. The addition of decoys will increase the probability of kill at a faster rate than the increase of weapons per salvo. Since decoys are a cheaper resource compared to the long-range fire weapons, the use of decoys in addition to the weapon salvo results in a bigger "bang for the buck" with increased probability of kill and lower probability of intercept with a lower cost.

B. INCREASE WEAPONS PER SALVO VERSUS DECOY ADDITION COMPARISON

For the base run of the ExtendSIM model, the probability of kill threshold was defined as 85%. To evaluate the effectiveness of the long-range fire weapon salvo, with and without improvements including the addition of decoys, the simulation was repeated varying the probability of kill threshold to 75%, 80%, 85%, 90%, and 95% or above.

Table 7 shows the results comparing the different probability of kill thresholds versus the percentage of target killed for excursion scenario 1 comparing the base simulation without improvements and with added weapons per salvo as an improvement. Table 7 shows the same exercise for excursion scenario 2. Improvements for excursion scenario 1 increases the number of weapons per salvo in each simulation run by one. The increase in weapons per salvo does increase the probability of kill, however, it is not increased enough to achieve the threshold of acceptability. Therefore, the use of decoys as simulated in excursion scenario 2 is required to reach the probability of kill threshold.

Table 7. Inputs for NOLH DOE Scenario #1

Weapon Characteristic INPUTS for NOLH DOE												
Weapon Qty low level	1	1	1	0.4	4	0.5	0.4	0.3	0.45	0.4	0.35	0.3
Weapon Qty high level	3	4	4	0.6	8	0.7	0.6	0.5	0.55	0.5	0.45	0.5
decimals	0	0	0	4	0	4	4	4	4	4	4	4
	WEP1	WEP2	WEP3	C4ISR	Decoys	Prob_HIT WEP1	Prob_HIT WEP2	Prob_HIT WEP3	PROB_Damage WEP1	PROB_Damage WEP2	PROB_Damage WEP3	Prob_Intercept

Scenario 1 Salvo Without Decoys					
Probability of Kill Threshold Values	75%	80%	85%	90%	95% or above
Probability of Achieving Threshold	60.28%	40.58%	21.22%	6.58%	0.43%

* - Improvements Adding extra, WEP1, WEP2, & WEP3 in NOLH DOE

Improvements (Increasing Weapons per Salvo) - INPUTS for NOLH DOE												
Weapon Qty low level	1	1	1	0.4	4	0.5	0.4	0.3	0.45	0.4	0.35	0.3
Weapon Qty high level	4	5	5	0.6	8	0.7	0.6	0.5	0.55	0.5	0.45	0.5
decimals	0	0	0	4	0	4	4	4	4	4	4	4
	WEP1	WEP2	WEP3	C4ISR	Decoys	Prob_HIT WEP1	Prob_HIT WEP2	Prob_HIT WEP3	PROB_Damage WEP1	PROB_Damage WEP2	PROB_Damage WEP3	Prob_Intercept

Scenario 1 Without Decoys but adding extra weapons per weapon type					
Probability of Kill Threshold Values	75%	80%	85%	90%	95% or above
Probability of Achieving Threshold	76.26%	62.12%	46.60%	24.06%	4.85%

The simulation was repeated for excursion scenario 2 with the inclusion of decoys with the weapon salvo. The results can be found in Table 8. The base simulation without improvements has a defined number of decoys assigned based on the DOE. Running the simulation with improvements increased the number of decoys used in the salvo. Increasing the number of decoys used in the salvo yields significant increases to the probability of kill against the Red Force target. Finally, the simulation was run by varying the number of weapons per salvo while the number of decoys remains the same as the initial DOE values.

Table 8. Inputs for NOLH DOE with Decoys for Scenario #2

Weapon Characteristic INPUTS for NOLH DOE												
Weapon Qty low level	1	1	1	0.4	4	0.5	0.4	0.3	0.45	0.4	0.35	0.3
Weapon Qty high level	3	4	4	0.6	8	0.7	0.6	0.5	0.55	0.5	0.45	0.5
decimals	0	0	0	4	0	4	4	4	4	4	4	4
	WEP1	WEP2	WEP3	C4ISRT	Decoys	Prob_HIT WEP1	Prob_HIT WEP2	PROB_HIT WEP3	PROB_Damage WEP1	PROB_Damage WEP2	PROB_Damage WEP3	Prob_Intercept

Scenario 2 with Decoys					
Probability of Kill Threshold Values	75%	80%	85%	90%	95% or above
Probability of Achieving Threshold	97.38%	94.62%	87.74%	72.15%	36.42%

Improvements-1 (Changing Decoy's quantities) - INPUTS for NOLH DOE												
Weapon Qty low level	1	1	1	0.4	6	0.5	0.4	0.3	0.45	0.4	0.35	0.3
Weapon Qty high level	4	5	5	0.6	12	0.7	0.6	0.5	0.55	0.5	0.45	0.5
decimals	0	0	0	4	0	4	4	4	4	4	4	4
	WEP1	WEP2	WEP3	C4ISRT	* Decoys	Prob_HIT WEP1	Prob_HIT WEP2	PROB_HIT WEP3	PROB_Damage WEP1	PROB_Damage WEP2	PROB_Damage WEP3	Prob_Intercept

Scenario 2					
Probability of Kill Threshold Values	75%	80%	85%	90%	95% or above
Probability of Achieving Threshold *	99.37%	98.11%	95.89%	90.02%	67.45%

Improvements-2 (Changing Weapons' quantities) - INPUTS for NOLH DOE												
Weapon Qty low level	1	1	1	0.4	4	0.5	0.4	0.3	0.45	0.4	0.35	0.3
Weapon Qty high level	4	5	5	0.6	8	0.7	0.6	0.5	0.55	0.5	0.45	0.5
decimals	0	0	0	4	0	4	4	4	4	4	4	4
**	WEP1	WEP2	WEP3	C4ISRT	Decoys	Prob_HIT WEP1	Prob_HIT WEP2	PROB_HIT WEP3	PROB_Damage WEP1	PROB_Damage WEP2	PROB_Damage WEP3	Prob_Intercept

Scenario 2					
Probability of Kill Threshold Values	75%	80%	85%	90%	95% or above
Probability of Achieving Threshold **	98.54%	98.02%	95.78%	85.40%	61.08%

C. REGRESSION ANALYSIS

We can use regression analysis to predict the response of or to determine which input variables and factors provide variation in predicting the simulation results. Regression analysis aids in identifying each independent variables' effect on the resulting dependent variable allowing us to understand how to prioritize how we might vary our experimental designs.

The regression analysis was performed using Minitab and JMP software. Tables 9, 10, and 11 show the regression equation, coefficients, and model summary for the regression analysis. Figure 23 shows how highly the relationship between the Blue Force probability of kill compared to all twelve factors are correlated. Each independent variable is shown to be statistically significant regarding the outcome of our simulation results and hypothetically could be adjusted to improve the mission's success via probability of kill. However, probability of hit, probability of damage, and probability of intercept are critical elements of our DOE defined by each weapon's design characteristics. Improvement to

these factors would require costly design modifications by weapon manufacturers. Therefore, our focus for these simulations is the adjustment of long-range fire weapons per salvo attack and the number of decoys employed by the Blue Force to improve the probability of kill.

Table 9. Regression Equation

Regression Equation

$$\begin{aligned} \text{Prob_Kill} = & 0.0354 + 0.029507 \text{ WEP1} + 0.028458 \text{ WEP2} + 0.029711 \text{ WEP3} + 0.004418 \text{ Decoys} \\ & + 0.35291 \text{ C4ISRT} + 0.16392 \text{ Prob_Hit_W1} + 0.14797 \text{ Prob_Hit_W2} \\ & + 0.12972 \text{ Prob_Hit_W3} + 0.1922 \text{ Prob_damage_W1} + 0.1594 \text{ Prob_damage_W2} \\ & + 0.1306 \text{ Prob_damage_W3} - 0.1002 \text{ Prob_Intercept} \end{aligned}$$

Table 10. Regression Coefficients

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.0354	0.0152	2.34	0.019	
WEP1	0.029507	0.000571	51.71	0.000	1.04
WEP2	0.028458	0.000419	67.96	0.000	1.02
WEP3	0.029711	0.000420	70.71	0.000	1.03
Decoys	0.004418	0.000763	5.79	0.000	5.65
C4ISRT	0.35291	0.00937	37.65	0.000	1.43
Prob_Hit_W1	0.16392	0.00681	24.06	0.000	1.01
Prob_Hit_W2	0.14797	0.00681	21.73	0.000	1.01
Prob_Hit_W3	0.12972	0.00682	19.03	0.000	1.01
Prob_damage_W1	0.1922	0.0137	14.06	0.000	1.01
Prob_damage_W2	0.1594	0.0137	11.60	0.000	1.02
Prob_damage_W3	0.1306	0.0136	9.57	0.000	1.01
Prob_Intercept	-0.1002	0.0163	-6.14	0.000	5.23

Table 11. Regression Model Summary

Model Summary			
S	R-sq	R-sq(adj)	R-sq(pred)
0.0321151	72.29%	72.24%	72.17%

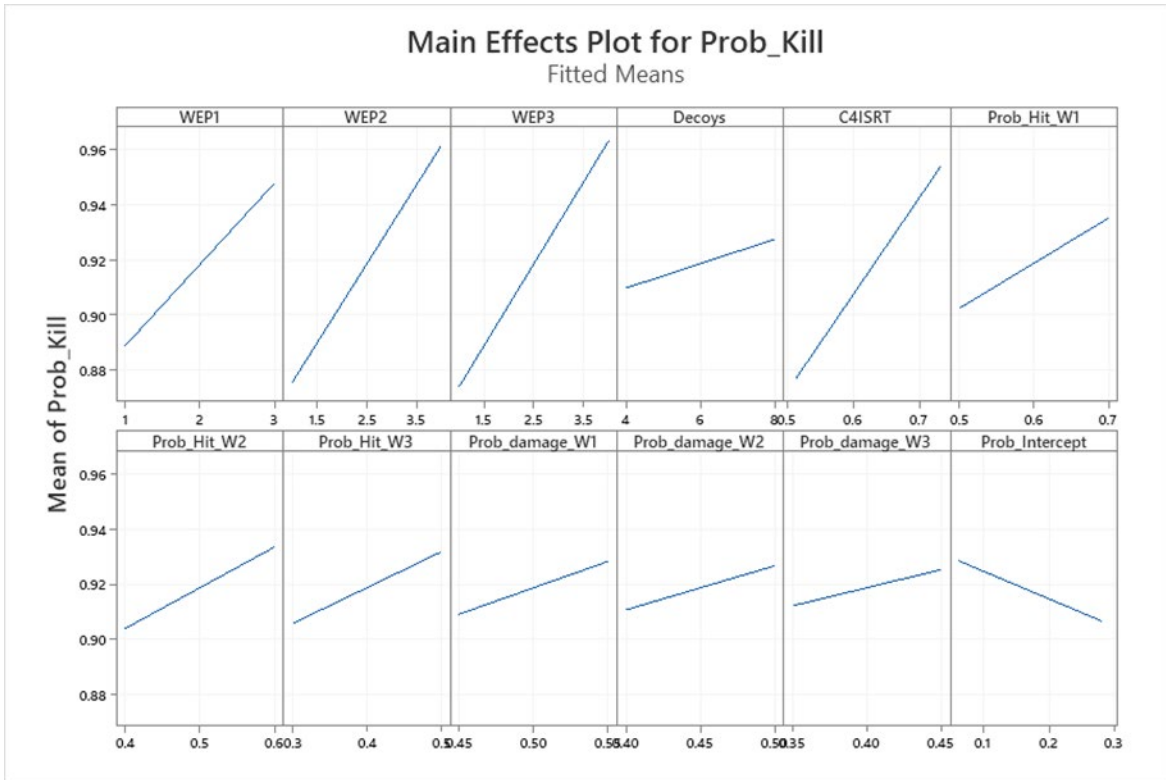


Figure 23. Regression Main Effects Plot for Probability of Kill

Considering the significant differences in cost between long-range fire weapons and decoys, we recommend using decoys employed with the weapon’s salvo attack as described in excursion scenario #2 to improve the probability of killing the Red Force target and increases mission success. Our analysis does show that the probability of kill can be increased with the addition of more long-range fire weapons per salvo. Yet, based on partition analysis, described next, reducing the degradation of C4ISRT using decoys results in more significant effects than the increase in weapons per salvo.

D. PARTITION ANALYSIS

Due to the main effects shown in Figure 23, we adopted another approach to understand the relationship between response factors (output) and independent factors (input variables) by using JMP software and performing predictive modeling with partition analysis.

The partition platform in JMP allows for determining the variable with the primary effect in the system. By recursively partitioning the dataset, multiple variables with significant influence can be determined and compared to show quantitatively how significant one variable effect is related to another (JMP Statistical Discovery LLC 2021).

A resulting probability of kill of greater than or equal to 85% is considered a successful mission. This means the target is completely neutralized such that it is incapable of functioning. A probability of kill less than 85% is considered a *mission fail* since the Red Force target may still have some capability to retaliate by launching their own weapons. For analysis purposes, success or failure is reduced to a binary value of 1 for success and 0 for failure. Using success versus failure, we found that the main input factor contributing to the maximum results of target kill mission success is C4ISRT. For partitioning purposes, as shown in Figure 24, we used number of decoys as our top-level priority and found that anytime the number of decoys employed is greater than or equal to 5, the simulation yields a 91% success rate. We then partitioned lower to verify how C4ISRT values can affect overall results (success vs. failure) from the variation of decoys employed. When the number of decoys used is greater than or equal to 5 and C4ISRT values are greater than 56.59%, the probability of successfully hitting the Red Force target reaches 92%.

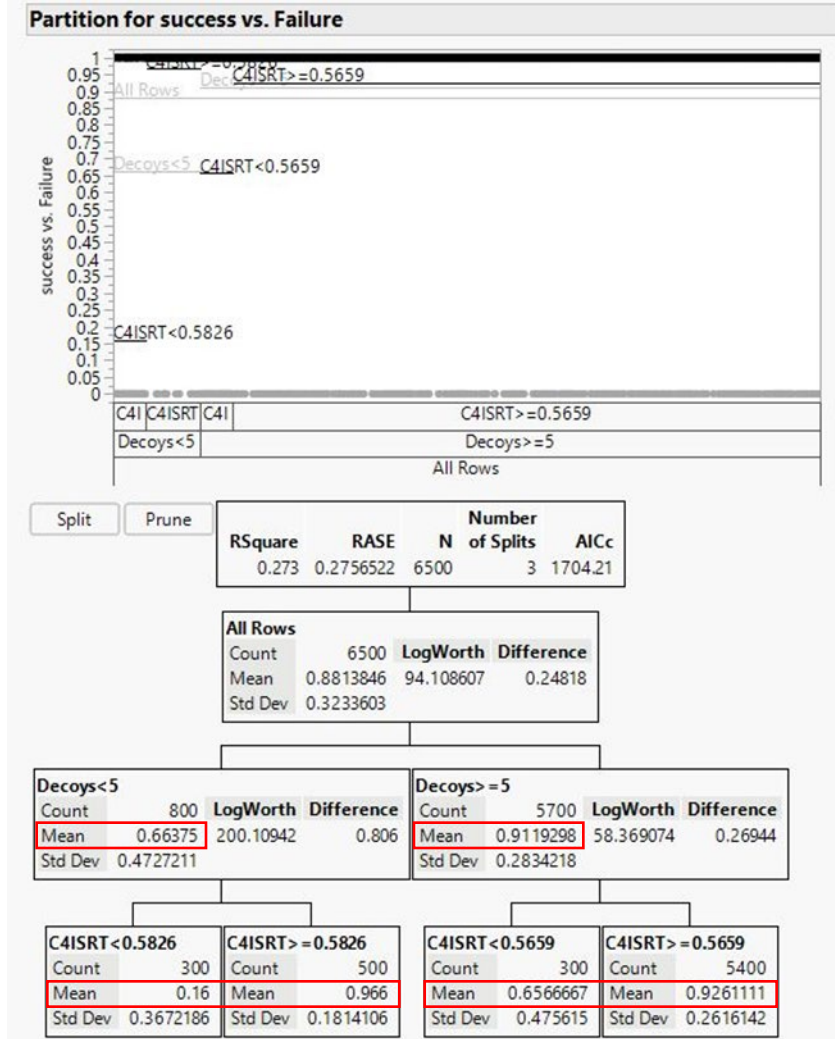


Figure 24. Partition for Success vs. Failure

E. EXCEL MODEL

Due to limitations within Excel, there is no variability in results based on DOE factorial design. Therefore, the probability of kill output will be a deterministic number provided by the formula entered in the Excel spreadsheet.

The Nearly Orthogonal Latin Hypercube (NOLH) data from the DOE was copied into Excel using 65 lines of data points repeated 100 times for robustness and a exhaustive statistical perspective. Our model is based on simplified reliability engineering approaches where many key factors are uncontrollable and cannot be altered.

The first Excel model is based on excursion scenario #1 which includes a salvo of long-range fire weapons attacking a single non-moving Red Force target. Using variables based on the DOE, 6,500 simulation runs were performed. Our results indicate that 1,100 simulation runs resulted in a successful hit and kill of the Red Force target. The simulation shows that altering the Blue Force weapon salvo alone using initial DOE variables, results in an ineffective probability of kill (<85%). However, probability of kill can be increased with the addition of increasing the long-range fire weapons per salvo.

The second Excel model is based on the excursion scenario #2 which includes the salvo of long-range fire weapons along with decoys to reduce the degradation of C4ISRT within the Red Force controlled area. We assume the probability of the Red Force target being hit by the Blue Force weapon salvo increases by 5% per decoy and a 10% degradation in the probability the Red Force can intercept the Blue Force weapons (engineering estimates). In this model, we were able to kill the target in 5,900 out of the 6,500 total simulation runs.

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VI. CONCLUSIONS AND FUTURE RECOMMENDATIONS

A. STUDY PURPOSE

The purpose of this study was to determine the effectiveness of a salvo of long-range fire weapons striking a single non-moving Red Force target located within an A2/AD environment. The study analyses the effectiveness of the salvo attack improved with the addition of decoys to reduce the degradation of the Blue Force C4ISRT and decrease the Red Force probability of intercept.

B. CONCLUSIONS

For this project, we were successfully able to create two ExtendSim models which calculated the probability of kill based on two different excursion scenarios. Both models were then verified using a stochastic Excel model.

From our models we were able to conclude that the salvo attack without any decoys would not be able to destroy the target and as a result would fail the mission. To improve the probability of kill, we could either add more weapons or decoys. However, adding more weapons is significantly more costly than adding decoys, and may not be as cost effective in achieving similar results. The decoy contributes to both reduced degradation of C4ISRT and decreased Red Force's probability of intercepting inbound weapons.

C. RECOMMENDATIONS AND FURTHER RESEARCH

For future research, we would recommend creating a higher-fidelity model. Adding more variables to refine the scenarios and simulation such as specific weapon reliability, number, and types of targets, target distances, target speeds, and distance between Blue Force weapons and Red Force targets, and specifics of C4ISRT assets could provide a greater understanding of the complexity of long-range fires in a denied or degraded C4ISRT environment.

For future research, we would also recommend modeling two excursion scenarios that includes the employment of UAVs and flares which were discussed in Chapter II.

Some points for future research are listed below:

- Run the simulation with added variables
 - Weapon flight speed which may reduce probability of intercept by Red Forces
 - Utilize Range Target Model information to enhance the simulation
 - Introduce time domain attributes to simulation
 - Weapon cruise altitude which may affect the probability of intercept by Red Forces
 - Range to target may affect the probability of intercept by Red Forces. Longer ranges may provide more time for the Red Forces to intercept the incoming weapon salvo
 - Target movement may affect the probability of kill by the Blue Force weapon salvo. Effect from the A2/AD environment may affect targeting capabilities of the Blue Force weapon salvo
- The simulation is designed to accommodate real world weapon and target attributes. However, the use of real-world weapon and target attributes will require following approved classification guidelines.
- The simulation is designed to accommodate real world C4ISRT assets and capabilities. However, the use of real-world C4ISRT values will require following approved classification guidelines.

APPENDIX. EXTENDSIM MODEL

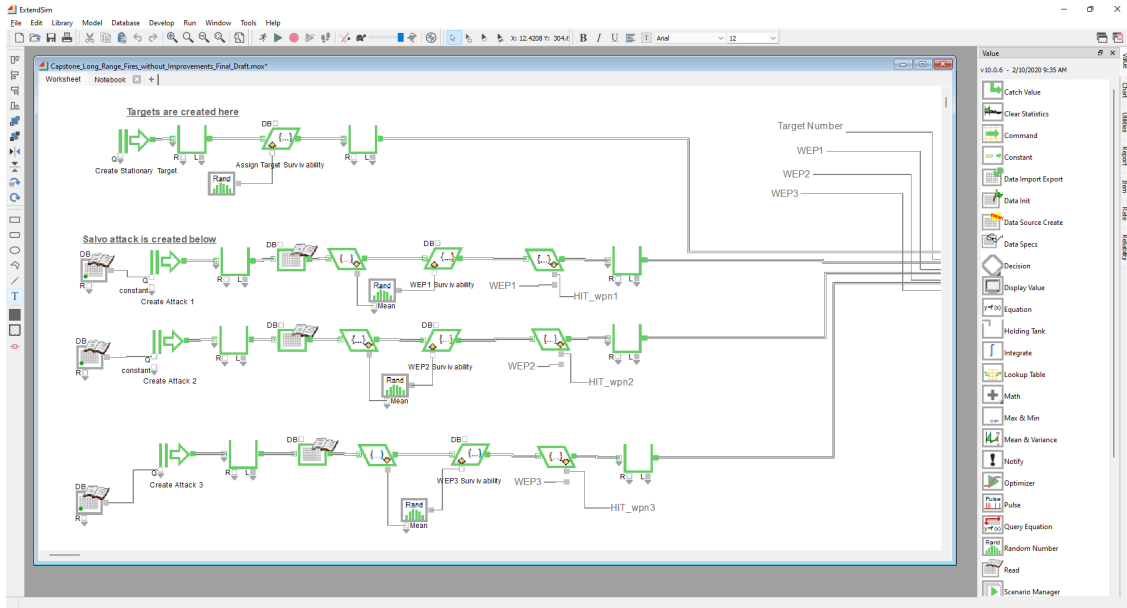


Figure 25. Randomizing the Weapon Survivability Attribute Using a Lognormal Distribution

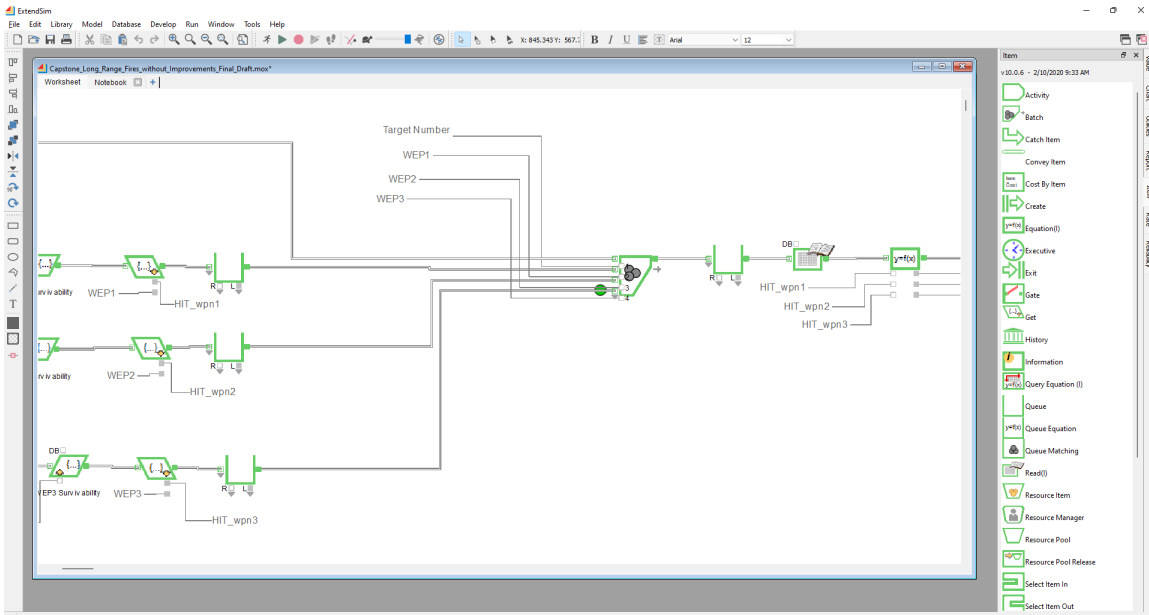


Figure 26. "Batching" the Weapons and the Target Together

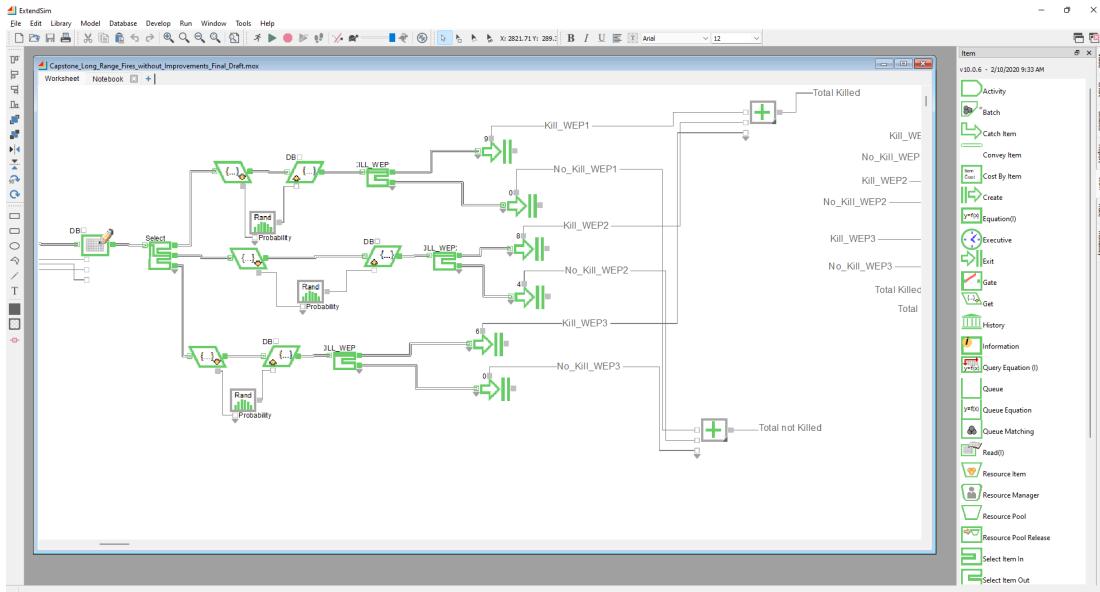


Figure 27. Complete Excursion Scenario #1

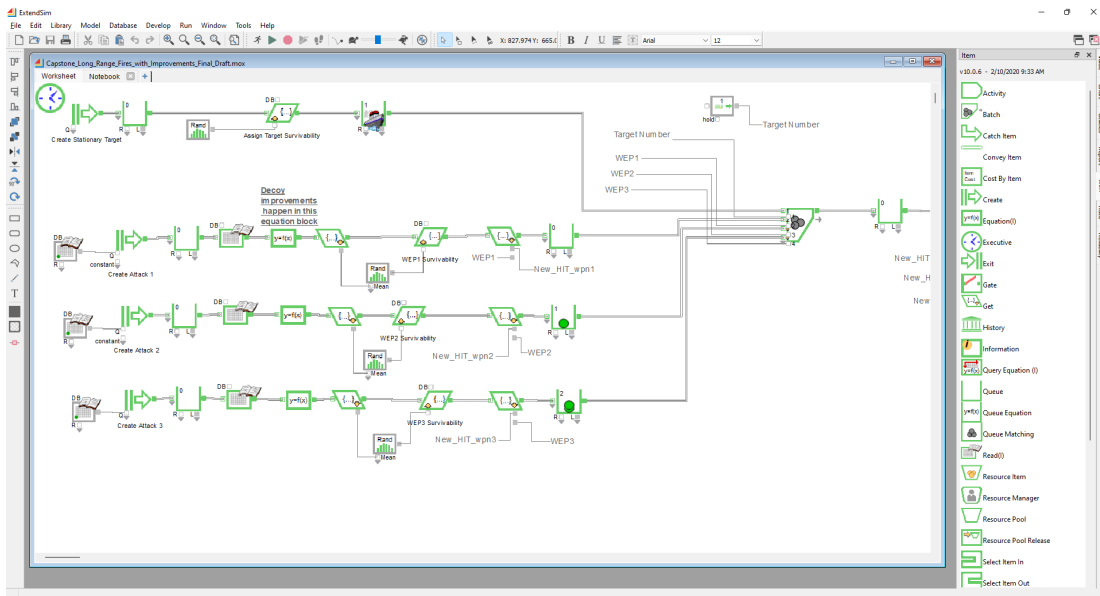


Figure 28. Complete Excursion Scenario #2

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