



NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**COST ANALYSIS FOR OPERATIONAL AND SYSTEM LEVEL
CONSIDERATIONS FOR THE ELECTROMAGNETIC
RAILGUN INTEGRATED ON AN AMPHIBIOUS PLATFORM**

by

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December 2020

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REPORT DOCUMENTATION PAGE			<i>Form Approved OMB No. 0704-0188</i>	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE December 2020	3. REPORT TYPE AND DATES COVERED Master's thesis	
4. TITLE AND SUBTITLE COST ANALYSIS FOR OPERATIONAL AND SYSTEM LEVEL CONSIDERATIONS FOR THE ELECTROMAGNETIC RAILGUN INTEGRATED ON AN AMPHIBIOUS PLATFORM			5. FUNDING NUMBERS	
6. AUTHOR(S) Christian Diaz				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.			12b. DISTRIBUTION CODE A	
13. ABSTRACT (maximum 200 words) Due to the nature of amphibious operations, the Navy's landing platform dock (LPD) amphibious ship is required to remain within close distance of the shore, which poses a threat to the ship and its supported elements such as a Marine Expeditionary Unit. To resolve this issue, this thesis investigates outfitting the LPD-17 with an electromagnetic railgun (EMRG), which is a high-velocity weapon that can fire projectiles at targets at ranges of up to 100 nautical miles by utilizing electromagnetic propulsion rather than traditional propellants. This EMRG concept in the amphibious fleet provides offensive capability in the form of Naval Surface Fire Support (NSFS) and a defensive capability against surface threats, missiles, and other airborne threats. Because the railgun can provide both offensive and defensive capabilities, there is a potential increase in operational effectiveness of amphibious ships conducting air defense and NSFS. This thesis contains a cost estimate of the railgun integration and a cost effectiveness analysis, from both operational and system perspectives, that quantifies the impact of integrating the railgun onto an amphibious platform. The cost estimate for the EMRG is FY20 \$134.66M, given a 32 MJ railgun. From an operational effectiveness perspective, hit probability of air targets has a greater impact on performance than cycle time, and when balancing cost versus effectiveness, a 10 MJ railgun is preferred to a 32 MJ railgun.				
14. SUBJECT TERMS systems engineering, cost, analysis, railgun, effectiveness, operational, estimate, Naval Surface Fire Support, NSFS, electromagnetic railgun, EMRG, landing platform dock, LPD, Marine Expeditionary Unit			15. NUMBER OF PAGES 77	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UU	

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CONSIDERATIONS FOR THE ELECTROMAGNETIC RAILGUN
INTEGRATED ON AN AMPHIBIOUS PLATFORM**

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MASTER OF SCIENCE IN SYSTEMS ENGINEERING

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**NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

Due to the nature of amphibious operations, the Navy's landing platform dock (LPD) amphibious ship is required to remain within close distance of the shore, which poses a threat to the ship and its supported elements such as a Marine Expeditionary Unit. To resolve this issue, this thesis investigates outfitting the LPD-17 with an electromagnetic railgun (EMRG), which is a high-velocity weapon that can fire projectiles at targets at ranges of up to 100 nautical miles by utilizing electromagnetic propulsion rather than traditional propellants. This EMRG concept in the amphibious fleet provides offensive capability in the form of Naval Surface Fire Support (NSFS) and a defensive capability against surface threats, missiles, and other airborne threats. Because the railgun can provide both offensive and defensive capabilities, there is a potential increase in operational effectiveness of amphibious ships conducting air defense and NSFS. This thesis contains a cost estimate of the railgun integration and a cost effectiveness analysis, from both operational and system perspectives, that quantifies the impact of integrating the railgun onto an amphibious platform. The cost estimate for the EMRG is FY20 \$134.66M, given a 32 MJ railgun. From an operational effectiveness perspective, hit probability of air targets has a greater impact on performance than cycle time, and when balancing cost versus effectiveness, a 10 MJ railgun is preferred to a 32 MJ railgun.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAV	amphibious assault vehicle
AGS	Advanced Gun System
ANOVA	analysis of variance
ARG	Amphibious Ready Group
ASCM	anti-ship cruise missile
ATF	amphibious task force
CER	cost estimating relationship
CG	guided missile cruiser
CIWS	Close-In Weapon System
CLA	cushion launch area
CONOPS	concept of operations
DAU	Defense Acquisition University
DDG	guided missile destroyer
DOD	Department of Defense
DOE	design of experiment
DON	Department of the Navy
EMRG	electromagnetic railgun
ESG	Expeditionary Strike Group
GAO	Government Accountability Office
HELIOS	High Energy Laser with Integrated Optical-dazzler and Surveillance
INP	Innovative Naval Prototype
IWS	Integrated Warfare Systems
JCS	Joint Chiefs of Staff
LARC	lighter, amphibious resupply, cargo
LCAC	landing craft air cushion
LCS	littoral combat ship
LCU	landing craft utility
LHA	landing helicopter assault
LHD	landing helicopter dock
LPD	landing platform dock

LRIP	low-rate initial production
LSD	Landing Ship Dock
MJ	megajoule
MOP	measure of performance
NAVSEA	Naval Sea Systems Command
NCCA	Naval Center for Cost Analysis
NSFS	naval surface fire support
NSWCDD	Naval Surface Warfare Center Dahlgren Division
O&S	operation and support
ONR	Office of Naval Research
PPS	pulsed power supply
PEO	Program Executive Office
R&D	research and development
RAM	Rolling Airframe Missile
RDT&E	research, development, test and evaluation
RGWS	railgun weapon system
SECDEF	Secretary of Defense
VLS	Vertical Launch System

EXECUTIVE SUMMARY

This thesis performs a cost analysis for operational- and system-level considerations for the electromagnetic railgun (EMRG) integrated with an amphibious platform. In support of that broader objective, this thesis develops a cost estimate for various railgun weapon systems (RGWS) and compares the cost points to performance outputs from an ExtendSim simulation of an amphibious assault. To create the most accurate cost model, it was important to combine various methods of cost estimation due to the developmental nature of the railgun technology and limitations in available data. The ExtendSim model is designed to allow alterations in the amphibious task force (ATF) composition, railgun characteristics, and enemy force makeup, which creates an opportunity to compare cost at a system level and between different operational concepts.

The Navy developed the railgun to expand surface ships' capability to perform self-defense and naval surface fire support (NSFS). Based on changes to the composition of the future fleet and the developmental nature of the RGWS, there is flexibility regarding the specific platforms that may employ the RGWS. Over the past decade, Naval Sea Systems Command (NAVSEA) has conducted several studies that explore the feasibility of installing this weapon system on various surface platforms. This thesis continues the ongoing work of the Navy by conducting cost effectiveness analysis of integrating the railgun with the LPD-17 platform, which is a good candidate for EMRG integration due to its size and utilization.

This thesis advances the research conducted by Drake (2020), which included an analysis of the impact of the EMRG integrated onto the LPD-17 platform within the construct of an ATF. The team developed a concept of operations (CONOPS) in which an ATF is tasked with regaining control of an occupied island from hostile enemy forces (Drake 2020). Using a discrete event simulation in ExtendSim, the team developed a model of the CONOPS and analyzed the operational effectiveness of an EMRG integrated onto the LPD-17. The simulation models an amphibious assault using four different ATF makeups. The ATF makeups vary the utilization of an LPD-17 equipped with the EMRG and a more traditional guided missile destroyer (DDG) equipped with a 5-inch gun across

operational scenarios. The analysis results show that the LPD equipped with the EMRG provided consistent performance benefit when compared to the DDG.

There are several cost estimation methods available that the Department of Defense (DOD) utilizes during the acquisition process. The deciding factor in which method to use is usually where the weapon system is in its life cycle, as shown in Figure 1. Early in a system's life cycle prior to Milestone A, analogy, or comparative cost, is used to compare a currently fielded system that is similar in design or operation to the proposed system (Defense Acquisition University [DAU] 2020a). Prior to Milestone B, a parametric analysis is used to analyze data from the system to develop cost estimating relationships (CER) between given cost elements and one or more independent variables (Secretary of Defense [SECDEF] 2014). The engineering buildup method decomposes the system into individual components and sums them up to estimate cost of entire system (DAU 2020b). An extrapolation of actual system costs can only be conducted later in the life cycle when production, deployment, operations, and support occur (DAU 2020c).

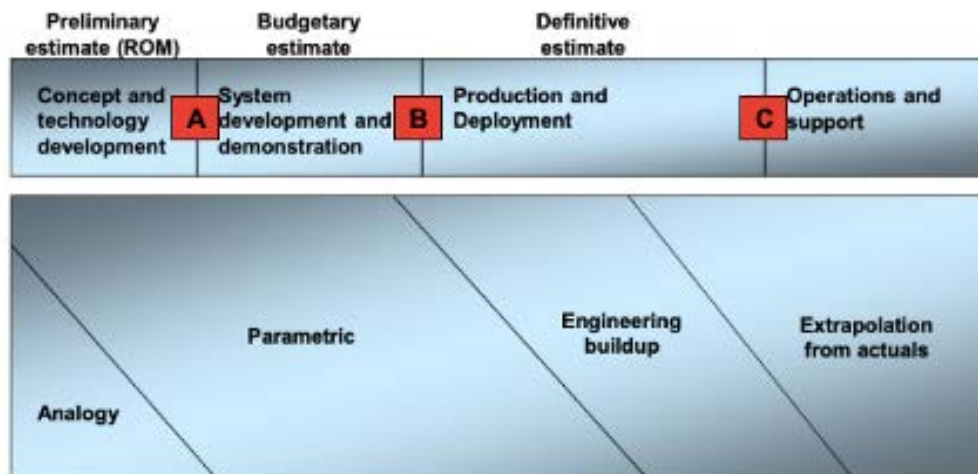


Figure 1. Cost Estimation Methods for Various Life cycle Milestones. Adapted from SECDEF (2014).

Because railgun technology remains under development and is not operational on seagoing platforms, a combination of these methods is required to develop a cost estimate

for the RGWS. Using the available data for the RGWS, the engineering buildup and analogy methods can be utilized. First, the railgun is decomposed into three subsystems: gun mount, pulsed power module, and program support (Department of the Navy [DON] 2018). The costs of the subsystems are then summed together to develop the final cost point. Since the platform being considered in past DON studies was a DDG and not LPD-17, the analogy method is used to compare the similar systems and develop the cost estimate. In order to perform the analogy, cost factors must be applied to the cost of the railgun subsystems to account for assembly and integration with the new platform. According to Nussbaum (2020), an average integration factor for new weapon systems is 17.3%, which is added to the base cost of FY20 \$114.8 M to become \$134.66 M.

Because the initial cost estimate is for a 32 megajoule (MJ) variant railgun, additional scaling factors are applied to produce cost data for use in the cost versus effectiveness analysis for the other railgun variants. The scaling factors used for this cost estimate are derived from the weight in metric tons (MT) of various railgun prototypes (DON 2018) and are shown in Table 1.

Table 1. Cost Estimates for Railgun Variants.

Railgun Variant (MJ)	Railgun Weight (MT)	Scaling Factor	Cost (FY20\$M)
32	300	1.000	134.66
20	275	0.917	123.44
10	150	0.500	67.33

To enhance the applicability of the cost estimates, cost-effectiveness analysis was conducted at both the operational and system levels to inform future investment in the RGWS. The initial results from the Drake (2020) simulation are used to conduct the cost versus effectiveness analysis from an operational perspective. Costs for each course of action (COA), which represent a single ATF configuration, are derived from historical costs for the 5-inch gun and the 32 MJ railgun estimate previously discussed. The simulation outputs results for three measures of performance (MOP) in low, medium, and

high levels of enemy concentration which include percent of enemy missiles destroyed, percent of targets destroyed, and number of ATF ships sunk. The results are shown in Table 2. COA 3, which represents the ATF where the DDG is replaced with the railgun equipped LPD, resulted in the best performance across all enemy concentrations. The traditional ATF represented by COA 1 displayed the worst performance across all enemy concentrations.

Table 2. Simulation Results. Source: Drake (2020).

	Low Enemy Concentration			Medium Enemy Concentration			High Enemy Concentration		
	# Targets Destroyed	% Missiles Destroyed	# ATF Ships Sunk	# Targets Destroyed	% Missiles Destroyed	# ATF Ships Sunk	# Targets Destroyed	% Missiles Destroyed	# ATF Ships Sunk
COA1	39.26	23.49%	0.85	39.26	26.22%	3.77	51.04	20.90%	4.00
COA2	212.26	29.78%	0.74	336.67	32.96%	2.39	395.50	30.58%	3.65
COA3	220.38	78.91%	0.05	339.83	70.67%	0.80	357.60	51.37%	2.37
COA4	213.16	35.44%	0.56	311.74	34.22%	2.56	341.94	30.95%	3.82
COA5	220.44	41.96%	0.35	378.20	45.14%	1.58	477.60	46.55%	2.86

Cost effectiveness combines performance and cost to create a better understanding of the value of the weapon system in this operational scenario. The MOPs are combined with the COA cost points to simplify the data and develop cost effectiveness scores; a higher score equates to a more cost effective COA. Each MOP percentage is equally weighted and added together, and their sum is divided by the cost for that COA. COA 4 is omitted because it has the same makeup as COA 5. Observations from Table 3 include the following:

- COA 3 is the most cost effective option across all enemy concentrations. It is more cost effective by a factor of 2–3 in medium and high enemy concentrations, when the system is under the most stress.
- COA 1, which has no railgun, is more cost effective in low enemy concentration than COA 2 and COA5, both of which have railguns.
- COA 2 and COA 5 are more cost effective than COA 1 in medium and high enemy concentrations (high stress on system).

Table 3. Cost Effectiveness Scores for COAs. Adapted from Drake (2020).

			Cost Effectiveness Score		
COA	Cost Driver	Cost (FY20\$M)	Low Enemy Concentration	Medium Enemy Concentration	High Enemy Concentration
1	DDG	80.12	1.5	0.52	0.37
2	LPD-E and DDG	214.78	0.97	0.72	0.49
3	1 LPD-E	134.66	2.06	1.74	1.13
5	2 LPD-E	269.32	0.86	0.74	0.58

Cost is also compared to effectiveness from a system level perspective by altering the ExtendSim model to simulate the different railgun variants and their performance parameters. There is limited data available for the EMRG; however, several inputs are still able to be changed to create variation in the results such as projectile velocity, cycle time between rounds fired, and probability of kill for various targets. Railgun cost metrics and MOPs are combined again to develop cost effectiveness scores for the 10, 20, and 32 MJ variants, and are shown in Table 4. Observations indicate that the 10 MJ railgun is the most cost effective followed by the 32 MJ and 20 MJ, respectively. The 10 MJ railgun has the lowest performance marks, but it has the highest cost effectiveness score because it is significantly lower in cost than the other two railguns.

Table 4. Cost Effectiveness Scores for Railgun Variants.

Railgun Variant	Cost Effectiveness Score
10 MJ	1.83
20 MJ	1.57
32 MJ	1.74

Based on the cost and effectiveness analysis conducted in this thesis, it appears that the EMRG, employed on an LPD class ship, can provide operational benefit. Recall that the 32 MJ railgun was estimated to have a cost of FY20 \$134.66M, the analysis suggested that this configuration provides the largest operational benefit but that a smaller, 10 MJ railgun estimated to cost FY20 \$67.33M may provide an increased balance of cost versus effectiveness.

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ACKNOWLEDGMENTS

I would like to thank Dr. Paul Beery and Dr. Daniel Nussbaum, who assisted me throughout the entire thesis process. I would also like to thank my fellow classmates Chris Hevey and Josh Hildebrand. They helped me grind through graduate school, and now, I will leave here with two lifelong friends.

Most importantly, I would like to thank my wife, X'andria, who has always supported me and got me through the tough times.

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I. INTRODUCTION

A. MOTIVATION AND BACKGROUND

The landing platform dock (LPD) San Antonio class ship currently provides the Navy and Marine Corps with a sea-based platform to conduct amphibious operations such as transporting and launching a multitude of air and amphibious assault craft. Due to the nature of these operations, the LPD is required to remain within close distance of the shore, which poses a threat to the ship and any of its supported elements. To combat this issue, it is proposed that the LPD-17, shown in Figure 1, be outfitted with an electromagnetic railgun (EMRG), which is a high velocity weapon that can fire projectiles at targets at ranges up to 100 nautical miles away by utilizing electromagnetic propulsion rather than traditional propellants. The EMRG would be inserted into the amphibious fleet to provide offensive capability in the form of naval surface fire support (NSFS) and a defensive capability against surface threats, missiles, and other airborne threats. Because the EMRG can provide both offensive and defensive capability, there is a potential increase in operational effectiveness of amphibious ships. This thesis contains a cost analysis, from both an operational and system perspective, that quantifies the impact of integrating the EMRG on an amphibious platform.



Figure 1. LPD-17 San Antonio (LPD-17) Class Ship without EMRG Installed. Source: O'Rourke (2020b).

B. PROBLEM STATEMENT

The Navy developed the railgun weapon system (RGWS) to expand surface ships' capability to perform self-defense and naval surface fire support (NSFS). Based on changes to the composition of the future fleet and the developmental nature of the RGWS, there is flexibility regarding the specific platforms that may employ the RGWS. Over the past decade, Naval Sea Systems Command (NAVSEA) has conducted several studies that explore the feasibility of installing this weapon system on various surface platforms. Due to the size and utilization of the LPD-17, there may be an opportunity to integrate the RGWS with LPDs; however, there are no official plans to do so. Consequently, there are no cost studies that analyze the feasibility of installing this weapon onto such a platform. High ranking military officials and members of Congress use cost analyses and cost effectiveness studies to assist in making decisions. This thesis develops a baseline cost estimate for the integration of the RGWS on an LPD-17. That estimate is integrated with existing operational analyses and can be used for future analyses regarding the cost effectiveness of the EMRG system.

C. THESIS OBJECTIVES

The following objectives are met with the research and analysis conducted within this thesis:

- Develop a cost estimate for integrating an EMRG onto the LPD-17 platform.
- Develop a model for integration cost versus operational effectiveness of EMRG to expand work of Drake (2020)
- Perform sensitivity analysis based on various integration costs as a percentage of total combat system cost.

This research adds to the ongoing work that the Office of Naval Research (ONR) is conducting in the area of shipboard use of electromagnetic railgun systems. The EMRG can provide ship self-defense and offensive capabilities in an amphibious assault scenario as well as NSFS to expeditionary land forces that require artillery support. Multiple configurations of the EMRG are compared and analyzed to examine the cost effectiveness of a railgun capable amphibious ship engaged in a combat scenario. The stakeholders that stand to benefit from this analysis include the Office of Naval Research, the Marine Corps Warfighting Laboratory, and the Naval Expeditionary Combat Command by providing a decision aid that can be used to inform investment and research into EMRG technology and utilization.

D. THESIS APPROACH

Given that the EMRG is not currently deployed on amphibious ships, this thesis is restricted to analysis of the potential impact of employment on those classes of ships. Accordingly, this thesis focuses nearly exclusively on analysis of the problem. An analytical research method is used to determine the cost effectiveness of implementing an electromagnetic railgun system on amphibious naval ships.

This thesis analyzes cost versus effectiveness of adding a railgun to an amphibious ship through the application of systems engineering and systems simulation analysis to a

scenario based on the Drake (2020) concept of operations (CONOPS) developed in conjunction project sponsor Tom Boucher from ONR. The CONOPS will be used to clearly define the operational scenario that will be explored. The results from the modeling program will be used to support analysis of an amphibious ship equipped with an EMRG to measure its operational effectiveness. In addition, this research includes an analysis of system integration costs for similar combat systems to develop a cost model of installing an EMRG onto the LPD-17 platform. From this, a cost versus effectiveness analysis is conducted to provide insight into the feasibility of fielding an EMRG on an amphibious ship.

II. LITERATURE REVIEW

This research develops a cost analysis model for the integration of an EMRG onto the LPD-17 platform. It is important to understand the role of the LPD-17 within the U.S. surface naval force and the mission capability that the EMRG provides in amphibious operations. Depending on where a program is in its life cycle and the information that is available, various analysis methods are used to predict the cost of a weapon system. The goal of this literature review is to select relevant literature to create a better understanding of the added capabilities of installing the EMRG onto LPD-17 and various cost estimation methods.

A. LPD-17 ROLE WITHIN AMPHIBIOUS OPERATIONS

Amphibious forces are task-organized, and their structure varies depending on whether the mission is a combat related such as a raid or an assault or humanitarian efforts such as disaster relief (Joint Chiefs of Staff [JCS] 2019). Generally, an amphibious force can be structured as an Amphibious Ready Group (ARG) or an Expeditionary Strike Group (ESG). The ARG is composed of a landing helicopter assault (LHA) or landing helicopter dock (LHD) ship, commonly referred to as big deck amphibious ships, a dock landing ship (LSD), and the LPD-17. The ESG is made up of the same ships and has a surface combatant such as a guided missile cruiser (CG) or destroyer (DDG) for enhanced air and surface warfare capabilities and to provide NSFS for ground forces.

Within the context of either an ARG or ESG, the LPD-17 class ship is a multi-mission platform designed to embark, transport, and land Marine forces and various equipment (O'Rourke 2020b). They are capable of carrying a variety of amphibious landing craft such as the landing craft air cushion (LCAC), landing craft utility (LCU), amphibious assault vehicle (AAV), and light amphibious resupply cargo (LARC) as well as any other support vehicles such as armored trucks, bulldozers, and tanks. The San Antonio class is equipped with the Close-In Weapon System (CIWS), Rolling Airframe Missile (RAM), MK-46 30-millimeter cannons, and other crew served weapons in support of the surface and air warfare mission areas. According to instruction, the ship is to operate in a low to medium density, multi-threat environment as part of a task force or

independently, provide its own anti-air and limited anti-surface defense, and perform sustained amphibious operations (Department of the Navy [DON] 2017b).

Each ship, including LPD-17, has a specific role within the amphibious operations structure. Figure 2 displays the layout of sea-based forces for an amphibious operation. The fire support area is designated for the DDG or CG to provide NSFS. This position is close to shore at no more than 4–5 nautical miles due to maximum effective range of their main battery. The LSD is responsible for launching AAVs and LCUs, so it alternates position between the transport area and the AAV launching area. The LPD launches the LCACs and will be stationed in the cushion launch area (CLA) in either the transport area or the sea echelon area. LCACs have a longer range than AAVs and are much faster than LCUs, which allows the LPD to take station further away, if necessary (JCS 2019). The command ship, LHA or LHD, may also launch LCACs from the sea echelon area but will retreat to the distant retirement area to perform flight operations. This operational concept may be changed through the introduction of new technologies such as the railgun weapon system.

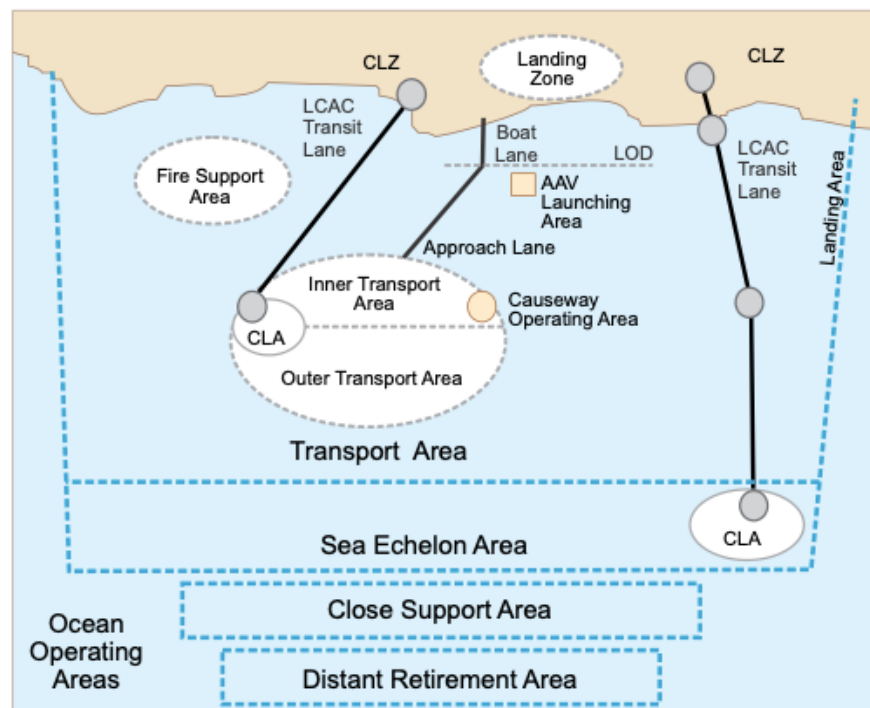


Figure 2. Amphibious Operation Layout of Forces. Source: JCS (2019).

B. EMRG

The significance of implementing emerging technology such as an EMRG starts with understanding how the system functions, the added capabilities to current and future surface Navy platforms, and the missions it can perform. Within a multi-threat amphibious operation, the EMRG gives commanders enhanced capabilities to suppress and defeat adversarial forces.

1. Background

The EMRG is a long-range weapon system that uses stored electromagnetic energy to fire hypersonic projectiles rather than conventional chemical-based propellants (BAE Systems, Inc. 2014). Figure 3 is a depiction of how the EMRG operates. Magnetic fields are created by an electrical current flowing through conducting rails to accelerate an armature to launch the projectile at speeds up to Mach 7 (Tzeng and Schmidt 2011, 149). The hypervelocity projectile impacts and destroys targets with kinetic energy rather than an explosive warhead. The EMRG also provides improved shipboard safety measures by eliminating the use of gunpowder and other high explosive material within the ship's magazines (DON 2017a).

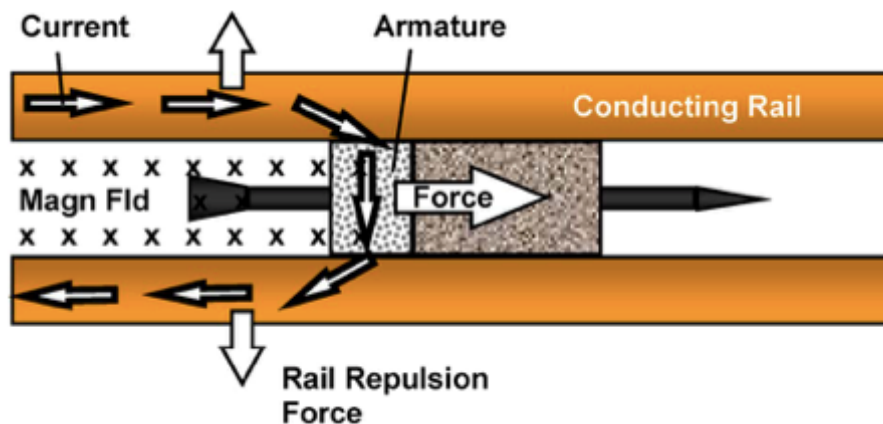


Figure 3. Operation of Railgun Launcher. Source: Tzeng and Schmidt (2011).

The Electromagnetic Railgun Innovative Naval Prototype (INP) developed by BAE Systems at the Naval Surface Warfare Center Dahlgren Division (NSWCDD), shown in Figure 4, is capable of launching projectiles at speeds approaching Mach 6 with a muzzle energy of 32 megajoules (MJ), which equates to a 110 nautical mile range (DON 2017a). This is a significant improvement over the currently employed MK 45 5-inch gun mount whose maximum effective range is approximately nine nautical miles. The system can support sustained military operations with a firing rate exceeding 10 rounds launched per minute and a magazine capable of carrying up to 500 projectiles (Chaboki et al. n.d.).



Figure 4. Electromagnetic Railgun Innovative Naval Prototype (INP)
Developed by BAE Systems. Source: DON (2017a).

2. Railgun Integration

In an analysis regarding the employment of an EMRG on the DDG-51 class, the railgun was “integrated into existing ship spaces without disrupting other weapon systems such as the Vertical Launching System (VLS)” (Chaboki et al. n.d., 27). The current space utilization of DDG-51 weapon systems was maintained while the addition of railgun electronic components and ammunition handling system was integrated with them. The

USS Portland, a San Antonio class ship much larger than the DDG-51, was chosen to house an in-development laser system because the ship had the space and weight capacity, so it is feasible that the EMRG system could be installed on the same ship class (O'Rourke 2020a). Based on this initial proof of concept, the U.S. Navy is also investigating the feasibility of utilizing the railgun on other ship classes.

While the EMRG was originally designed solely to provide fire support for ground forces, it was determined to be a viable option for air and surface defense (O'Rourke 2020a). The addition of an EMRG would add to LPD-17's list of operational capabilities with the capabilities specified in the CG Required Operational Capabilities instruction. This includes providing NSFS support to amphibious ground forces with direct and indirect fires (DON 2014). With firing ranges exceeding 100 nautical miles, a ship can station itself far enough from shore to avoid being susceptible to land-based anti-ship cruise missiles (ASCM) while maintaining the ability to launch LCACs and conduct flight operations. Engagement of air targets would occur at shorter ranges due to the requirement of the EMRG launched projectile to physically strike the target and destroy it with kinetic energy rather than an explosive warhead (O'Rourke 2020a). This also makes Navy planning more flexible due to the elimination of the requirement for an ARG to be augmented with a CG or DDG to provide fire support and area defense. While there are potential operational gains from the integration of the RGWS on multiple ship classes, the cost consequences of these decisions require additional exploration.

3. NPS Research Efforts

In 2020, an NPS capstone team conducted an analysis of the EMRG and the impact of its integration onto the LPD-17 platform within the construct of an amphibious task force (ATF). The team developed a CONOPS, shown in Figure 5, in which an ATF is tasked with regaining control of an occupied island from hostile enemy forces (Drake 2020). Using a discrete event simulation in the commercial simulation software package ExtendSim 10, the team was able to develop a model of the CONOPS and analyze the operational effectiveness of an EMRG integrated onto the LPD-17.

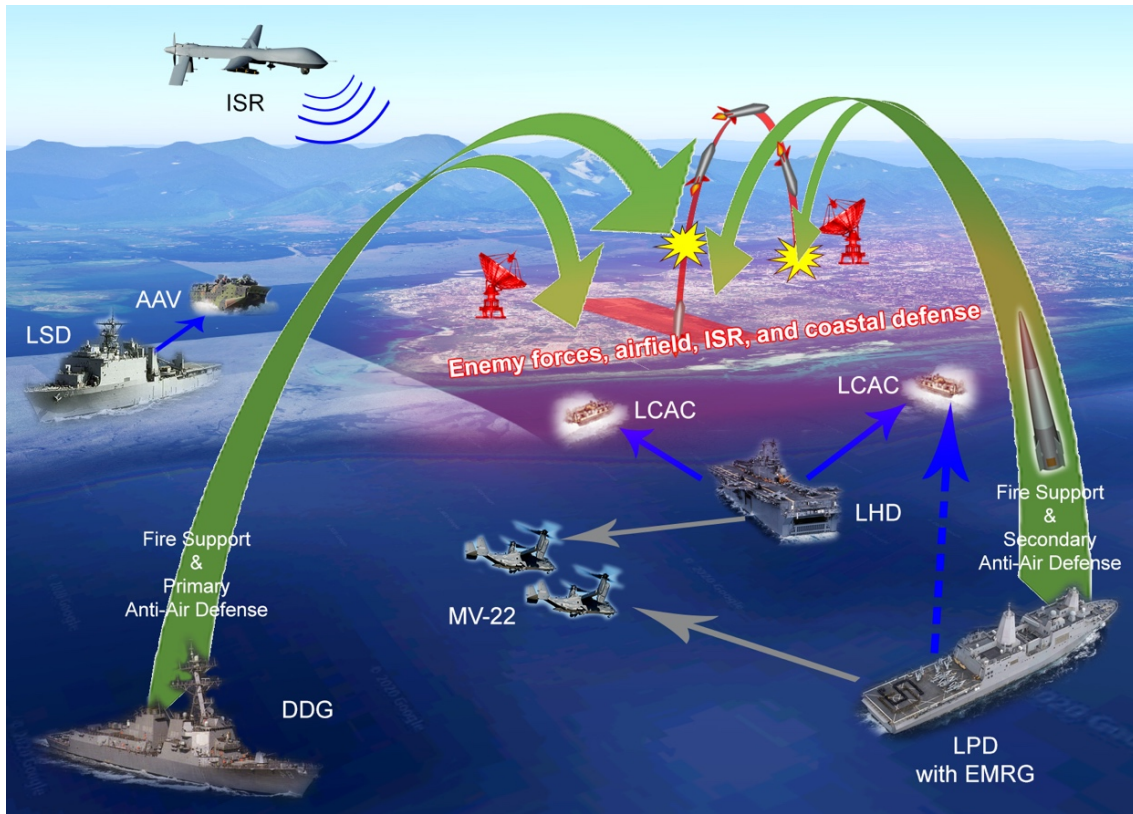


Figure 5. High-level Operational Concept (OV-1) of Amphibious Assault Conducted in a Scenario in which EMRG is Integrated With LPD-17 Class Ship. Source: Drake (2020).

The ExtendSim simulation uses a range of inputs to closely model a realistic amphibious operation. By varying the railgun performance parameters and ATF makeup, the research team was able to alter the outcome of the amphibious operation and compare the operational effectiveness of each course of action (COA) (Drake 2020). The analysis includes five different ATF configurations, or COAs, shown in Table 1, each of which resulted in varying values for the measures of performance (MOP) that were tracked. The MOPs include targets destroyed, enemy missiles destroyed, and ATF ships sunk (Drake 2020).

Table 1. ATF Makeup for Simulation. Adapted from Drake (2020).

COA	Ship 1	Ship 2	Ship 3	Ship 4	Description
1	LPD	LSD	LHD	DDG	Traditional ATF, no EMRG, DDG provides NSFS and area defense
2	LPD-E	LSD	LHD	DDG	EMRG added to LPD (LPD-E) to assist in NSFS and area defense
3	LPD-E	LSD	LHD	N/A	DDG removed, EMRG provides all NSFS and area defense
4	LPD	LSD	LHD	LPD-E-C2	EMRG C2 flagship coordinates mission and provides all NSFS and area defense
5	LPD-E	LSD	LHD	LPD-E-C2	All ATF LPDs equipped with EMRG. Secondary LPD-E assists with NSFS and area defense

The results indicate that the EMRG integration onto the LPD-17 improves the operational effectiveness of the ship and enhances the ATF's ability to complete the assigned mission. The observations made from the simulation results include the following (Drake 2020):

1. COA 1, which has no railgun, shows the poorest performance against all responses.
2. The addition of an EMRG in COA 2 through COA 4, and two EMRGs in COA 5, shows an increase in effectiveness against all responses.
3. COA 3 shows the best performances against all responses.

A table of the results as well as a graphical representation is shown in Table 2 and Figure 6. COA 3 is the best performing ATF configuration (LHD, LSD, and a single LPD-E), and the results suggest that the EMRG is a capable weapon system with the potential to fill the role of the DDG by performing area defense and NSFS. A continuation of this

research paired with a cost analysis of railgun and ship integration in an effort to explore cost versus effectiveness is discussed in Chapter IV of this thesis.

Table 2. Simulation Results. Source: Drake (2020).

	Low Enemy Concentration			Medium Enemy Concentration			High Enemy Concentration		
	# Targets Destroyed	% Missiles Destroyed	# ATF Ships Sunk	# Targets Destroyed	% Missiles Destroyed	# ATF Ships Sunk	# Targets Destroyed	% Missiles Destroyed	# ATF Ships Sunk
COA1	39.26	23.49%	0.85	39.26	26.22%	3.77	51.04	20.90%	4.00
COA2	212.26	29.78%	0.74	336.67	32.96%	2.39	395.50	30.58%	3.65
COA3	220.38	78.91%	0.05	339.83	70.67%	0.80	357.60	51.37%	2.37
COA4	213.16	35.44%	0.56	311.74	34.22%	2.56	341.94	30.95%	3.82
COA5	220.44	41.96%	0.35	378.20	45.14%	1.58	477.60	46.55%	2.86

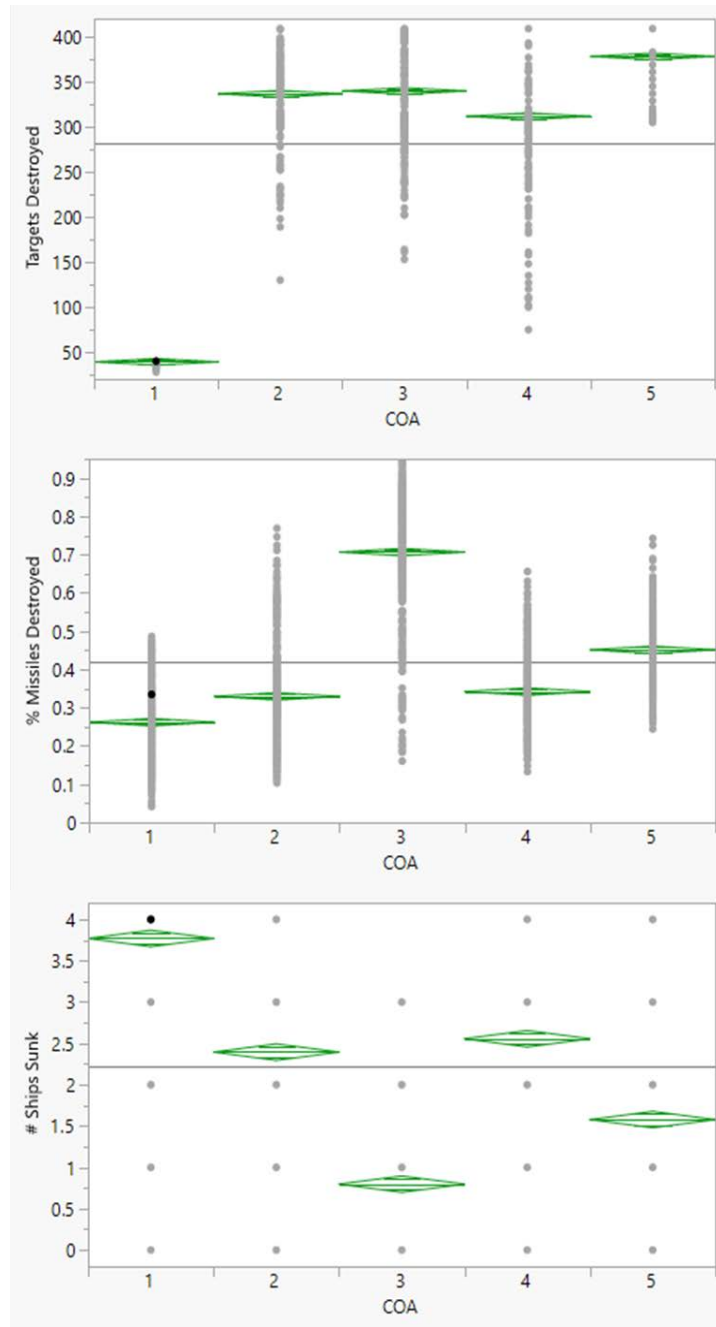


Figure 6. Simulation Results at Medium Enemy Concentration.
Source: Drake (2020).

C. COST ESTIMATION METHODS

Life cycle cost estimates provide decision makers with an accounting of cost elements associated with the development, production, deployment, and sustainment of a

particular program (Secretary of Defense [SECDEF] 2014). Such estimates are required for key decision points and milestone reviews. Life cycle cost estimates help to determine the budget and ensure all costs are accounted so that the appropriate resources are allocated to support the program (SECDEF 2014). According to the Government Accountability Office (GAO), life cycle costs are the sum of four phases of a system's life cycle:

- **Research and Development (R&D)** – Includes design and engineering costs for design, fabrication, construction, and test and evaluation. R&D also consists of program management requirements and other support elements required for product development.
- **Investment** – Includes procurement and other related costs such as hardware and program management from low rate initial production (LRIP) through deployment of the primary system.
- **Operations and Support (O&S)** – Includes all costs from sustainment of system throughout entire life cycle including fuel, manpower, training, and maintenance.
- **Disposal** – Cost of disposal or decommissioning of system after life cycle is complete (Richey 2009).

Figure 7 shows an example of the life cycle cost profile for a system; however, this will vary depending on the type of system. Although the majority of costs are incurred in the O&S phase, they are obligated in the R&D and investment phases, necessitating quality cost estimates early in the system development life cycle.

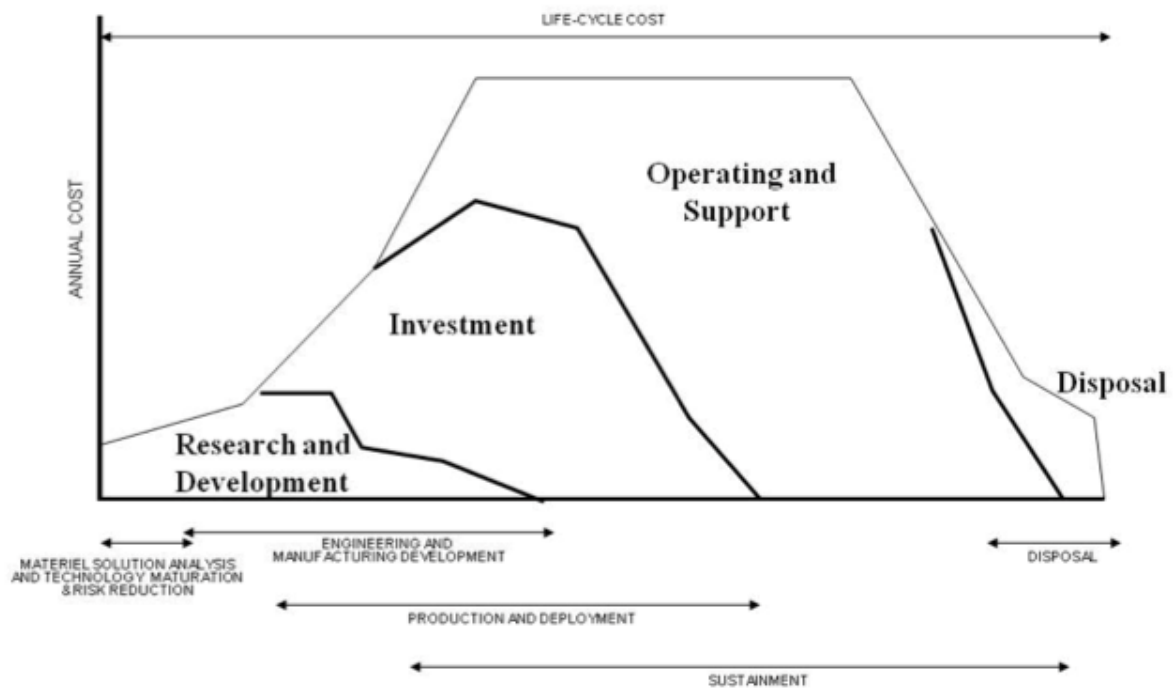


Figure 7. Life Cycle Cost for Notional DOD Program. Source: SECDEF (2014).

Within the DOD's acquisition process is a requirement to conduct a cost analysis at each milestone review (Boito et al. 2018). Figure 8 shows the various cost estimation methods recommended for each milestone. The four most common methods the DOD uses for developing a cost estimation include

- Analogy
- Parametric
- Engineering build-up
- Extrapolation based on actual cost

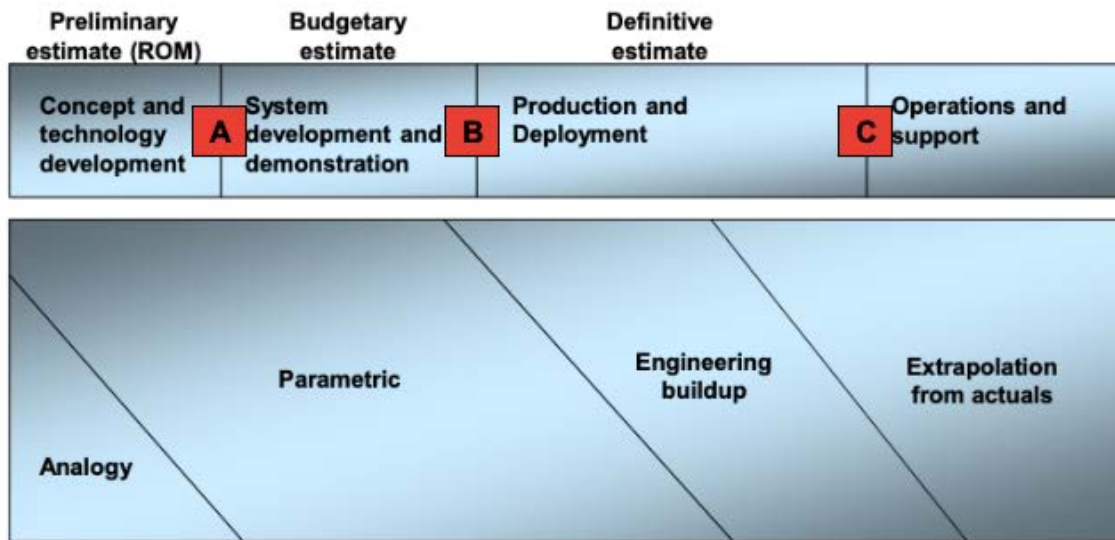


Figure 8. Cost Estimation Methods for Various Life Cycle Milestones.
Adapted from SECDEF (2014).

Early in a program life cycle prior to Milestone A, system development is focused on completion of a Material Solutions Analysis and transition to Technology Maturation and Risk Reduction. Within this timeframe the analogy method may be used for cost estimation. Analogy, or comparative cost, is used when program requirements are unknown (Defense Acquisition University [DAU] 2020a). A currently fielded weapon system that is similar in design or operation to the proposed system is used for the analogy. Historical cost data from the current system is adjusted using scaling factors to predict the cost of the proposed system (SECDEF 2014). For the railgun, a comparative analogy may be considered with missile or gun systems.

Prior to Milestone B, which involves system development and demonstration, a parametric analysis can be used to analyze data from the system to develop cost estimating relationships (CER) between given cost elements and one or more independent variables (SECDEF 2014). This technique is more objective due to the CERs being derived via statistical methods rather than relying on the subjectivity of experts with the analogy method (DAU 2020b). In 2010, a study was conducted at NPS to develop CERs between 19 different ships' speed, displacement, length, draft, and crew size and the lead ship production cost (Ting 2010). A statistical analysis software was used to measure the

interactions between cost factors and their effects on the final construction cost of the ship. The CERs were then used to estimate the lead ship production cost for a replacement amphibious craft for the LCAC.

Following Milestone B, when engineering and manufacturing development occur, an engineering buildup cost analysis method may be employed. The proposed system is broken down into subcomponents where labor, material, and integration costs are accounted for, and algebraic equations are used to estimate the cost of the entire system (SECDEF 2014). This process is usually time consuming and expensive, and it is necessary to have knowledge and technical understanding of the entire system (DAU 2020c). To use this technique the system must be decomposed using a work breakdown structure (WBS). A WBS is used to breakdown a system into subsystems at lower levels of detail as shown in Figure 9. Labor, material, and overhead costs are then applied to each subsystem to develop an overall system cost (DAU 2020c).

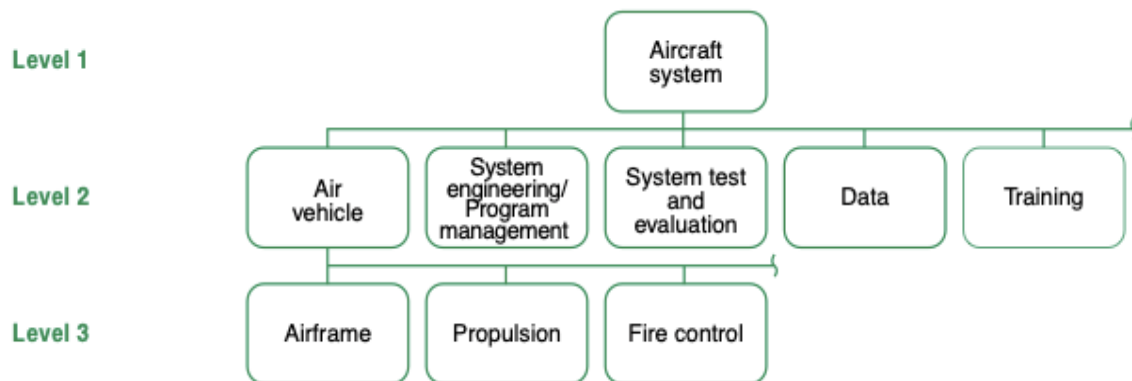


Figure 9. Work Breakdown Structure Used for Engineering Build-Up Method. Source: Richey (2009).

In 2012, NAVSEA conducted a study regarding the integration of a railgun onto the Littoral Combat Ship (LCS) platform by using the engineering buildup method. In the study, the RGWS was decomposed into its five major components, the mount module, the pulsed power supply (PPS) module, the mount support module, the power generation module, and the seawater cooling module (Nelson 2012). NAVSEA was able to determine

the structural alterations required for the railgun to be installed onto the LCS based on the weight of each railgun component. The final acquisition cost would be calculated by adding together the cost of the structural changes, the railgun components, research and development, and test and evaluation (RDT&E) (Nelson 2012).

An extrapolation of actual system costs can be conducted later in the life cycle near Milestone C, when production, deployment, operations, and support occur. This technique is used when little has changed in the engineering and manufacturing processes and the program has collected cost data regarding its own activities (DAU 2020d). For example, when the lead ship in a class has been constructed and is undergoing sea trials, the program is gathering data regarding fuel consumption, maintenance and repairs, training costs, and other cost data. This information can be used to estimate O&S costs for future ships of the same class. Table 3 summarizes the cost appropriate methodologies discussed in this section as well as their advantages and disadvantages.

Table 3. Summary of Cost Estimation Methods. Adapted from DAU (2020a, b, c, d).

Methodology	Description	Advantages	Disadvantages
Analogy	Compare system with currently employed similar system	Can be used before detailed requirements are known	Similar systems must exist
Parametric	Use statistical software to determine cost estimating relationships between cost factors and independent variables	Models are fast and easy to use. CERs developed using parametrics can be easily modified for changes to what is being estimated and matched to a specific development environment	Models can be inaccurate if the underlying data is not reliable. Requires several data points
Engineering Build-Up	Break out system into individual components and sum them up to estimate cost of entire system	Provides good insight into major cost contributors because of level of detail	Time consuming and costly. Small errors become large in system summation estimate
Extrapolation of Actual Cost	Use historic cost data to estimate cost of continued production in the future over the course of system life cycle	Highly detailed and accurate due to using actual data from the system being analyzed	Method cannot be used until production and manufacturing costs have stabilized. Cost data can be difficult to acquire.

Once the cost estimation is complete, a sensitivity analysis is conducted to determine the effects of changes to one or more cost drivers. This is an effective way to determine which variables affect the cost estimate the most (Richey 2009). It is important to include the assumptions that are most likely to change due to lack of knowledge or effects of uncontrollable forces. A sensitivity analysis is done by recalculating the cost estimate with different quantitative values for selected input parameters, and then

comparing the new cost estimate to the original (Richey 2009). Sensitivity analysis also provides insight for the potential best and worst case for cost estimates of a system.

III. COST ESTIMATE DEVELOPMENT

A. COST ESTIMATE METHOD

As stated in Chapter II, the type of cost estimate that can be conducted is dependent upon the data available for the system. Because the RGWS is in between Milestones A and B of the system life cycle and not currently fielded on any U.S. Navy platforms, there is little to no cost data available for analysis. The parametric method is unable to be used because there is not an adequate number of data points to accurately determine the CERs between cost factors and independent variables. It is important to note that the use of a parametric cost model would have resulted in the most accurate estimate of the system cost had it been feasible to populate the dataset with various railgun prototypes. If there had been a large enough number (data points) of RGWS of various sizes and operational capabilities with their associated costs available for release, then this data would have been most useful in developing the cost model for the railgun-capable LPD-17. With the emerging technology of the RGWS being an invention of the early 21st century, making it the first in service in the U.S. Navy, a parallel approach is taken to make up for the sparseness in the dataset. For this reason, the cost estimation method of extrapolating actual costs cannot be used either. The most effective method for developing a cost estimate with the available information is a combination of the analogy and engineering build-up methods.

The first step in developing a cost estimate for the railgun using the engineering build-up method is to decompose the various components of the weapon system. A study conducted by the Integrated Warfare Systems (IWS) Program Executive Office (PEO) provides the following breakout, as well as the graphical representation shown in Figure 10, of the RGWS components (Department of the Navy [DON] 2018):

- Gun mount
- Barrel
- Gun electronics

- Pulsed Power Transfer
- Pulsed Power Supply

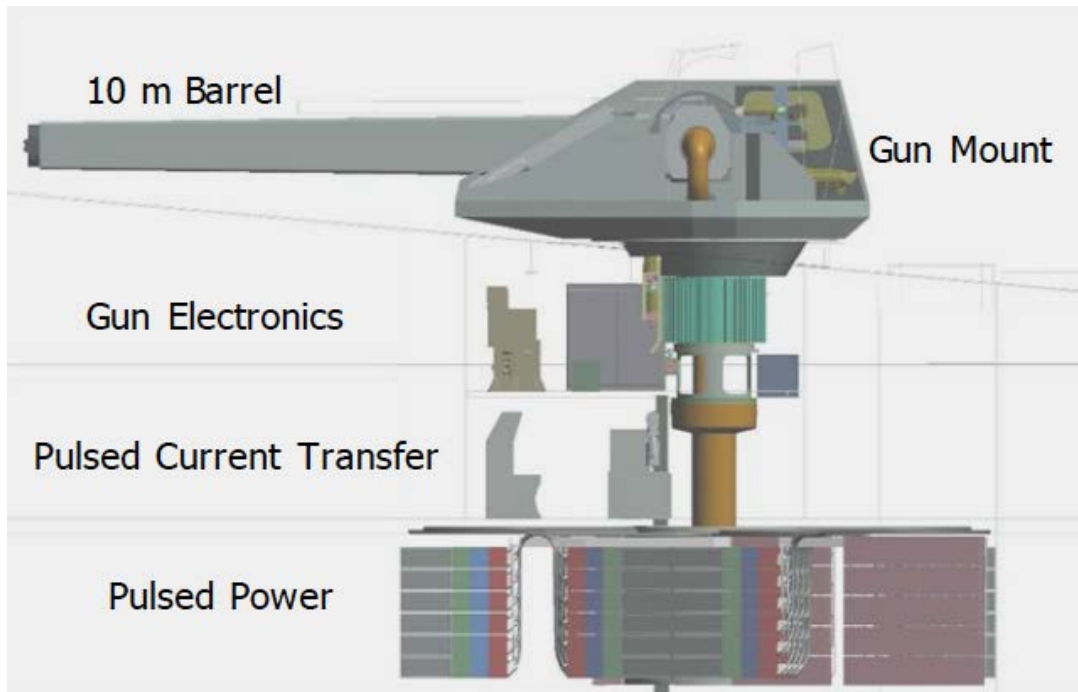


Figure 10. Layout of RGWS. Adapted from DON (2018).

These components are included in the WBS, shown in Figure 11, for the railgun system that is required for the engineering build up method. For the cost estimate provided in this study, the gun mount includes the barrel and the gun electronics, and the pulsed power supply includes the power transfer components (DON 2018). Because the platform being considered in this study is a DDG rather than an LPD, the analogy method is used to compare the similar systems and develop a cost estimate.

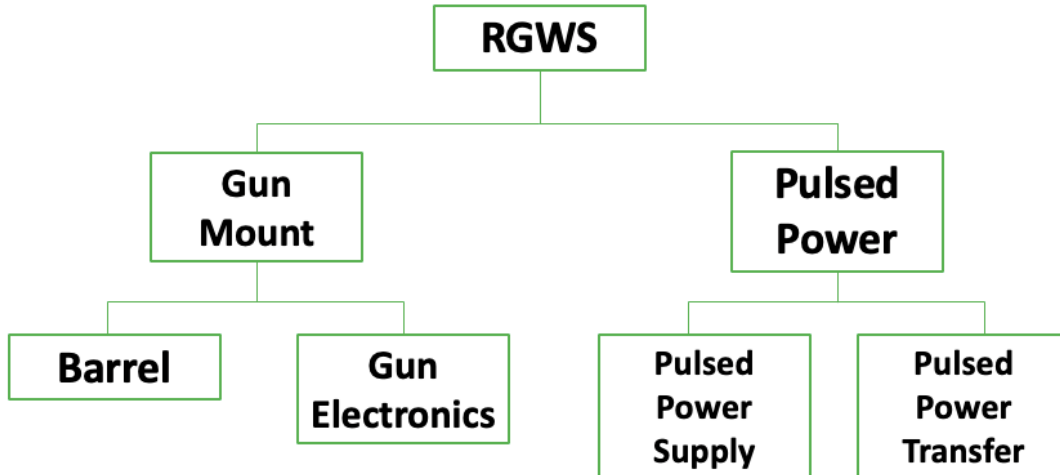


Figure 11. RGWS Work Breakdown Structure. Adapted from DON (2018).

The analogy method requires similar systems to exist and for their costs to be known. The proposed RGWS and DDG integration project will provide the base cost that is used for the RGWS and LPD cost estimate. In development of the estimate, scaling factors are used to alter the cost of the analogous weapon system to account for changes in design, material, and manpower. When applied to the cost of the analogous system, these scaling factors create a cost estimate for the weapon system being analyzed. The scaling factors employed for the cost estimate in this thesis will be discussed in the following section.

B. INTEGRATION FACTORS

The Naval Center for Cost Analysis (NCCA) sets policies and procedures for conducting cost estimates, cost analysis, and economic analysis and for reporting cost estimates and comparisons to the budget (Naval Center for Cost Analysis [NCCA] 2020). The NCCA publishes the *Standard Cost Factors Handbook*, which provides general rules of thumb to senior management regarding cost estimates of programs. The cost factors in the handbook represent a percentage of “total program funding typically allocated to specific elements of the program,” such as design, hardware, software, program management and integration (DON 1992). It is important to note that these percentages are rough estimates and have some variability due to the sources of data. Because these cost

factors are often applied to new and developing weapon systems, the specific technical parameters that may affect the overall cost cannot be accounted for. The use of CERs is the preferred method for cost estimates; however, if a CER is not available, a cost factor is an appropriate primary estimating methodology for a quick planning or tradeoff type of estimate (DON 1992).

Cost factors for cost estimations are usually adapted from historical data such as the ones provided in Nussbaum (2020). Aside from being an instructor at NPS, Nussbaum provides cost estimating and business case analyses for DOD organizations such as Navy, Air Force, Army, and SECDEF. He developed a compilation of cost factors derived from actual programs and additional nonspecific cost factors that can be used throughout various phases of a developing combat system such as engineering and manufacturing development and production (Nussbaum 2020). Similar to the *Standard Cost Factors Handbook*, Nussbaum decomposes these life cycle phases into more specific cost factors which include integration and assembly, training, and program management (Nussbaum 2020). As previously discussed, these cost factors do not encompass all aspects of system costs and are used as tools to assist in the development of cost estimates.

While these documents contain cost factors that span the entirety of various combat system programs, the focus of this thesis is system integration. The integration factors shown in Table 4 are for specific life cycle cost estimates and are used in conjunction with the engineering build-up method to develop an initial cost estimate of the weapon system alone. The list of integration factors shown in Table 5 are for specific systems and are used to define the range for the final cost estimate of integrating the RGWS with LPD-17. The lower range is 15.9% and the upper range is 40.9%. The integration factor for the Advanced Gun System (AGS) fielded on DDG-1000 is 35.2%; this is significant because it is the combat system that is the most similar to the EMRG and RGWS. The range of cost estimates is used for further sensitivity analyses at the end of this chapter.

Table 4. Integration Factors by Life Cycle Phase. Adapted from Nussbaum (2020).

Life cycle Phase	% Integration Factor
Engineering & Manufacturing Development	17.3
Production	8.3

Table 5. Integration Factors by System. Adapted from Nussbaum (2020).

System	% Integration Factor
AN/SLQ-32(V)6 Electronic Warfare System	40.9
AN/SLQ-32(V)7 Electronic Warfare System	25.6
High Energy Laser with Integrated Optical-dazzler and Surveillance (HELIOS)	15.9
Advanced Gun System (MK 51 AGS)	35.2
Independence Class LCS Combat Systems Upgrades	36.8
Freedom Class LCS Combat Systems Upgrades	37.9

C. COST ESTIMATE

In this section of the thesis, the calculation for the initial cost estimate of the RGWS is shown; however, the cost data must be normalized due to inflation

1. Normalize Cost for Inflation

Data from different sources must be normalized so it constitutes a consistent data base on which to perform statistical analysis. Normalization provides consistent cost data by neutralizing the impacts of external influences (DOD 2011). To account for inflation and compare the cost data across the different years they were reported in, the Joint Inflation Calculator is used to normalize cost data between the base year reported in the reference document and the fiscal year 2020, which is the year of comparison selected for the purpose of this thesis. The Joint Inflation Calculator was developed by the NCCA to

provide the DOD with inflation rates and indices for the cost estimating community (NCCA 2020). Rates of inflation differ for each market basket; therefore, indices will vary across types of activity or procurement (DOD 2011). The inflation category chosen for this normalization is RDT&E (COMPOSITE) Research, Development, Test, and Evaluation, Navy (1319). An example of an Inflation Query within the Joint Inflation Calculator is shown in Figure 12.

Inflation Query Sheet

1. Select Service ⇨

NAVY

ARMY

Marine Corps

DoD Wide

NAVY

2. Select Appropriation/Cost Element from this List ⇨

RDT&EN (COMPOSITE) Research, Development, Test & Eva...

*Note: *DON Inflation only Composite Indices are the last entries in the pick list*

3. Enter Base/Input Year(1970 - 2060)

2018

Generate Inflation Table

Go To SAR Calculator Worksheet

Optional - For Quick Look, complete steps A, B & C below

A. Select Inflation Type from List ⇨

Then-Year \$ to Then-Year \$

B. Enter Output/Target Year ⇨

2020

C. Enter Starting Values in Input Column (blue cells) Below

Quick Look

RDT&EN (COMPOSITE) Research, Development, Test & Evaluation, Navy (1319)			
	Input	Inflation Factor	Output/ Result
7/29/20			
Years	2018	⇨	2020
Escalation Type	TY\$	⇨	TY\$
	100,000.00	1.0402	104,022.50
Enter starting values in the blue input cells. The inflation factor (based on your selected appropriation, year, and type) is applied and the results given in the output column		1.0402	-
		1.0402	-
		1.0402	-
		1.0402	-
		1.0402	-

Figure 12. Inflation Query in the Joint Inflation Calculator. Source: NCCA (2020).

As an example, Figure 12 shows a cost of \$100,000 in FY18 dollars, and after applying the inflation factor of 1.0402 provided by the Inflation Query sheet, the cost

becomes \$104,022.50 in FY20 dollars. This process is repeated for all RGWS components to develop the cost estimate.

2. Cost Estimate Calculation

After applying the inflation factor to all of the RGWS cost elements, they are able to be summed together for an initial cost of the weapon system. A summary of the cost elements is shown in Table 6. When the 17.3% integration factor is applied to account for the engineering and manufacturing development life cycle phase, the cost estimate for the RGWS becomes \$134.66M.

Table 6. Cost Elements of the RGWS. Adapted from DON (2018).

RGWS Cost Elements	Input	Inflation Factor	Output/ Result
	FY18 \$M	→	FY20 \$M
Gun Mount	52.32	1.0402	54.42
Pulse Power Module	37.34	1.0402	38.84
Program Support	20.70	1.0402	21.53
		Base Cost (FY20\$M)	114.80

Because the estimate is derived from an analogous railgun prototype on a DDG, the integration factors from Table 5 are used to scale the dollar amount to create a cost estimate for integrating the RGWS with the LPD-17. A range of 10% to 40% is used and is shown in Table 7.

Table 7. Cost Estimate for Construction and Integration of RGWS with LPD-17.

Integration Factor (%)	Integration Cost (FY20\$M)	Total System Cost (FY20\$M)
10	11.48	146.14
15	17.22	151.88
20	22.96	157.62
25	28.70	163.36
30	34.44	169.10
35	40.18	174.84
40	45.92	180.58

3. Cost Estimates for Additional Railgun Variants

The cost estimate developed in the previous section is based on a railgun with a power output of 32 MJ. Although cost estimates for various RGWS have been developed by NAVSEA, the reports they are contained in are classified as Distribution Statement D and only releasable to specified DOD personnel and contractors. For this reason, additional scaling factors are applied to the cost estimate developed in this thesis to produce cost data for use in the cost versus effectiveness analysis in Chapter IV. The scaling factors used for this cost estimate are derived from the weight in metric tons (MT) of various railgun prototypes (DON 2018). The weight of the 10 and 20 MJ railgun prototypes are divided by the weight of the 32 MJ railgun, resulting in scaling factors of 0.917 and 0.5 shown in Table 8. The cost estimates for the 10 and 20 MJ are the result of applying the scaling factors to the 32 MJ railgun variant cost estimate. These estimates only account for system size and weight but can serve as a starting point for the RGWS/EMRG and LPD-17 integration efforts.

Table 8. Cost Estimates for Railgun Variants. Adapted from DON (2018).

Railgun Variant (MJ)	Railgun Weight (MT)	Scaling Factor	Cost (FY20\$M)
32	300	1.000	134.66
20	275	0.917	123.44
10	150	0.500	67.33

D. SENSITIVITY ANALYSIS

Finally, a sensitivity analysis is provided to show how various base cost estimates of the RGWS are affected by adjusting the integration factors. The base costs for the railgun range from FY20 \$85 to \$130M with integration factors up to 40%. Each line of the graph in Figure 16 represents an isocost for a railgun variant. This means that every combination of base cost on the secondary y-axis plus integration cost on the x-axis corresponds with the same total cost of the railgun (production + integration) on the primary y-axis for each given line. An example is shown in the Figure 13. Variations in integration and baseline costs can be the result of material and labor costs, test and evaluation, and other technical details related to weapons development (i.e., LPD-17, difficulties of developing new technology, integrating two systems together for the first time).

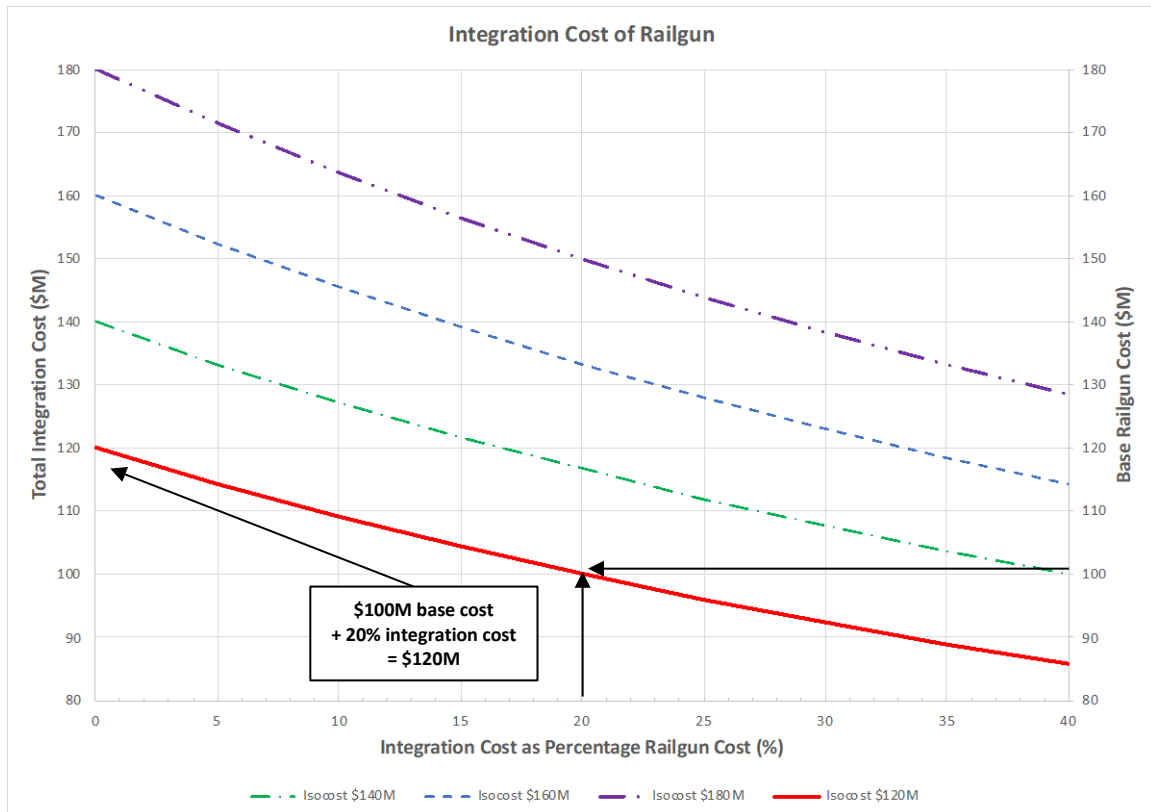


Figure 13. Integration Costs of Railgun.

IV. ANALYSIS

This chapter of the thesis expands the research of Drake (2020) discussed in Chapter II by using the simulation results and pairing them with the cost estimates developed in Chapter III in a cost versus effectiveness analysis of the RGWS/EMRG from an operational perspective. A sensitivity analysis is also provided to explore how significantly the cost of the RGWS would be affected due to adjustments in the integration factors.

A. COST VERSUS EFFECTIVENESS

Cost-effectiveness analysis is a form of economic analysis that compares system costs and effects, or outcomes, of different COAs (Bleichrodt 1999, 682). In Drake (2020), each COA represents a different ATF makeup, each having their own associated costs, which makes it possible to compare the outcome of each COA to a cost point. This represents an operational level comparison of cost and effectiveness. To compare system level costs to weapon effectiveness, the model from Drake (2020) is reconfigured to input the system parameters from various RGWS variants. The results are compared to the cost points for those RGWS variants developed in Chapter III.

B. COA COST METRICS

The cost estimates from Chapter III are used to develop the cost points for each COA, as defined in Chapter II. To focus this analysis on the RGWS, the cost point for each COA, will only represent the RGWS or the DDG's 5-inch gun and not the entire group of ships or any other weapon systems. COA 1 represents the makeup of a traditional ATF, which includes the LPD, LSD, LHD and DDG, and has a cost point of FY20 \$80.12M due to the 5-inch gun (Bipindra 2019). The cost points for each COA are listed in Table 9. Although COA 4 resulted in a unique set of performance parameters, it is not included due to the similarities in ATF makeup and identical cost point to COA 3.

Table 9. Cost Points for COAs.

COA	Cost Driver	Cost (FY20\$M)
1	DDG	80.12
2	LPD-E and DDG	214.78
3	1 LPD-E	134.66
5	2 LPD-E	269.32

C. OPERATIONAL COST-EFFECTIVENESS ANALYSIS

1. Normalize Simulation Results for Comparison

The results from the Drake (2020) simulation give the stakeholders information about the system required to make well-informed decisions. For this analysis, the data requires normalization to ensure the metrics are interpreted on a consistent scale. The MOPs “Targets Destroyed” and “ATF Ships Sunk” are altered to percentages to match “Missiles Destroyed” making it possible to plot all three on the same axis. “ATF Ships Sunk” is changed to “ATF Ships Survived” to make the graphical representation more intuitive to match the other MOPs, whose performance is better the higher it lays on the y-axis. The normalized values are shown in Tables 10–12. This allows all three metrics to be plotted on the same graph.

Table 10. Normalized Data for RGWS Performance against Low Enemy Concentration. Adapted from Drake (2020).

COA	Cost (\$M)	% Targets Destroyed	% Missiles Destroyed	% ATF Ships Survived
1	80.12	17.76	23.49	78.75

COA	Cost (\$M)	% Targets Destroyed	% Missiles Destroyed	% ATF Ships Survived
3	134.66	99.72	78.91	98.75
2	214.78	96.05	29.78	81.50
5	269.32	99.75	41.96	91.25

Table 11. Normalized Data for RGWS Performance against Medium Enemy Concentration. Adapted from Drake (2020).

COA	Cost (\$M)	% Targets Destroyed	% Missiles Destroyed	% ATF Ships Survived
1	80.12	9.60	26.22	5.75
3	134.66	83.09	70.67	80.00
2	214.78	82.32	32.96	40.25
5	269.32	92.47	45.14	60.50

Table 12. Normalized Data for RGWS Performance against High Enemy Concentration. Adapted from Drake (2020).

COA	Cost (\$M)	% Targets Destroyed	% Missiles Destroyed	% ATF Ships Survived
1	80.12	8.61	20.90	0.00
3	134.66	60.21	51.37	40.75
2	214.78	66.69	30.58	8.75
5	269.32	80.54	46.55	28.50

2. Cost versus Effectiveness between COAs

This section contains a cost versus effectiveness analysis of the RGWS from the operational level perspective. In Figures 13–15, each COA and its associated cost metric is compared to system performance in low, medium, and high enemy concentration. As stated in Chapter II, COA 1 has the poorest performance and COA 3 has the best performance across all enemy concentrations; however, it is important to distinguish effectiveness from cost effectiveness. Initial observations may trigger leadership to suggest scrapping the DDG and its 5-inch gun due to poor performance, but cost must be considered when reallocating millions of dollars in a defense budget. Figure 14, which corresponds to the low enemy concentration, suggests that there is minimal improvement to operational effectiveness for COAs 2 and 5 compared to COA 3. The same applies to Figures 15 and 16, which represent medium and high enemy concentration. Figures 14–16 also show COA 3 consistently performing well while there is disparity in the MOP scores among all other COAs.

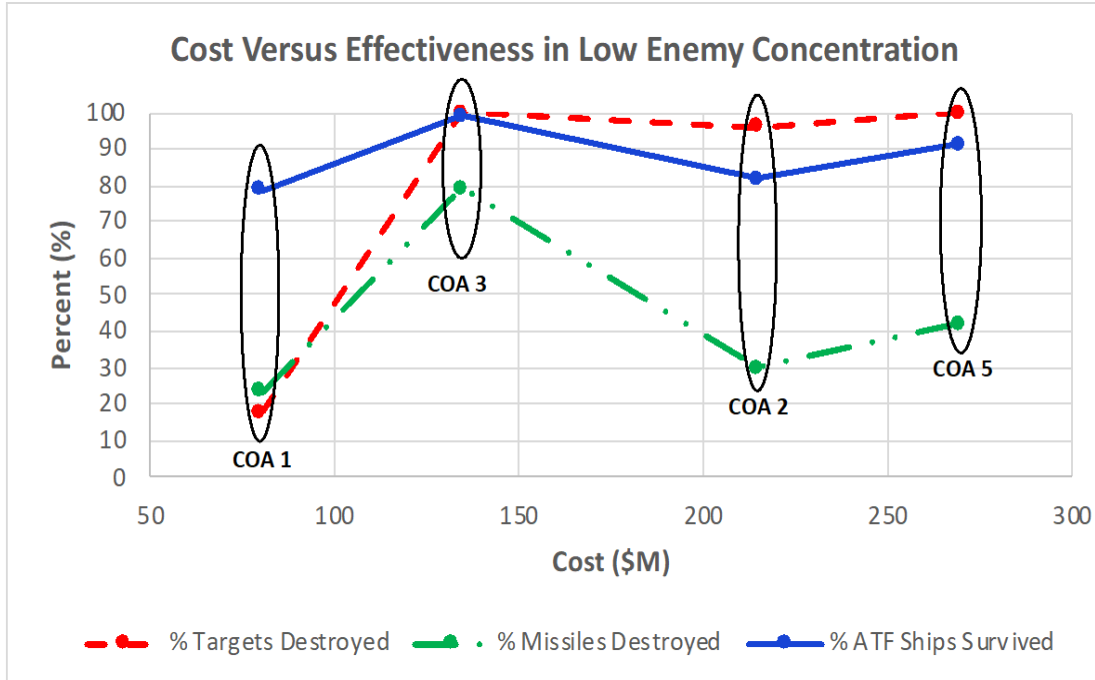


Figure 14. Cost versus Effectiveness of COAs in Low Enemy Concentration.
Adapted from Drake (2020).

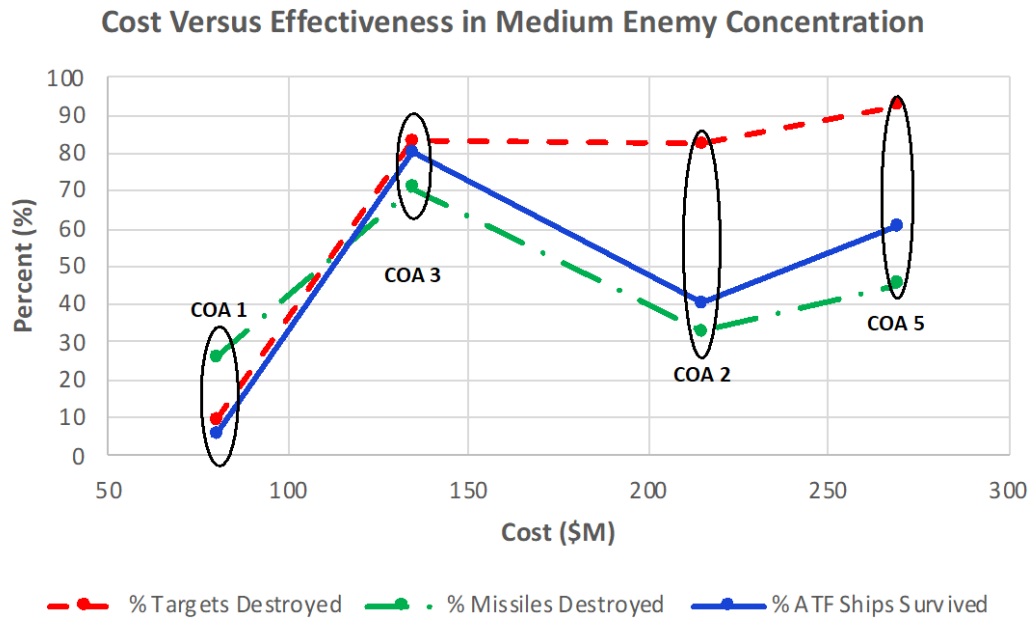


Figure 15. Cost versus Effectiveness of COAs in Medium Enemy Concentration. Adapted from Drake (2020).

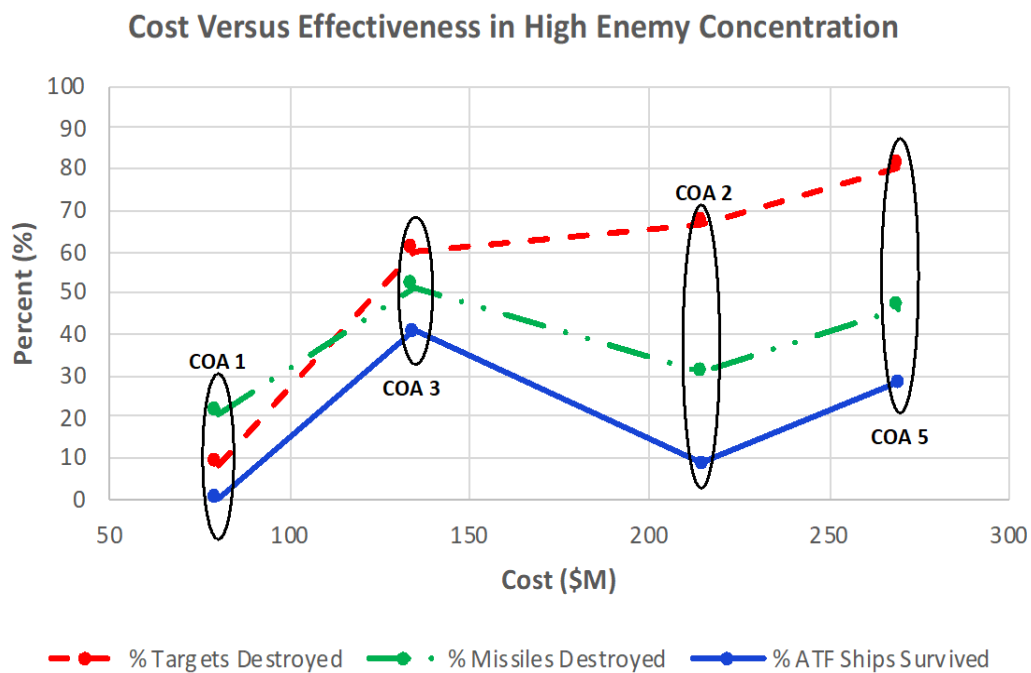


Figure 16. Cost versus Effectiveness of COAs in High Enemy Concentration. Adapted from Drake (2020).

By using the cost metrics and performance marks, a scoring system (i.e., “bang for buck”) can be developed to compare each COA and determine which one is the most cost effective. To calculate the cost effectiveness scores, each MOP percentage is equally weighted, added together, and their sum is divided by the cost for that COA. The scores for each COA are compiled in Table 13. Observations indicate the following:

- COA 3 is the most cost effective option across all enemy concentrations. It is more cost effective by a factor of 2–3 in medium and high enemy concentrations, when the system is under the most stress.
- COA 1, which has no railgun, is more cost effective in low enemy concentration than COA 2 and COA5, both of which have railguns.
- COA 2 and COA 5 are more cost effective than COA 1 in medium and high enemy concentrations (high stress on system).

Table 13. Cost Effectiveness Scores for COA Comparison.

COA	Cost Effectiveness Score		
	Low Enemy Concentration	Medium Enemy Concentration	High Enemy Concentration
1	1.50	0.52	0.37
2	0.97	0.72	0.49
3	2.06	1.74	1.13
5	0.86	0.74	0.58

From an operational perspective, the DDG being replaced with one railgun equipped LPD within the ATF results in a higher rate of mission success. Although it may seem intuitive to think that more firepower equates to more targets destroyed, that has proven to not be true in this situation. With respect to COA 3, the benefits of integrating a

RGWS onto LPD-17 are two-fold. The estimated cost of the RGWS is FY20 \$45M more than the in-service 5-inch gun, but it is significantly more cost effective, and the now displaced DDG can be utilized by commanders to carry out other missions, conduct additional training, or enter port for necessary repairs.

D. SYSTEM COST VERSUS EFFECTIVENESS ANALYSIS

This section contains a cost versus effectiveness analysis of the RGWS from a system level perspective. By altering the RGWS power output and its associated system parameters such as cycle time and projectile velocity, it is possible to model additional variants of the weapon system. This allows for development of a cost effectiveness comparison between railgun variants. Because COA 3 was determined to be the most cost effective across all enemy concentrations in the previous section, this analysis only explores that COA in one scenario (medium enemy concentration). The 10 and 20 MJ railgun variant system parameters are used to alter the Drake (2020) model with the results being compared to the cost estimates listed in Table 8.

Cycle time, projectile velocity, and range are directly related to railgun power output, making them the first properties subject to changes between variants (DON 2018). Although there is no operational or test data due to maturity in the railgun program, the probability of hit for various targets and missiles were slightly reduced to alter the model further and account for changes in power output. In each run, the cycle time of the railgun is a random number between the minimum and maximum values and follows a uniform distribution. The probability of hit values are either the minimum or maximum value based on a five-factor, two-level variable design of experiment (DOE) with 16 replications (512 runs) for ease of execution of the Drake (2020) ExtendSim model. Table 14 lists the inputs for the 10 MJ and 20MJ simulation runs with the updated results being shown in Table 15 and Figure 17.

Table 14. Altered Simulation Inputs.

EMRG Properties (10 MJ)			
Variable	Min	Max	Units
Cycle Time	9	12	sec
Range	15	75	nm
Velocity	3.6	3.6	Mach
P-hit for Moving Aircraft	0.4	0.75	-
P-hit for Stationary Ground Targets	0.4	0.85	-
P-hit for Mobile Ground Targets	0.4	0.75	-
P-hit for Incoming Missiles	0.4	0.7	-
EMRG Properties (20 MJ)			
Variable	Min	Max	Units
Cycle Time	6	9	sec
Range	15	85	nm
Velocity	5.8	5.8	Mach
P-hit for Moving Aircraft	0.4	0.85	-
P-hit for Stationary Ground Targets	0.4	0.9	-
P-hit for Mobile Ground Targets	0.4	0.85	-
P-hit for Incoming Missiles	0.4	0.75	-

Table 15. Results from the Altered Simulation Run.

Railgun Variant	Cost (\$M)	% Targets Destroyed	% Missiles Destroyed	% ATF Ships Survived
10 MJ	67.33	52.57	39.23	31.25
20 MJ	123.44	70.66	61.15	62.50
32 MJ	134.66	83.09	70.67	80.00

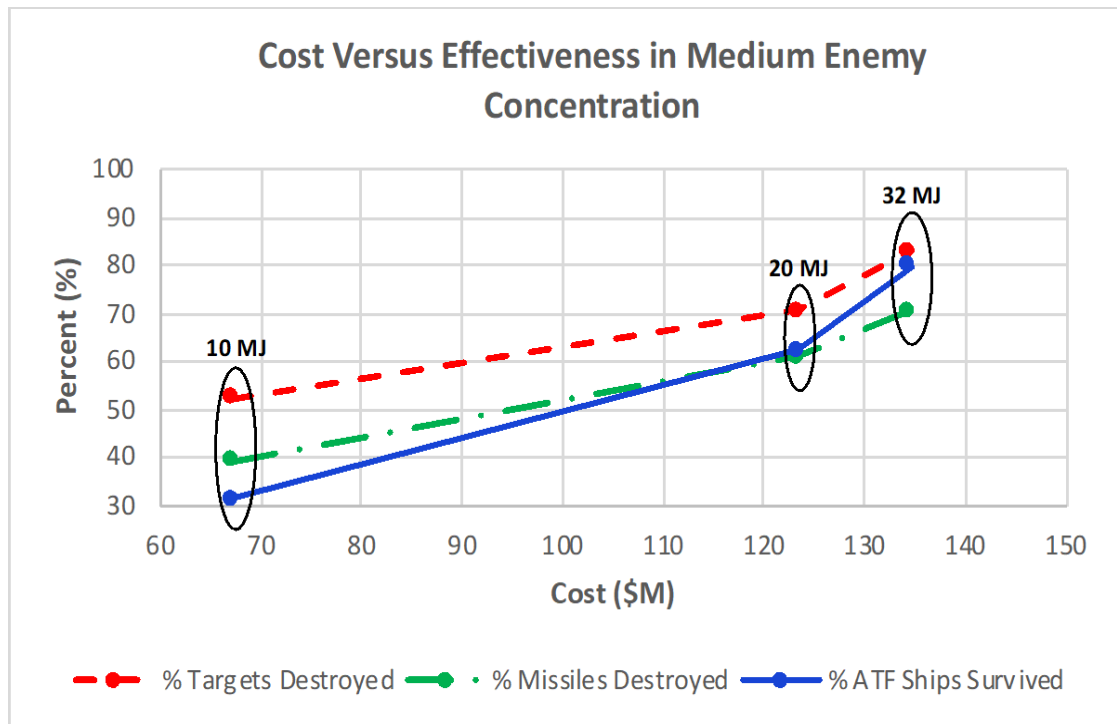


Figure 17. Cost versus Effectiveness of Railgun Variants.

The results from running the simulation with the altered input parameters show the differences in the railguns' performance. The 10 MJ railgun variant performs the poorest among the group and the 32 MJ railgun performs the best, as was the case in Section 3 of this chapter, however, that is not the entirety of the useful information gained from this analysis. While there is disparity in railgun performance, there are also varying costs which equate to varying cost effectiveness measures. Cost effectiveness scores are again listed in Table 16 which are derived from the cost metrics and MOPs. The table shows that the 10 MJ railgun is the most cost effective followed by the 32 MJ and 20 MJ, respectively. Although the 10 MJ railgun has the lowest performance marks, it has the highest cost effectiveness score because it is substantially lower in cost.

Table 16. Cost Effectiveness Scores for Comparison of Railgun Variants.

Railgun Variant	Cost Effectiveness Score
10 MJ	1.83
20 MJ	1.57
32 MJ	1.74

The results of this analysis do not rule out any individual RGWS variant. Simply because a railgun has the lowest cost, highest performance, or best cost effectiveness score does not mean it is the best fit to replace or supplement existing weapon systems. The trade space between cost and performance is certainly a discussion for directors of program offices and high-ranking commanders, but other factors such as feasibility, ease of integration, and technological advancement also influence decisions.

E. ANALYSIS OF MODEL INTERACTIONS

Now that the cost effectiveness analysis is complete, it is possible to examine the MOPs and determine which of the model inputs have the greatest impact. This investigation is focused specifically on the 10 MJ configuration, which had the highest cost effectiveness score, to identify the design characteristics of the EMRG that have the largest impact on operational effectiveness. This is done by performing an analysis of variance (ANOVA) for targets destroyed, missiles destroyed, and ATF ships sunk and making observations from interaction plots created in Minitab. The variables and their impact on the model are shown in Table 17 and are organized by MOP. The probability of hit (P-Hit) of air targets (missiles, air stationary, and air mobile) has the most impact on the results. Increasing the hit probability of air stationary targets from the minimum value to the maximum value resulted in an increase in percent of targets destroyed. Although cycle time is included in the interactions with a low p-value (albeit not ≤ 0.05), it does not appear to have a great impact on the actual number of targets destroyed. For example, the interaction

plots for Cycle Time in Figure 18 do not show degraded performance with a longer time between shots but does show improved performance in the interactions with P-Hit stationary air targets, P-Hit stationary ground targets, and P-Hit missiles. Because of this, it may be more cost effective to allocate funds and research into improving accuracy of the gun and projectile rather than maximizing shots in a certain time frame. Analysis of the impacts of changing various hit probabilities do not show actionable conclusions in all interactions. It appears that other factors such as firing scheme and target prioritization have an impact on railgun performance as well and may be explored in the future.

Table 17. Effects Summary.

Targets Destroyed	
Factors	P-value
P-hit AirStationary	0.009
P-hit GroundStationary*P-hit GroundMobile	0.022
Missiles Destroyed	
Factors	P-value
P-hit AirMobile*P-hit Missile	0.000
P-hit AirStationary	0.010
CycleTime*P-hit AirMobile*P-hit Missile	0.108
Ships Sunk	
Factors	P-value
P-hit AirMobile*P-hit Missile	0.002
P-hit AirStationary	0.008
CycleTime*P-hit AirMobile*P-hit Missile	0.097

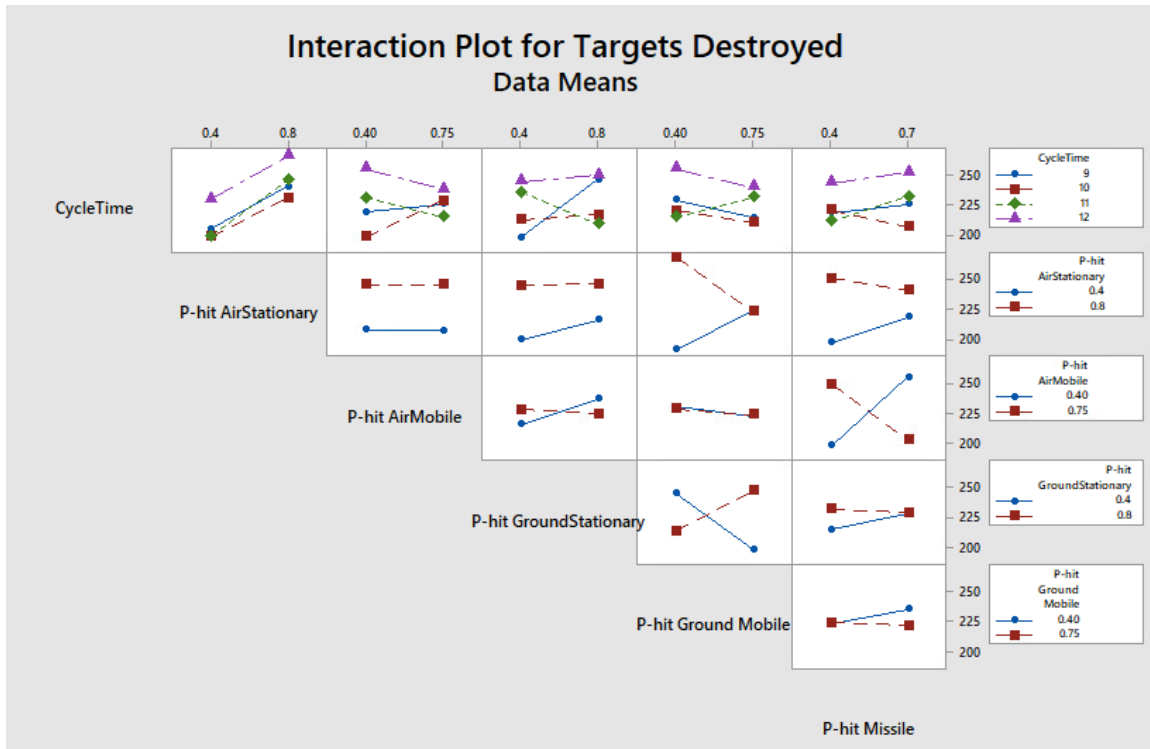


Figure 18. Interaction Plots for Targets Destroyed.

The relationships between the variables in the model are important to understand because of their effects on operational effectiveness and system costs. Recall from the cost effectiveness analysis that the less capable 10 MJ railgun was preferred to the more capable 32 MJ railgun. Although increasing hit probability of air targets leads to an increase in percent of air targets destroyed, this improvement in performance may lead to increased costs. Reaching the desired level of operational effectiveness without requiring maximum hit probabilities and power output will result in increased cost effectiveness. While this analysis provides insight for one particular operational scenario, these results provide a baseline for future CONOPS and expanded research.

V. CONCLUSION

A. SUMMARY OF FINDINGS

The goal of this thesis was to develop a cost estimate for the Navy's railgun prototype and advance the Drake (2020) operational analysis of integrating the RGWS into an ATF and conducting an amphibious assault. A cost effectiveness analysis of the railgun from a system and operational perspective was then developed by comparing the cost estimates to the result of the aforementioned analysis.

By using a combination of cost estimation methods, a cost model for the 32 MJ railgun was developed. This cost estimate accounts for inflation and includes various life cycle phase system specific integration factors. The estimate developed in this thesis is FY20 \$134.66, but it is subject to change due to variations in developmental and integration costs. The known weights of other railgun prototypes, in metric tons, were used as scaling factors to develop additional cost estimates, which were used to conduct a comparative system level cost effectiveness analysis between railguns.

Expansion of Drake (2020) with operational modeling of integrating the railgun with LPD-17 resulted in a cost effectiveness analysis to determine the most cost effective ATF makeup for an amphibious mission. The most cost effective ATF makeup was determined to be COA 3, which consists of the LSD, LHD, and the railgun equipped LPD-17. The ExtendSim model was updated with the performance parameters for the other railgun prototypes and new cost effectiveness scores were calculated. In descending order, the cost effectiveness of each railgun is as follows:

1. 10 MJ
2. 32 MJ
3. 20 MJ

The ANOVA results that examine the impact of changes to railgun system design suggest that hit probability of air targets has a greater impact on performance than cycle time. This provides an opportunity for tradeoffs to be made in the design of the railgun and

its projectile in which the power requirements (and size) can be scaled down without negatively impacting effectiveness. Longer cycle time does equate to less shots down range, which could make it difficult to combat multiple targets at close range, and a possible solution for this is an additional CIWS for terminal self-defense. Another design tradeoff to be made will be for hit probabilities for air targets versus ground targets, which could possibly be made in the design of the projectile and be loaded onto ships for specific mission sets.

B. FUTURE WORK

Because the railgun remains in the early stages of development, there is room for improvement and advancement of the research conducted in this thesis. Although many assumptions regarding the ExtendSim model were discussed with stakeholders and military experts, they are highly speculative due to the limitations in railgun technology maturation. Fine tuning and continuous updating of the model will result in more accurate simulation outputs for cost effectiveness analyses. The cost estimates can also be improved as more data becomes available for use in the other cost estimation methods described in Chapter II. Areas for which to expand this research in the future include

- Develop additional CONOPS, mission sets, and firing schemes to use as a baseline for additional operational modeling and simulation.
- Develop more accurate cost estimates for the EMRG/RGWS as cost data becomes available for release and more information is known regarding construction, materials, integration process, and testing.
- Explore integrating the RGWS/EMRG with other military platforms.

APPENDIX. BASELINE EXTENDSIM INPUT PARAMETERS

Table 18. Simulation Inputs from Original ExtendSim Model.
Source: Drake (2020).

EMRG Properties			
Variable	Min	Max	Units
Cycle Time	3	6	sec
Retargeting Delay	10	25	sec
Range	15	100	nm
Velocity	5.8	7.3	Mach
P-hit for Moving Aircraft	0.4	0.9	-
P-hit for Stationary Ground Targets	0.4	0.98	-
P-hit for Mobile Ground Targets	0.4	0.9	-
P-hit for Incoming Missiles	0.4	0.8	-
Missile Engagement Range	2	22	-
TLAM Properties			
Variable	Min	Max	Units
Velocity	0.62	0.62	Mach
Range	869.3	869.3	nm
P-hit for Stationary Ground Targets	0.98	0.98	-
P-hit for Mobile Ground Targets	0.95	0.95	-
Quantity	30	30	-
ESSM Properties			
Variable	Min	Max	Units
Velocity	4	4	Mach
Range	2	40	nm
P-hit for Moving Aircraft	0.95	0.95	-
P-hit for Incoming Missiles	0.95	0.95	-
Quantity	264	264	-

ATF Properties			
Variable	Min	Max	Units
ATF Initial Standoff Distance	60	80	nm
LCAC / MV-22 Deployment Distance	15	15	nm
Number of LCACs Deployed			
From LPD	2	2	-
From LHD	3	3	-
Number of LCAC Trips			
From LPD	8	8	-
From LHD	9	9	-
Number of MV-22s Deployed			
From LPD	2	2	-
From LHD	6	6	-
From LSD	2	2	-
Number of MV-22 Trips			
From LPD	21	21	-
From LHD	70	70	-
From LSD	4	4	-
AAV Deployment Distance	2	2	nm
Number of AAVs Deployed	15	15	-
Probability of Sink			
LPD	0.1	0.1	-
LHD	0.1	0.1	-
LSD	0.1	0.1	-
DDG	0.1	0.1	-
DDG Support Distance	10	10	nm
Number of DDG VLS Cells	96	96	-
VLS Cycle Time	2	2	sec
VLS Retargeting Delay	10	15	sec
Landing Force Properties			
Variable	Min	Max	Units
Force per LCAC	75	75	-
Force per MV-22	25	25	-
Force per AAV	25	25	-

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