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ANALYSIS OF RARE EARTH ELEMENT SUPPLY CHAIN RESILIENCE DURING A MAJOR CONFLICT

by

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June 2021

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13. ABSTRACT (maximum 200 words)

This report explores the extension of the conventional "kill chain" in a counterintuitive manner. Utilizing lessons learned from the SEA29 work in "Logistics in a Contested Environment" the "kill chain" is re-defined backward from warhead detonation to "metal bending and metal delivery." This process provides a more well-rounded examination of Department of Defense (DOD) efforts to maintain supply lines in a major conflict; specifically, those supply lines that provide key rare earth elements (REE) to DOD weapons contractors. Using linear programming and optimization, this report documents a design of three alternatives for the mining, refinement, and production of REEs. By defining a production equations around our Measures of Effectiveness and Performance (MOE/MOP), we maximized the weighted MOPs while minimizing damage to convoys. From the analysis of results, we found REE components produced remotely (OCONUS) and near CONUS had the best results while using medium and large convoys. Finally, the diverse background of the team, professionally and academically, allowed for a combination of perspectives during the research and modeling process, which ultimately led to the creation of this final report.

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ABSTRACT

This report explores the extension of the conventional “kill chain” in a counterintuitive manner. Utilizing lessons learned from the SEA29 work in “Logistics in a Contested Environment” the “kill chain” is re-defined backward from warhead detonation to “metal bending and metal delivery.” This process provides a more well-rounded examination of Department of Defense (DOD) efforts to maintain supply lines in a major conflict; specifically, those supply lines that provide key rare earth elements (REE) to DOD weapons contractors. Using linear programming and optimization, this report documents a design of three alternatives for the mining, refinement, and production of REEs. By defining a production equations around our Measures of Effectiveness and Performance (MOE/MOP), we maximized the weighted MOPs while minimizing damage to convoys. From the analysis of results, we found REE components produced remotely (OCONUS) and near CONUS had the best results while using medium and large convoys. Finally, the diverse background of the team, professionally and academically, allowed for a combination of perspectives during the research and modeling process, which ultimately led to the creation of this final report.

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LIST OF ACRONYMS AND ABBREVIATIONS

ADIZ	air defense identification zone
APOE	aerial port of embarkation
CCP	Communist Chinese Party
CNO	Chief of Naval Operations
COI	critical operational issue
CONUS	Continental United States
CV	Coefficient of Variance
DOD	Department of Defense
DOE	Design of Experiments
DR	data requirements
EM	electromagnetic
EEZ	Economic Exclusion Zone
FFBD	functional flow block diagram
GAO	Government Accountability Office
GPC	Great Power Competition
HN	host nation
IAS	intelligent autonomous system
IPR	in progress review
IRB	Institutional Review Board
ISR	intelligence, surveillance, and reconnaissance
LWT	light weight torpedo
MOE(s)	measure(s) of effectiveness
MOP(s)	measure(s) of performance
NPS	Naval Postgraduate School
NUS	National University of Singapore
NUWC	Naval Undersea Warfare Center
OPNAV N9I	Office of the Chief of Naval Personnel branch N9I
PESTLE	Political, Economic, Social, Technological, Legal, Environmental

PLA	People’s Liberation Army
R&D	research and development
RCS	radar cross section
REE	rare earth element
REM	rare earth metals
SE	Systems Engineering
SEA30	Systems Engineering Analysis Cohort 30
SOR	system operational requirements
SPOE	seaport of embarkation
TDSI	Temasek Defense Systems Institute
USMC	United States Marine Corp
USN	United States Navy
WIC	Warfare Innovation Continuum

EXECUTIVE SUMMARY

A. BACKGROUND

The 30th Systems Engineering Analysis (SEA30) cohort, with support from students in the National University of Singapore (NUS) Temasek Defense Systems Institute (TDSI) program and other students in various degree programs at the Naval Postgraduate School (NPS), were assigned by the Office of the Chief of Naval Personnel branch N9I (OPNAV N9I) to provide an analysis and solution to logistics support in a major conflict.

SEA30 researched the backwards extension and re-defining of the “kill chain” to include the processes of metal bending and metal delivery. The association of a “kill chain” is tied to the commonly accepted and practiced Surface Warfare (SUW) and Air Warfare (AAW) methodologies of F2T2EA (find, fix, track, target, engage, assess) and DTE (detect, track, engage). SEA30 focused on the non-kinetic kill chain, the “industrial kill chain” discussed during the Warfare Innovation Continuum (WIC), which allows the United States Navy to have a kinetic kill chain at sea.

Building off the initial tasking statement from the Systems Engineering Analysis Chair:

> Reaping lessons learned from all the WIC activities, analyze mission resilience in a major conflict by extending the “kill chain” from “metal bending to metal delivery.” This study will be a “demonstration of an analysis method” like the SEA 26 cohort that used set base design for force structure analysis. This will be an extension to the SEA29 work in “Logistics in Contested Environments.” As an example, select a critical mission like antisubmarine warfare then trace the way back from say, a lightweight torpedo (LWT) attack by an SH-60 on a SSK to all the elements required to make that happen, from manufacture, to material, to personnel, to logistics, in order see vulnerabilities in the entire kill chain, or in the case of weapon inventories, the 300th LWT drop. These would include, but not be limited to, critical metals in the LWT and their source; manpower and production capability at NUWC and manufacturing systems; logistics lift from manufacturer to APOE and SPOE sites; logistics lift to contingent bases; and for capability for re-arming at sea. (Matthew Boensel, email to authors, September 23, 2020)

The team conducted literature reviews, made boundaries and assumptions, and received feedback from the stakeholders to refine our tasking statement. Knowing the coming decades of global operations are not just about striking capabilities but also being able to operate continuously with limited or no resources in the face of supply disruptions triggered by an adversary. Therefore, we aim to model ways to **increase the resilience of the operational supply chain to ensure continuous operational output in the face of an extended conflict with other global powers.**

B. MODELING

The complexity of the model created is captured in Figure 1.

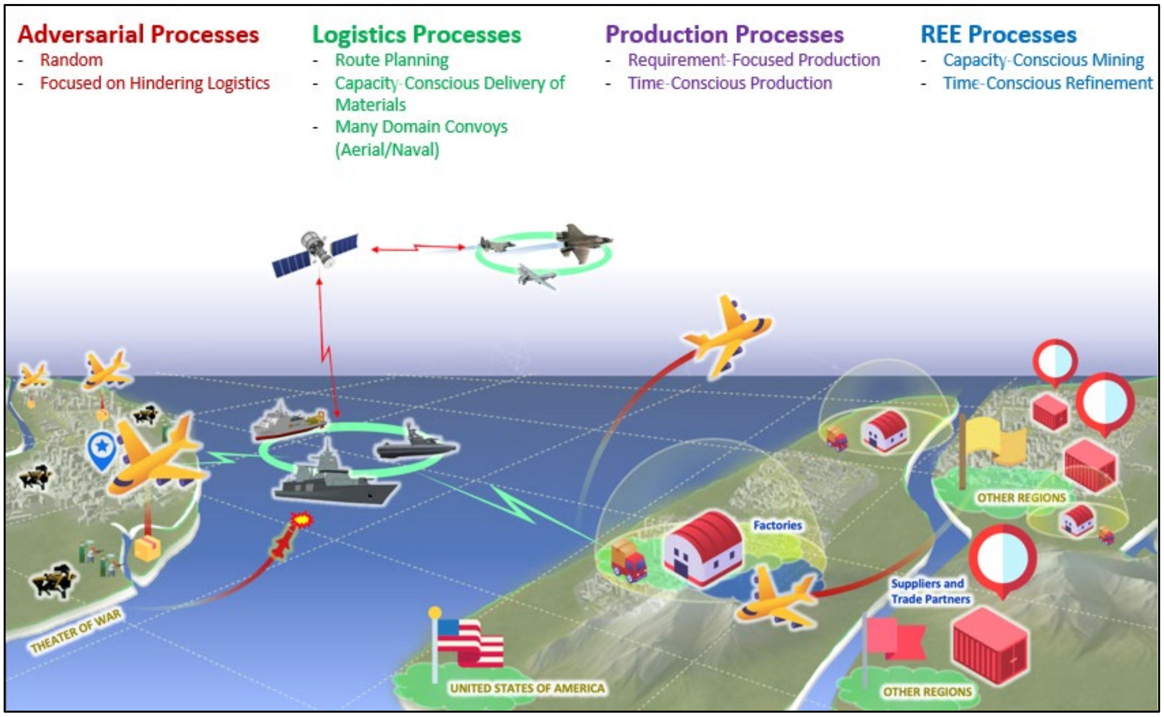

Figure 1. Processes Incorporated as Part of the Optimization Model

Here one sees the four processes considered for the model: adversarial, logistics, production, and Rare Earth Element (REE). These processes were the foundation for the technical aspects of the model, shown in Figure 2.

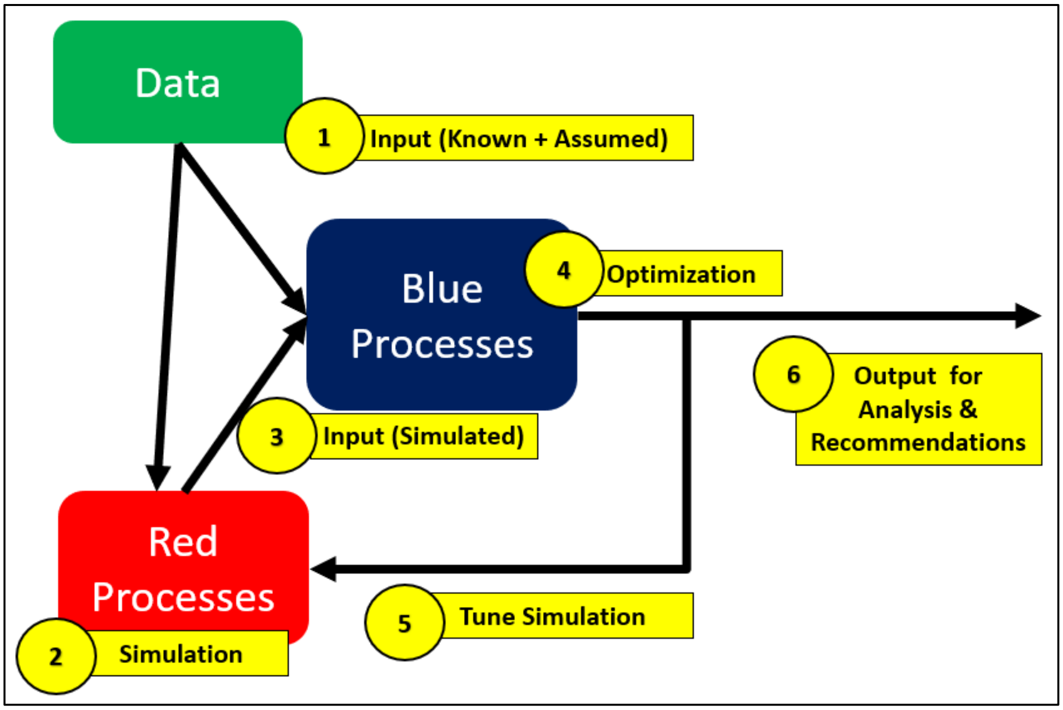

Figure 2. Technical Aspects of the Modeling Approach

The red processes represent actions that may be executed by a potential adversary. Using simulation, these actions are generated by data inputs fed into the optimization model as scheduled attacks targeting specific routes traveled by convoys at certain times. The blue process is the operation of one's force, which encompasses the movements of the various convoys along different routes, collection of REE materials, and component production at factories.

Thus, outputs from the simulated red processes and the available data inputs are fed into the blue processes model. The model outputs are subsequently optimized using available large-scale optimization tools. In addition, the simulation model is further tuned where necessary to improve the robustness of the model design to produce reliable outputs when presented with different operational scenarios. The goal of the large-scale optimization model would be to derive the optimal combination of factors that would maximize the weighted MOPs (measures of performance).

C. SCENARIO AND ALTERNATIVES

Figure 3 depicts the overview of the input data used in the model. All input data used in the model were unclassified information and can be obtained from open source. Due to the limited information available in open source, some assumptions had to be made in order for the model to run and make the necessary analysis. The input data can be classified into four broad categories: (1) mines, (2) factories, (3) convoys, and (4) distances between location nodes.

Figure 3. Overview of Input Data

This overview was the centerpiece to create the three design alternatives for analysis. Alternative 1 is to Produce Locally, where component production is limited to within the Continental United States (CONUS). Alternative 2 is to Produce Remotely, expanding the production capability to outside the Continental United States (OCONUS) only. Finally, Alternative 3 is to Produce "Near Me," where production is not limited geographically but optimized to the MOPs directly.

D. ANALYSIS AND CONCLUSION

The optimization resulted in several interesting insights. First, when components were produced remotely and “Near Me” they tended to perform better and were almost identical when using medium or large convoys. Local production performed the worst in all convoy variants, which is a counterintuitive data point that can be explained by the lack of mining in CONUS. These metrics are shown in Figure 4.

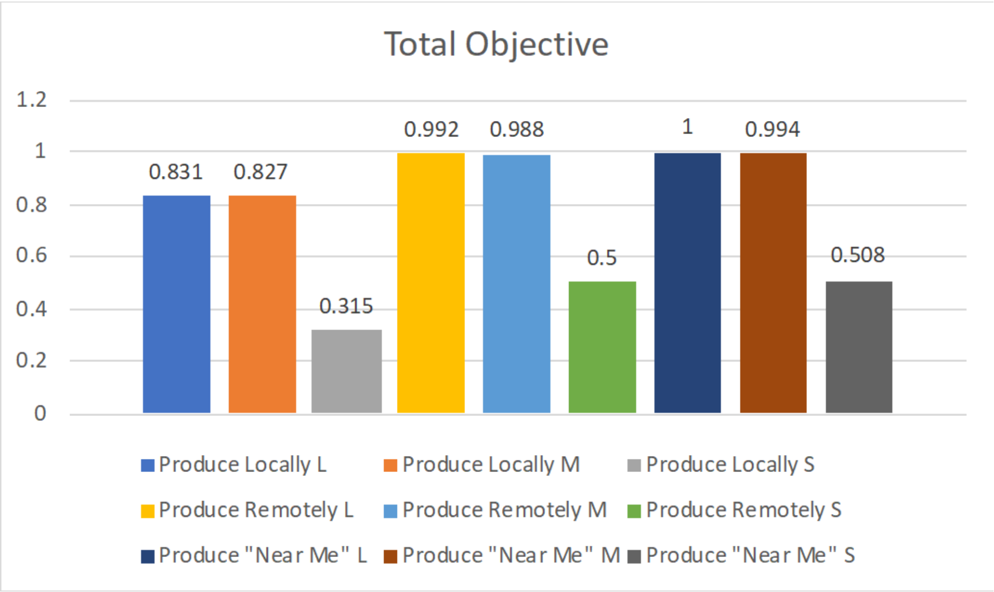

Figure 4. Normalized Objective Values by Alternative and Location of Production

Our examined scenario has shown how flexibility in production location, referred to as Produce “Near Me” in this work, achieves the best results amongst the alternatives and variants explored. We have also noted that balanced fleet of fast-and-medium convoys offers a good mixture of the total balanced MOP as well as specific MOPs of interest. Our recommendation is to further explore this alternative in terms of Location Design and Fleet Design under additional scenarios. Such scenarios should include larger fleet design and longer time-period for examination.

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The Systems Engineering Analysis Cohort 30 Team would like to thank our project advisors, Dr. Papoulias and Dr. Huang, who provided us with support and guidance throughout the capstone process.

We would also like to thank the long list of professors across curriculums at the Naval Postgraduate School who taught us during our time on and remotely on campus. It is because of their instruction we had the requisite knowledge to undertake the task of this capstone and present a product at the end of three quarters of work.

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I. INTRODUCTION

The United States Navy has entered a new era of operations commonly referred to as the Great Power Competition (GPC) between the United States and our near peer competitors to the East and West. We are continuously competing for an advantage in trade, technology, finance, and more specifically military strength to preserve the American world order. This order has stood since the split between China and Taiwan when the United States backed Chiang Kai-shek in 1920 until the defeat of his party in 1949 (Culver 2020). Since the end of the conflict, the world stage has involved two key countries: the United States and Russia. Starting in 1979, however, China began to advance toward unification of Taiwan into the Communist Chinese Party (CCP). This process involved a rapid modernization of the Chinese military to the point of U.S.-themed power projection deployments around the globe. The actions taken by the CCP have led planners back to a Second World War color-coded plan aptly named by military professionals "Resurrecting War Plan Blue."

A. PROJECT BACKGROUND

The 30th Systems Engineering Analysis (SEA30) cohort, with support from students in the National University of Singapore (NUS) Temasek Defense Systems Institute (TDSI) program and other students in various degree programs at the Naval Postgraduate School (NPS), were assigned to conduct this capstone to provide the Office of the Chief of Naval Personnel branch N9I (OPNAV N9I) an analysis and solution to logistics support in a major conflict. The group's diversity allowed for a multi-disciplinary approach to the systems engineering process that resulted in a well-rounded problem definition, modeling, and analysis.

1. Warfare Innovation Continuum

NPS hosts an annual conference known as the Warfare Innovation Continuum (WIC), which applies the efforts of military and civilian students and faculty from around the nation towards solving a relevant real-world problem. The focus of the 2020 WIC was "Resurrecting War Plan Blue," a scenario where the United States is engaged in global war in 2035. The WIC week events and their integration into the SEA30 capstone process are shown in Figure 1.

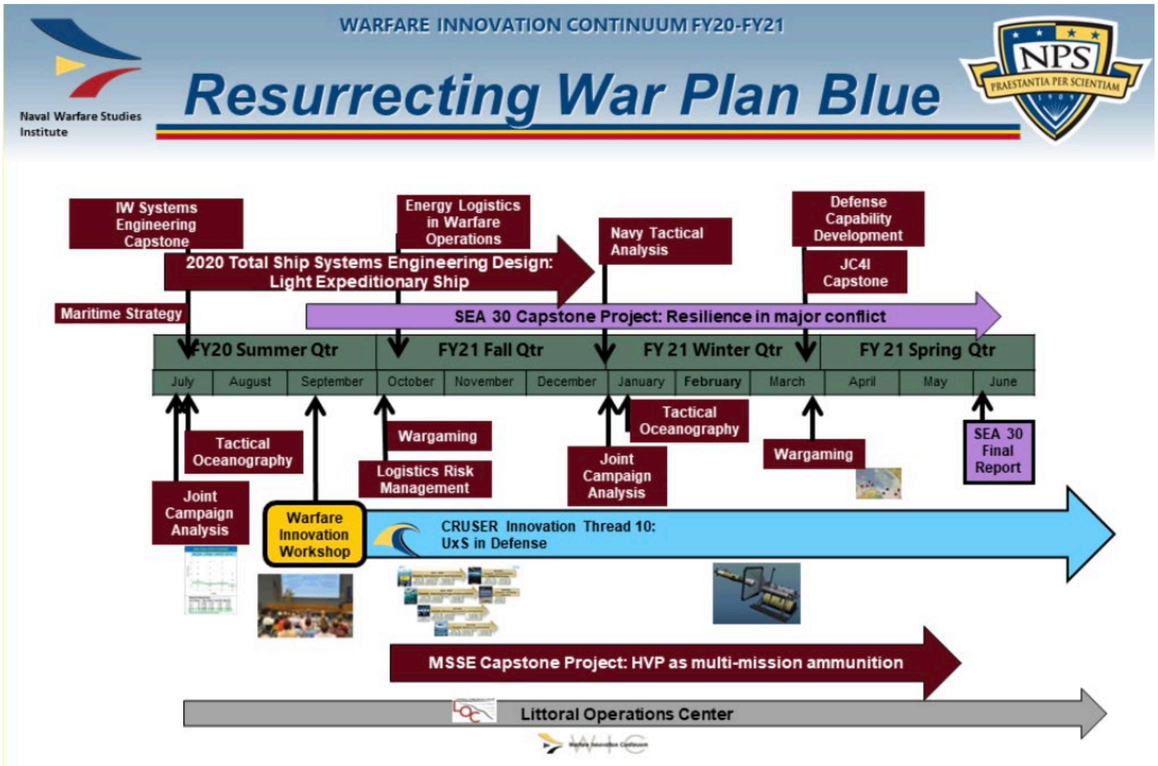

Figure 1. 2020 Warfare Innovation Continuum and Integration to SEA30. (Source: Englehorn 2020).

The WIC focused on four primary topics related to a future conflict: intelligence, reconnaissance, and surveillance (ISR) and defense technology; industrial resilience and supply chain vulnerability; intelligent autonomous systems (IAS) and biologics; and innovation. SEA30's contributions centered on infrastructure, data, and workforce solutions to propose three concepts: A Resilient Infrastructure, Digital Thread, and a (Camo) Green New Deal. The first two concepts deal with connectivity and data security in agile manufacturing, and the third envisions a whole-of-society approach to develop human capital as a long-term resource (Englehorn 2020). From the activities of the 2020 WIC week, SEA30 had a reference for where to begin research for their tasking statement.

2. Tasking Statement

The tasking statement to the SEA30 group from the Systems Engineering Analysis Chair follows:

> Reaping lessons learned from all the WIC activities, analyze mission resilience in a major conflict by extending the "kill chain" from "metal bending to metal delivery." This study will be a "demonstration of an analysis method" like the SEA 26 cohort that used set base design for force structure analysis. This will be an extension to the SEA29 work in "Logistics in Contested Environments." As an example, select a critical mission like antisubmarine warfare then trace the way back from say, a lightweight torpedo (LWT) attack by an SH-60 on a SSK to all the elements required to make that happen, from manufacture, to material, to personnel, to logistics, in order see vulnerabilities in the entire kill chain, or in the case of weapon inventories, the 300th LWT drop. These would include, but not be limited to, critical metals in the LWT and their source; manpower and production capability at NUWC [Naval Undersea Warfare Center] and manufacturing systems; logistics lift from manufacturer to APOE [aerial port of embarkation] and SPOE [seaport of embarkation] sites; logistics lift to contingent bases; and for capability for re-arming at sea. (Matthew Boensel, email to authors, September 23, 2020)

B. PROJECT TEAM COMPOSITION

The SEA30 team was composed of a diverse group of 20 students from different NPS programs, and countries (Singapore, Israel, and the United States). The various services and specialties across the team allowed for a multitude of viewpoints and a more complete analysis of the tasking statement. The composition of the team and each team member's country, service, and specialty are shown in Table 1.

Table 1. SEA30 Team Composition

Name	***Country***	***Service***	***Specialty***
Adrian Chua	Singapore	Air Force	Air Force Engineer
Alexander Kavall	United States	Navy	Surface Warfare Officer
Alvin Chan Baixian	Singapore	Civilian	Systems Engineer
Amit Carmeli	Israel	Army	Software Engineer
Axel Tan Choon Seng	Singapore	Army	Infantry Officer
Collin Hust	United States	Navy	Surface Warfare Officer

Name	***Country***	***Service***	***Specialty***
Eugene Lee Boon Kien	Singapore	Air Force	Air Force Engineer
Jason Yap Kok Siong	Singapore	Civilian	Operational T&E
Joel Li Haocheng	Singapore	Army	Ammunition Engineer
Joseph Meier	United States	Marine Corps	Aviation Maintenance
Lim Wei Qin	Singapore	Air Force	Air Force Engineer
Marcus Tai Jia En	Singapore	Civilian	Tracked Vehicle Development
Marian Jester	United States	Navy	Engineering Duty Officer
Matthew McClary	United States	Army	Special Forces
Miroslav Bernkopf	United States	Marine Corps	Aviation Supply
Ng Wee San	Singapore	Air Force	Air Force Engineer
Nicholas Ng Wei Xiang	Singapore	Civilian	Manufacturing Operations
Owen Ong Wen Xiang	Singapore	Air Force	Aircraft Weapons
Peh Ming Hui	Singapore	Army	Infantry Officer
Robert Justin Morales Naquila	Singapore	Army	Combat Engineer Officer

Due to the scope of the problem, the SEA30 team was initially divided into three subgroups to streamline data gathering during the literature review process. The first subgroups focused on reviews of SEA26's work, SEA29's work, and Rare Earth Elements (REE). The review process led up to our first in progress review (IPR) and allowed the SEA30 team to revise the tasking statement into a problem statement. Following the first IPR, the teams were re-structured again from the literature review construct to a systems engineering (SE) team construct. The three teams in the SE construct were a research team, modeling team, and SE team. The research team worked to provide parameters and data-based assumptions for the measure of effectiveness (MOE). This allowed the modeling team to build a model of the system, and the SE team worked to define assumptions, boundaries, and the measures of effectiveness and performance for the system. The separate teams are shown in Table 2.

Table 2. SEA30 Sub-Group Organization

Research Team	Adrian Chua Axel Tan Choon Seng Eugene Lee Boon Kien Jason Yap Kok Siong Joel Li Haocheng Marcus Tai Jia En Ng Wee San Owen Ong Wen Xiang
Modeling Team	Alvin Chan Baixian Amit Carmeli Joseph Meier Lim Wei Qin Marian Jester Nicholas Ng Wei Xiang Peh Ming Hui Robert Justin Morales Naquila
Systems Engineering Team	Miroslav Bernkopf Collin Hust Alexander Kavall Matthew McClary

C. OUTLINE

The following chapters present the literature reviews the team did to support the formulation of the model exploring supply chain resiliency for REEs. The efforts of the team mirror the classical systems engineering V-Model, a logical project definition leading to implementation and finally test and integration. The steps are shown through our problem definition, requirements generation with stakeholder inputs, design of a model, implementation of the model through MOEs, and the testing of the model to analyze the results and provide recommendations.

Chapter II focuses on the reviews and data collection performed before the first IPR. This gives the reader an insight into the importance of REEs in a major conflict, and the process of mining, refinement, and production. The chapter ends with an analysis of REE supply from multiple perspectives through a PESTLE (Political, Economic, Social, Technological, Legal, Environmental) analysis.

Chapter III presents the overview of the SE process the team used, beginning with stakeholder analysis, and ending with the creation of the model. The chapter also discusses the project boundaries and assumptions, critical issues, and measures of effectiveness and performance. These are linked to the research presented in the previous chapter.

Chapter IV demonstrates our modeling approach, creation, and implementation. This gives the reader insight into why we chose our approach and the complexities contained within the model. Additionally, the chapter addresses portions of the model which are used in the following chapter for a sensitivity analysis.

Chapter V includes the outputs from the model and the analysis of these outputs on the system. These outputs contain a baseline output, as well as outputs after changing parameters and variables in the model. This allowed for a robust set of recommendations for application of the model.

Chapter VI provides recommendations for REE supply chain resiliency and methods of tailoring the process to various REEs. The recommendations are based off the sensitivity analysis conducted and give an updated outlook on a "Resurrected War Plan Blue."

II. LITERATURE REVIEW

A. CHIEF OF NAVAL OPERATIONS NAVPLAN 2021/BATTLEFORCE 2045

The United States is currently locked in a great power competition with China, with frequent involvements by the Russians as well. The countries are competing simultaneously in multi-faceted domains, including trade, technology, financial markets, and military strength, with United States trying to retain its superpower status, while China attempts to gain global acceptance and recognition as a force to be reckoned with (Wilson Center 2021).

The U.S. Navy (USN) is at the forefront in facing off against the threats posed by both China and Russia. Both China and Russia are actively pursuing strategies to gain unfair access and control over valuable resources beyond their exclusive economic zones (EEZ).

1. Ascension of the Dragon: China

China now possesses the world's largest naval fleet and continues to rapidly modernize its weapon systems and platforms, including surface combatants, submarines, amphibious assault ships, aircraft carriers, and the next-generation fighter aircraft. China has not been afraid to showcase the superiority of its naval capabilities with its regional neighbors. As discussed in the Chief of Naval Operations (CNO) NAVPLAN 2021 "this was done through a combination of unlawful claims over their regional neighbors' territorial waters, and thinly veiled threats which were backed by China's willingness to demonstrate its military prowess and technological superiority during exercises and test firing of live munitions" (Chief of Naval Operations 2021, 2). Case in point, most recently in early April 2021, the People's Liberation Army (PLA) of China executed simultaneous military exercises east and west of Taiwan. At least ten PLA war planes, including fighter jets, anti-submarine warfare aircraft, and early warning aircraft entered Taiwan's self-declared air defense identification zone (ADIZ), a move that defense analysts stated was a warning to both Taiwan and the United States for being Taiwan's primary supporter. Faced with such aggressive posturing by China, the United States has labeled China as its "most pressing long-term strategic threat" (Lendon 2020).

2. Awakening of the Hibernating Bear: Russia

The Russian military has grown increasingly bold in the last decade and was starting to flex its military might again after remaining dormant ever since the end of Cold War and the dissolution of the old Soviet Union. This was evidenced by Russia's clandestine annexation, or re-colonization, of Crimea in 2014, as noted by observers (Charron 2020). Interestingly, just days shy of President Joseph R. Biden's first 100 days in the White House as the 46th President of the United States, Russia probed the U.S. limits again and made headlines by overtly amassing more than 100,000 military troops near the Ukrainian border and in the annexed Crime. On the naval front, the United States expressed its "deep concern" regarding Russia's plan to enforce a blockade in parts of the Black Sea to prevent foreign naval ships and vessels from entering (Reuters 2021). Observers have likened Russia's recent military actions as saber-rattling and posturing, and most likely done in a bid to remind Washington that Russia remains a force to be reckoned with, and that the Kremlin could easily reignite conflicts with the United States at will should its interests continue to be ignored (Reevell 2021). Today, Russia continues to be a formidable nuclear-powered adversary, having finally awakened from the chills of the Cold War, and is hungrily searching for an opportune time to strike.

Against the backdrop of scenarios where near-peer adversaries are constantly vying for greater attention on the world stage, and possibly hoping to dethrone the world's sole superpower, the U.S. military needs to rapidly build-up its forces. That formed the impetus for the Battle Force 2045, an ambitious plan proposed by the U.S. Navy which aims for a naval fleet expansion to the tune of 500 manned and unmanned ships by 2045, with the transitional goal of 355 traditional naval ships by 2035, while working within a resource constrained budgetary environment (Eckstein 2020). The Battle Force 2045 plan, as presented by former Defense Secretary Mark Esper in October 2020, entailed the following.

1. To expand the attack submarine fleet from the existing 70 to 80.

2. To supplement the existing Nimitz-class and Ford-class nuclear-powered submarines with six to eight light aircraft carriers equipped with the future air wing, including the F-35 Joint Strike Fighters.
3. To expand the usage of between 140 to 240 unmanned and optionally manned ships, both on the surface and subsurface, to conduct traditional naval missions, including mine-laying, missile strikes, and resupply.
4. To increase and free up capacity of larger warships for more complex missions by expanding the fleet of smaller surface ships, such as frigates, from 60 to 70.
5. To increase the logistics and resupply capabilities for distributed maritime operations by increasing the number of logistics ships from 70 to 90.
6. To increase the employment of unmanned aircraft from aircraft carriers to cover missions traditionally undertaken by today's air wings, including fighters, refueling, and early warning missions.
7. To increase the level of integration of and synergy between the U.S. Marine Corps (USMC) and the main U.S. Navy forces, and to expand the fleet of amphibious warships from 50 to 60. (Eckstein 2020)

B. RARE EARTH ELEMENTS

In NAVPLAN 2021 and Battleforce 2045 (Sadler 2020), the Navy and the Joint Forces highlighted the need to deter an adversary's aggression through projecting power and influencing ranges in a contested cyberspace and electromagnetic (EM) spectrum. This means there is a need for Navy and Joint Forces to employ the kill chain with a resilient network of sensors, command and control nodes, unmanned platforms, and weapons with increased range, speed, and persistence. REEs are critical for the assembly of these kill chain capabilities as they are required in manufacturing processes. Notably, the United States has limited influence over the supply chain of REEs as China has become the main producer and holds the highest reserve of REEs across the world, as seen in Figure 2 (Garside 2021).

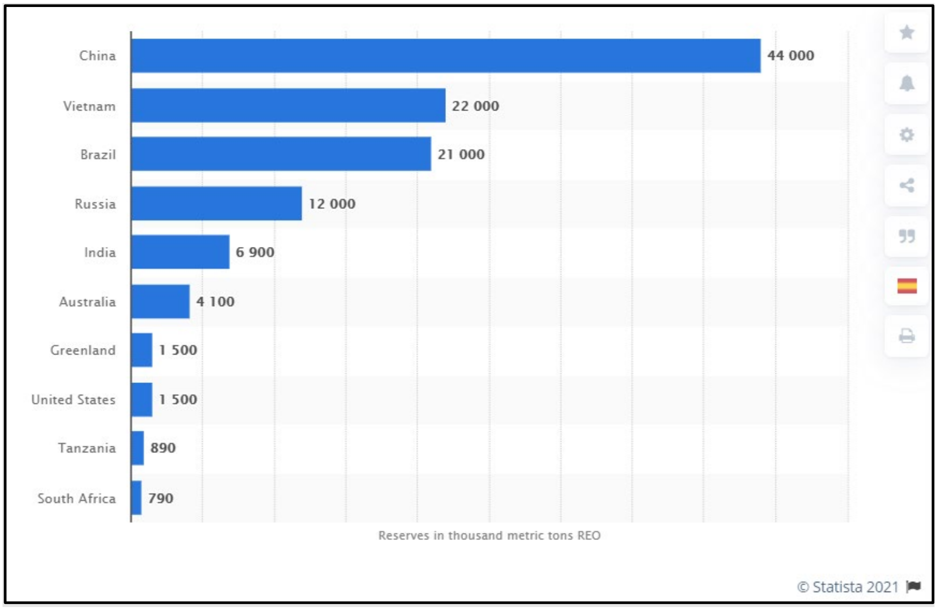

Figure 2. Rare Earth Reserves Worldwide as of 2020, by Country. Source: (Garside 2021).

REEs, also called rare earth metals (REM), comprise 17 metallic elements (American Geosciences Institute 2021). They include the 15 lanthanides plus scandium and yttrium, and are often an essential constituent with minerals ore, which makes the REE production process expensive and complex.

With their unique properties that can retain magnetic strength, amplification of energy, and resolution of signals in an elevated temperatures environment, REEs are ideal and crucial for military applications, such as Guidance and Control systems (Figure 3), Defense Electronic Warfare (Figure 4), Targeting and Weapon Systems (Figure 5), and Communication (Figure 6).

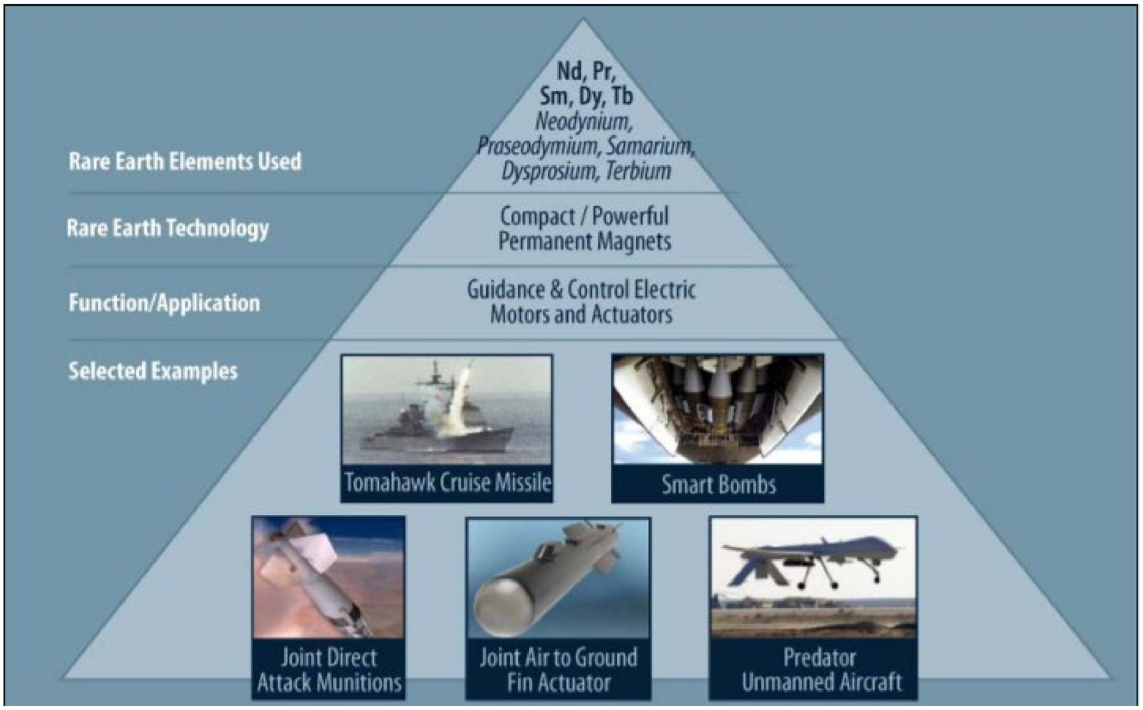

Figure 3. Rare Earth Elements in Guidance and Control Systems. Adapted from Grasso (2013).

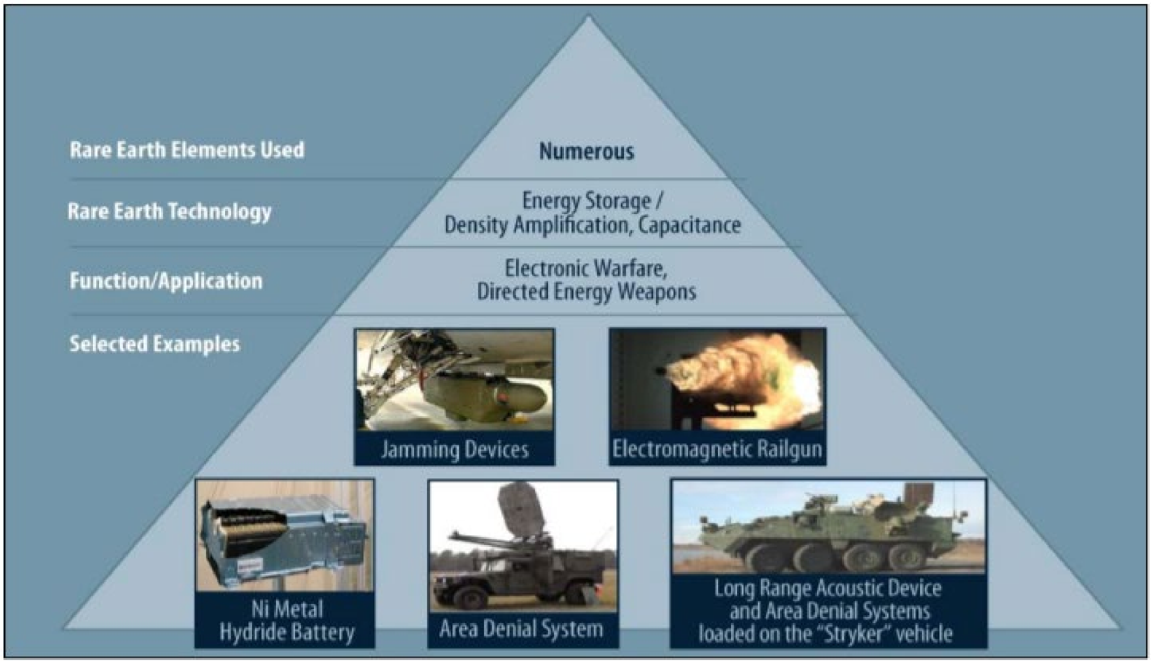

Figure 4. Rare Earth Elements in Defense Electronic Warfare. Adapted from Grasso (2013).

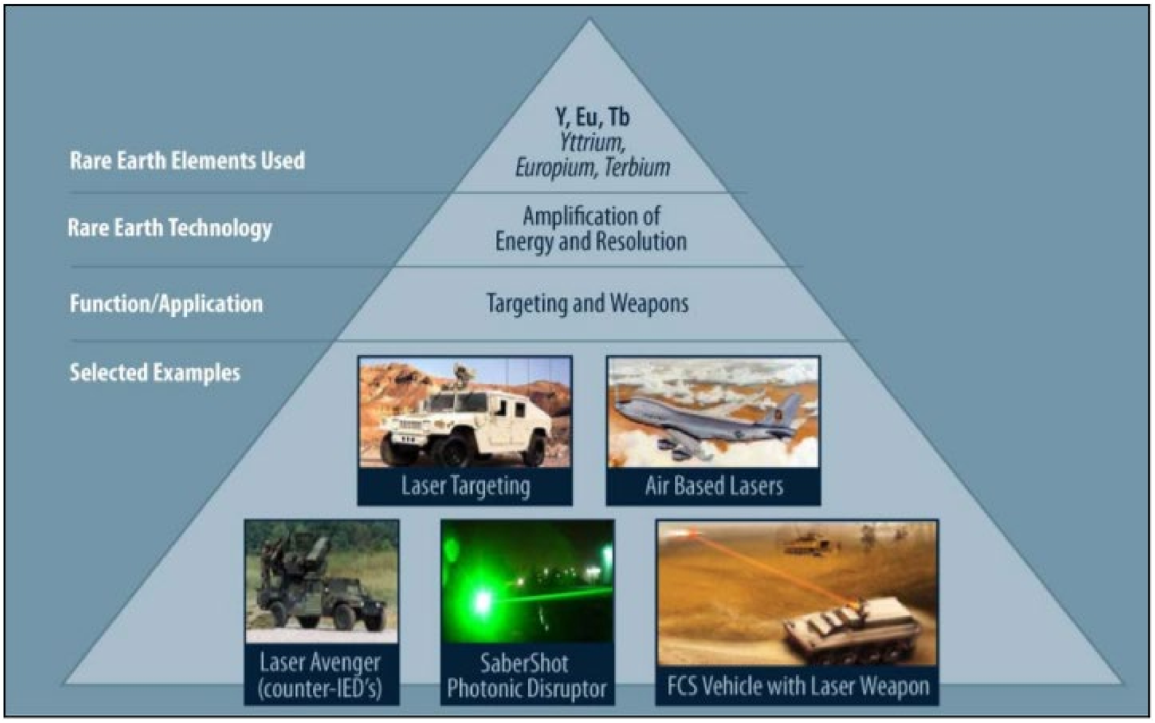

Figure 5. Rare Earth Elements in Targeting and Weapon Systems. Adapted from Grasso (2013).

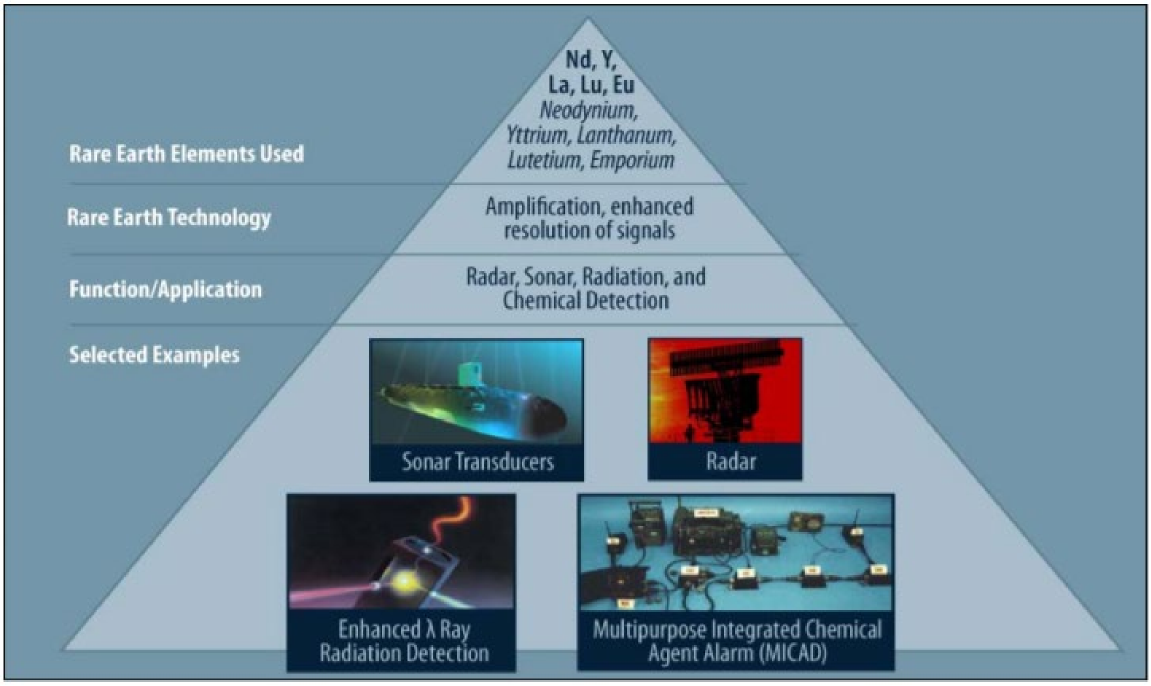

Figure 6. Rare Earth Elements in Communication. Adapted from Grasso (2013).

With the changes to future warfare, the military's increasing reliance on such capabilities is inevitable. The resources required for battle will no longer be just bullets or soldiers, but in fact will rely more on rare earth metals. For Navy and Joint Forces to maintain a constant influence over the adversary's action, there is a need to hold a significant amount of REM reserve, ensure a constant and diversified supply chain especially during wartime, and secure sufficient in-house manufacturing and production capabilities, so that there will be no degraded capabilities during operation and that a constant edge over the adversaries can be maintained. In Figure 7, an example of the process of a mined ore, similar to REE, being produced into component is depicted.

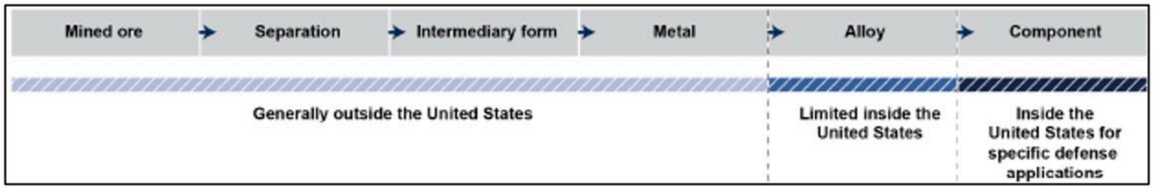

Figure 7. Generalized Rare Earth Materials Supply Chain for Metal Components. Adapted from GAO (2016).

C. PESTLE ANALYSIS ON RARE EARTH ELEMENTS

The PESTLE analysis was employed to further investigate the challenges that the U.S. faces regarding the supply chain for REEs. The name PESTLE refers to Political, Economic, Social, Technology, Legal, and Environmental factors. PESTLE analysis is a tool for situational analysis, which considers key aspects in the external environment and appraises each of them to form conclusions on current industry performance and future trends (Perera 2017).

1. Political Aspects

The United States faces a major issue in REE development for future production due to a lack of refining, alloying, and fabricating capacity. China, on the other hand, according to a 2013 Government Accountability Office (GAO) report "produces about 95% of the REE raw materials, about 97% of rare earth oxides, and is the only exporter of commercial quantities of rare earth metals" (Grasso 2013, 15). Noting the rise in U.S.-China trade tensions in recent years, the United States is at risk from political measures that China may implement to limit the export of REEs. A prime example of such risk occurred in 2010, when China embargoed exports of rare earth oxides to Japan during a maritime border dispute. The embargo greatly threatened Japan's high-tech industries and their export market as the rare earth oxides were used by automakers for products such as the Toyota Prius (Gholz 2014). During that period, the export control by China led to significant price increases world-wide, which affected the United States' REE imports as seen in Figure 8.

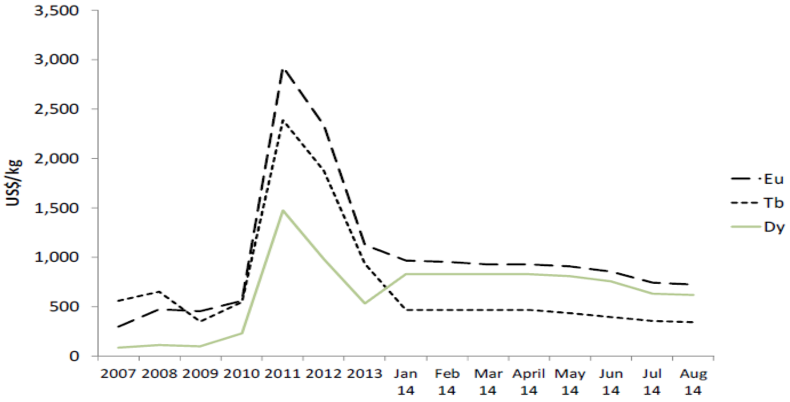

Figure 8. REE Price Trends 2007–2014. Source: Haque et al. (2014, 623).

As a result of the 2010 embargo by China, many other countries also started to look inwards and began efforts to develop mining and refining capabilities in their countries. Notably areas such as Europe and Australia have since explored new mining and refining sites, presenting potential ally partners that the United States can leverage to diversify its REE supply sources.

2. Economic Aspects

From the economics perspective, the lower mining and processing costs of REEs from China have also contributed to the world's increased reliance on that country for these processes and products (Bolton 2016). As seen in Figure 9, in a survey done in 2016 by the U.S. Department of Commerce on businesses that import REEs, 116 of the 211 vendors (approximately 50%) surveyed reported importing their REEs from China. In recent years there has also been an increase in the demand for REEs as they are being used in the commercial sectors for handheld phones, smartphones, and electric vehicles. With limited supply and increasing demand, it is not surprising that the "invisible hand' of the free-market economy would have driven and will continue to drive the prices of REE upwards. To ensure the United States continues to have a sustainable source of REE, it is imperative that new sources of REE should be explored.

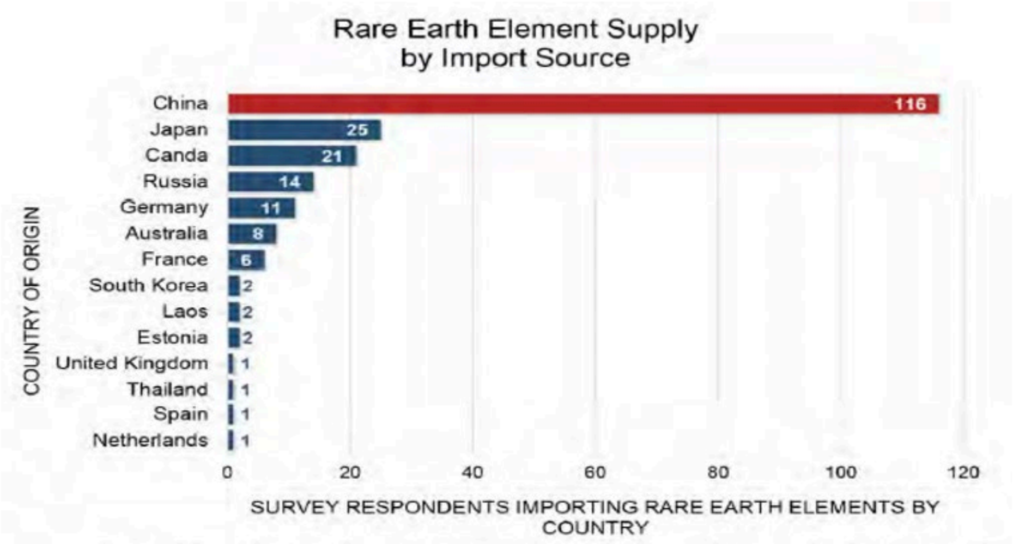

Figure 9. U.S. Department of Commerce Strategic Materials Assessment. Source: U.S. Dept. of Commerce (2016).

3. Social Aspects

REE extraction and processing results in chemical waste. A particular concern raised by Georgios Charalampides is "the common association of REE with thorium and uranium and thus the need to strictly control the dispersion of radioactive elements into the environment" (Charalampides et al. 2016). In addition, for mine operators, the exposure to respirable dust and chemicals have also tainted its image a profession. This negative image hinders the growth of mining capability in the United States.

4. Technological Aspects

Other clean energy technologies have the potential to contribute significantly as REE demand increases in the longer term. These include grid storage batteries important for wind and solar energy storage, fuel cells used for vehicle propulsion, and nuclear power. According to a 2011 Department of Energy report, "unlike other commodities, REE mining generally does not appeal to the major global mining firms because it is a relatively small market (about $3 billion in 2010), is often less predictable and less transparent than other commodity markets, and the processing of rare earth elements into high-purity REOs is fundamentally a chemical process that is often highly specialized for specific customers" (Chu 2011, 53). This also means that the research funding from private entities for more efficient methods of extracting REEs may be limited since it is a niche market. Hence, it is necessary for the government to weigh in and provide research funding to alleviate REE shortages. Such research can be focused on the development of (1) alternative materials with similar material properties, (2) recycling of REEs, and (3) improving mining methods to improve REE extraction efficiency.

5. Legal Aspects

The REE supply chain is often heavily regulated and subject to certain procedures, especially at the early processes of extraction and separation. For example, mining on federal property in the United States requires a company to prepare and submit a plan of operations and a statement of environmental impact for approval before breaking ground on a mining site. At the various levels across the states, there are separate mining, reclamation, and environmental laws, as well as health and safety standards, that a company must follow prior to mining operations. This lengthy process of attaining permits for mining increases the complexity and cost of mine development and may discourage investors or banks from financing such projects. Thus, the growth of mining capability in the United States is hindered.

6. Environmental Aspects

In his article, Charalampides et al. also discussed the "presence of radioactive thorium and in some cases uranium in rare earth deposits where the concentration of radioactive elements, usually relatively benign for human health in the ore body, rises significantly during beneficiation—a process during REE extraction" (Charalampides 2016, 3). This waste by-product could be of serious concern. In addition, the process of REE extraction was also assessed to require high levels of water consumption, energy, and chemicals. While these factors are noted, the benefits of REE to the development of critical military technology may outweigh those concerns. It is not to say, however, that the environmental factors will necessarily be ignored. There exists current research focused on the recycling of REE to alleviate the demands from mining them.

D. SUPPLY CHAIN RESILIENCE AND LESSONS LEARNED FROM SEA29

This section concludes the literature review conducted by the SEA30 team with a discussion on Supply Chain Resilience and Lessons Learned from the SEA29 project. In Supply Chain Resilience we discuss four methods to enhance logistics resilience. Finally, in the lessons learned portion we discuss the key takeaways from the SEA29 project and their applicability to this report.

1. Supply Chain Resilience

From the PESTLE analysis just presented, we recognize the existing challenges pose a threat to REE supply chains internally and externally. Internally, the increasing investment and other measures can be taken to promote the growth of in-country REE mining capability and to research alternative materials with similar material properties. As for external considerations, the opportunities to capitalize on the global emphasis on REE should work with ally partners to diversify the supply chain as an option.

An important aspect of material resources is the sustainability of the supply chain, even in a contested and dynamic environment. Due the importance of rare earth elements, the fragility of the supply chain as well as the environment is a concern. Although the REE supply chain was expected to increase exponentially, China unexpectedly introduced control of its REE export policy to rein in reckless and polluting practices of the mining process, which not only cut China's export quotas by about 40% but also resulted in increasing the value of REEs by four times. The fact is that 80% of the REE supply in the

United States continues to come from China, which has the highest reserve of REE for export (Grasso 2013).

In the aspect of supply chain, Sprecher defines resilience as “the capacity to supply enough of a given material to satisfy the demands of society, and to provide suitable alternatives if there are insufficient supplies” (Sprecher 2015, 6741).

Therefore, the following paragraphs highlight various methods and provide suitable alternatives. To enhance resilience in the supply chain in terms of Resistance, Recovery, and Flexibility, it is important to consider the following requirements. Resistance is the ability to tolerate various forms of disturbances without a significant loss of function. Recovery refers to being quick to recover from a disruption to meet the supply chain goal within a short period of time. Flexibility refers to the ability to meet the demands of a supply chain with disruptions by switching.

These are the following methods to enhance resilience in the supply chain: (A) For resistance, increase diversity with a variety of raw material sources to potentially reduce the impacts of disruptions on the supply chain, such as building more mines in different countries. Improve material properties by increasing the lifetime of products used intensively. Substitution is another method where one material is substituted for a different material. Additionally, consider technological substitution while re-engineering products to operate without any use of REEs. (B) For recovery, pre- and post-consumer recycling promotes the reuse and stockpiling of substances, which can act as a buffer to lessen the impact of temporary supply disruptions while also absorbing sudden price or demand supply fluctuations in an emergency. (C) For flexibility, consider implementing a mineral tax to promote the sustainable use of raw materials, redistributing profits made from the exploitation of non-renewable resources. Supporting research and development (R&D) also helps in bolstering the demand for other REEs by focusing on efforts to find new applications, or the resiliency of a supply chain as companies and governments partner to reduce the time needed to find solutions.

2. Lessons Learned from SEA 29-Logistics in a Contested Environment

In the SEA29 report, four key ideas are examined: (i) Transport and delivery of logistics in contested environments. (ii) The effectiveness of various platforms and delivery methods. (iii) Utilization of well-defended convoys on supply routes. (iv) System survivability—radar cross section (RCS) and noise reduction. By adopting the waterfall modeling method, it is possible to refine the task for incorporating background research, stakeholder analysis, functional analysis. Various types of vessels are used for the modeling. (A) The Network Flow Model was used to determine maximum supply flow, as well as most critical ports and routes, and to assign specific assets to individual routes. (B) Monte-Carlo Simulation was used to compare performance based on RCS, acoustic signature, size, carrying capacity, self-defense capability, unit cost, and speed. (C) The Circulation Model provided insight into survivability given a layered threat.

Results provided the following ideas for enhancing logistics resilience. (1) Adding defensive layers in conjunction with convoy operations offers the most significant improvement in successful delivery. Another good strategy is to unitize well-defended convoy operations on any supply route where bulk supply is supported. As for smaller deliveries, assets should be widely dispersed to minimize the chance that they are detected and engaged. (2) Another option is underwater operation delivery where survivability is higher if detected or engaged, as this method allows for the avoidance of surface threat layers, although it is time consuming and raises other risk factors. (3) Large, simple, commercial vessels should be used in defended convoys to convey large volumes across long haul routes to decrease cost per ton delivered. (4) Vessels highly susceptible to detection by sub-surface threats should be avoided or upgraded to minimize the threat. (5) RCS and noise reduction create a positive effect under certain conditions. Cost permitting, vessels should be upgraded prior to use within the logistics architecture. (6) Finally, to keep up with high attrition rates, any future logistics system must be inexpensive, rapidly replaceable, and either unmanned or minimally manned to reduce the loss of life.

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III. SYSTEMS ENGINEERING

A. SYSTEMS ENGINEERING PROCESS

To apply what we have learned at NPS and to create a starting point for this project, the SEA30 team had to decide on an SE model to follow that would structure the management of the capstone. From the three commonly accepted SE models, the Waterfall, Vee, and Spiral, shown in Figure 10, the team decided to utilize the “Vee” model for the project.

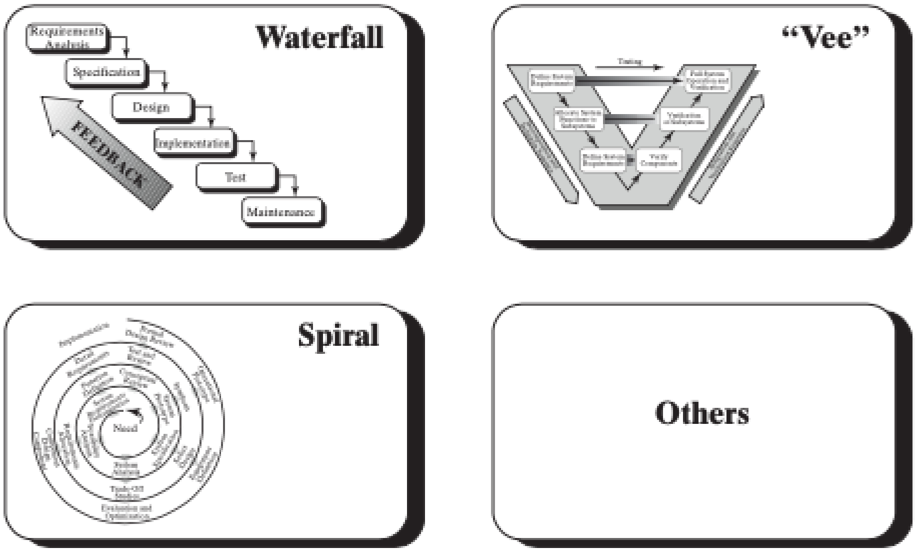

Figure 10. Common Systems Engineering Process Models. Source: Blanchard and Fabrycky (2010, 36).

The “Vee” model describes the “technical aspect of the project cycle” (Blanchard 2010, 36) where the left side of the “Vee” involves the decomposition of a problem to create a system architecture and the right side integrates components and subsystems until the full system is operational and verified. At each step of the process there is a feedback loop to the user to ensure the user’s needs are being met throughout the project. The “Vee” provides a large amount of traceability from the beginning since each subsequent step refers back to the system definition and requirements. These relationships are shown in greater detail in Figure 11.

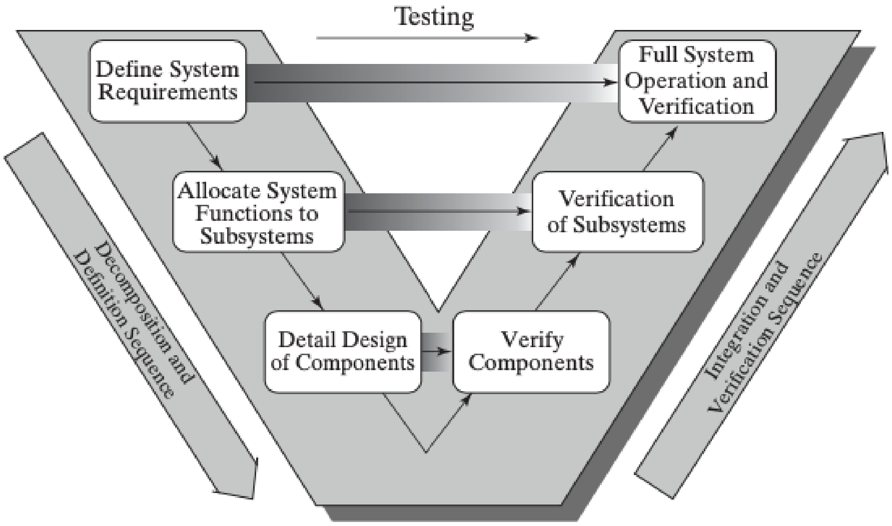

Figure 11. “Vee” Process Model. Source: Blanchard and Fabrycky (2010, 37).

The next step for the team was tailoring the “Vee” process to an executable form of program management. The team chose a semi-checklist tailored “Vee,” which provided multiple checkpoints for stakeholder input as we progressed further with the project. The team began with the tasking statement and then developed the rest of the project based off the process shown in Figure 12.

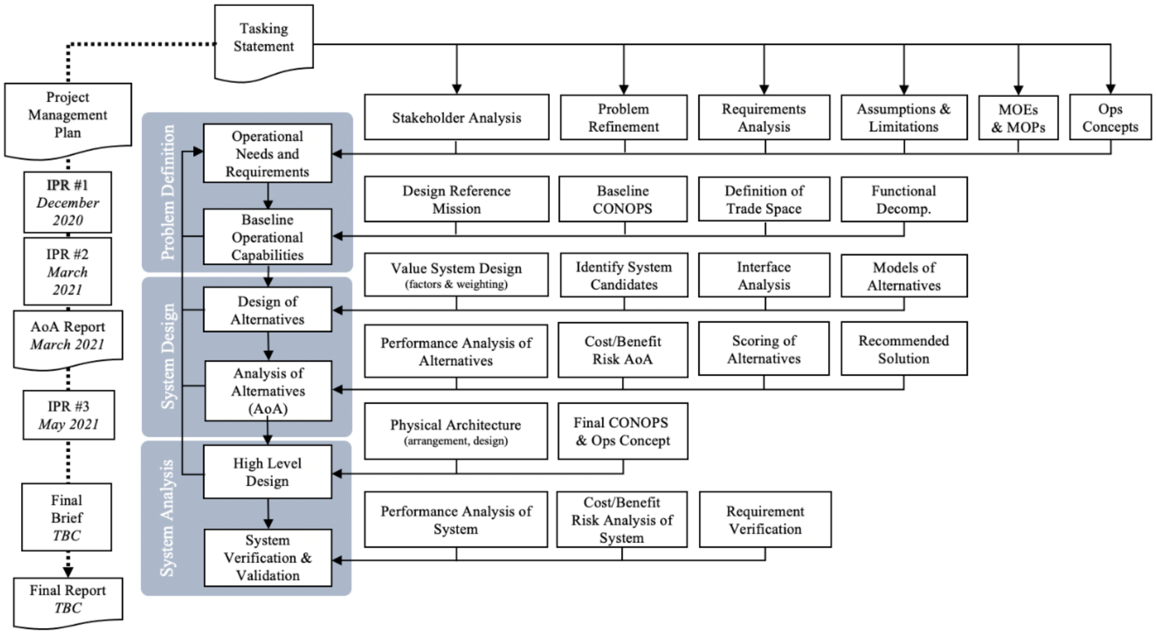

Figure 12. SEA30 Tailored "Vee" Process Model

The process shows the clear feedback loops to the Operational Needs and Requirements during each step for the process, from problem definition to system analysis. This loop aided in keeping the project on track and in line with the tasking statement.

B. PROJECT BOUNDARIES AND ASSUMPTIONS

The tasking statement for this project laid out a broad scope within which the SEA30 team had to work. The breadth of "metal bending to metal delivery" presented us with a variety of topics, all of which were valid paths for research, but we needed to scope and bound the problem space to formulate questions for stakeholders and eventually create a model of the problem. Following this thought process, we narrowed down a list of project boundaries and assumptions.

1. Boundaries

To bound the problem along the lines of the "Resurrecting War Plan Blue" GPC construct we limited the project to operations in the Pacific Region. This later helped the teams develop the appropriate MOEs and MOPs to model. We also determined the scope of the "kill chain" resiliency to begin with raw material mining and procurement, progress to manufacturing and assembly, and end with distribution. The end point of distribution brings the SEA30 project up to the beginning of SEA29 project. We examined the resiliency of the process leading to distribution in a potentially contested environment. The project also models present-day industry practices to use for a resiliency analysis. Finally, we bounded the project to the electronic sector's reliance on REEs for component production.

2. Assumptions

After bounding the project, we drew up assumptions based on the boundaries and the literature reviews. We assumed the full influence of relevant industries' business models on the subsequent resilience analysis, the utmost cooperation from allied countries and trade partners, and uninterrupted communications and logistics operations within the Continental United States (CONUS). Along with the last assumption, we added the willingness of the United States to invest in and begin mining REEs within CONUS in the near future to overcome technological or environmental limitations to create new reserves of REEs. This would reduce or eliminate the reliance on REE supplies from a potential near peer competitor.

C. STAKEHOLDER ANALYSIS

To validate our boundaries and assumptions, as well as gain insight from subject matter experts into the problem we were tasked with researching, the SEA30 team put together a stakeholder questionnaire to conduct the stakeholder analysis. Due to the nature of the 2020 pandemic, the stakeholder analysis was conducted solely via email. Nonetheless, even with communication limitations the team was still able to gain insight outside our realms of experience and receive guidance past our own assumptions on where to further our efforts. Each stakeholder involved in the project had his or her own insight to add, as is shown in Table 3.

Table 3. List of Stakeholders

Stakeholder	Title	Primitive Need
VADM Ricky Williamson, USN	Deputy Chief of Naval Operations for Fleet Readiness and Logistics (OPNAVN4)	Insight, analysis, and recommendations for logistics systems, architectures, and concepts of operations. Recommendations to close capability gaps with identification of tradeoffs.
RADM Daniel Fillion, USN	Director, Warfare Integration (OPNAVN9I)	
CAPT (Ret) Michael Stewart	Deputy Director, Integrated Warfare(N9IB)	
CAPT Eric Morgan, USN	OPNAV N4iL – Logistics Analytics Branch (LAB)	
CAPT (Ret) Jeffrey Kline	OPNAV N9I Chair, Systems Engineering Analysis	Completion of graduation requirements. Relevant recommendations to OPNAV N9I.
CDR (Ret) Matthew Boensel	OPNAV N9I Chair, Systems Engineering Analysis	
Dr. Jefferson Huang	Operations Research Advisor	Completion of graduation requirements. Relevant recommendations to OPNAV N9I. Challenging and rewarding academic experience.
Dr. Fotis Papoulias	Systems Engineering Advisor	
SEA30 Student Cohort		Completion of graduation requirements. Application of critical thinking and reinforcement of curricula skills.

We sent each of the stakeholders a list of ten questions, vetted through the NPS Institutional Review Board (IRB). The questions and their focus are shown in Table 4.

Table 4. Stakeholder Questionnaire

No.	Question	Aim
1	Rank importance of capabilities needed in the “kill chain.”	Identify importance of these capabilities in the “kill chain” following the production in industry.
2	What is a realistic budget to constrain our solutions?	Identify a realistic budget constraint to produce components.
3	Top 3 effective ways of incentivizing a skilled USN maintenance force.	Identify means to enhance the maintenance workforce.
4	USN preference for insourcing/outsourcing maintenance.	Explore potential of the Navy having contractors and sailors doing maintenance onboard.
5	How the USN sees regional allies and strategic partners as part of the solution.	Identify level of responsibility to which we share with Allies in future wars, especially when the distance to the fight is far.
6	Should the eventual “sensitivity analysis” be focused on variables which are within USN/DOD’s scope of influence or Industry-wide/National scope of influence?	Scope the analysis to how much leverage we can obtain.
7	Rank the top 3 areas of Naval warfare which unmanned ships would play the greatest role.	Identify future of unmanned vessels in the next decade or two, where is the emphasis going to be.
8	Rank the following spheres of influence that an adversary’s control of rare earth element has.	Identify the barriers to controlling REEs.

No.	Question	Aim
9	Rank the following areas of concern that the USN would have by 2035.	Identify, with manned vessels and the weapons onboard, what the primary concern will be by 2035. Determine the effects of where the supplies and REEs are drawn from and distributed.
10	Rank the reliance of the following industries on foreign companies/stakeholder.	Identify which industry is most reliant on foreign companies, electronics, metal fabrication, mining, or oil/energy.

The full graphical representation of the stakeholder responses is shown in Appendix A. To refine the tasking statement into a problem definition, the team focused on the responses to questions about the importance of capabilities, the role of regional allies and partners, the focus of the sensitivity analysis, the impact of adversary control of REEs, and sector reliance on foreign companies.

The responses to the first question aligned with our expectations for future capabilities, especially against a near peer competitor. Given the importance of intelligence gathering in the current Navy, the need for continued development of ISR capabilities will only increase as we approach 2035. The sentiments of the stakeholders are shown in Figure 13.

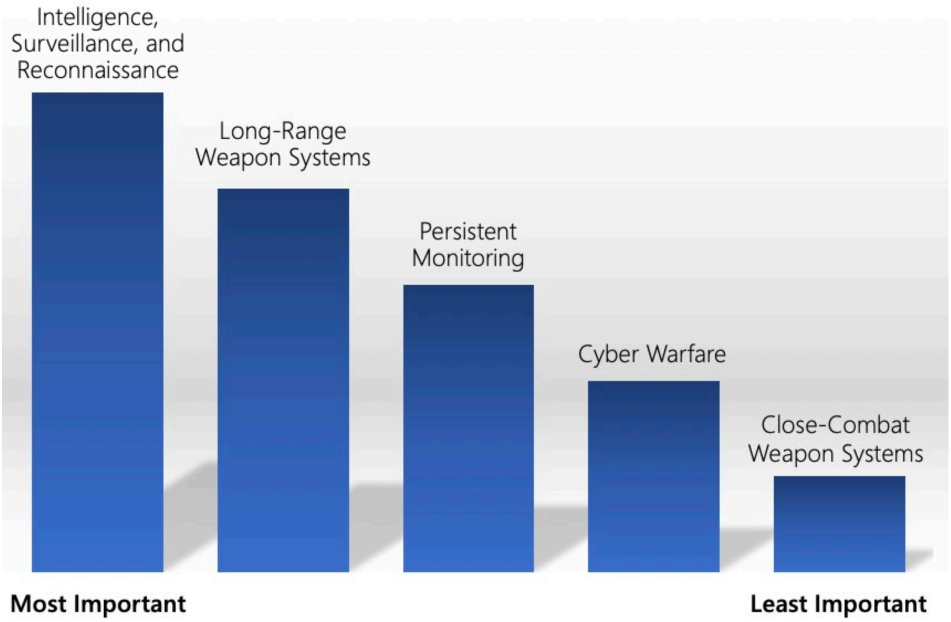

Figure 13. Stakeholder Response to Importance of Capabilities

The question relating to the role of regional allies deals with the level of shared responsibility allies would have in a future conflict. This translates to providing security for REE shipments should they come from overseas as well. The response from the stakeholders is shown in Figure 14.

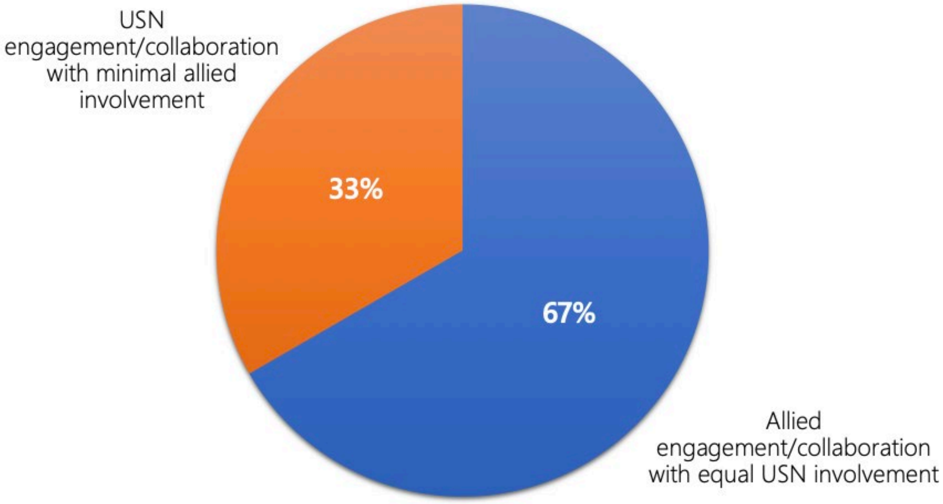

Figure 14. Stakeholder Response to Role of Regional Allies and Partners

The SEA30 team had a proposed direction for the eventual sensitivity analysis, which was shared by the stakeholders as well. Since the scope of the project deals with the Department of Defense (DOD) working with the commercial sector, the analysis logically should include efforts at both the commercial and national government levels. This is shown in Figure 15.

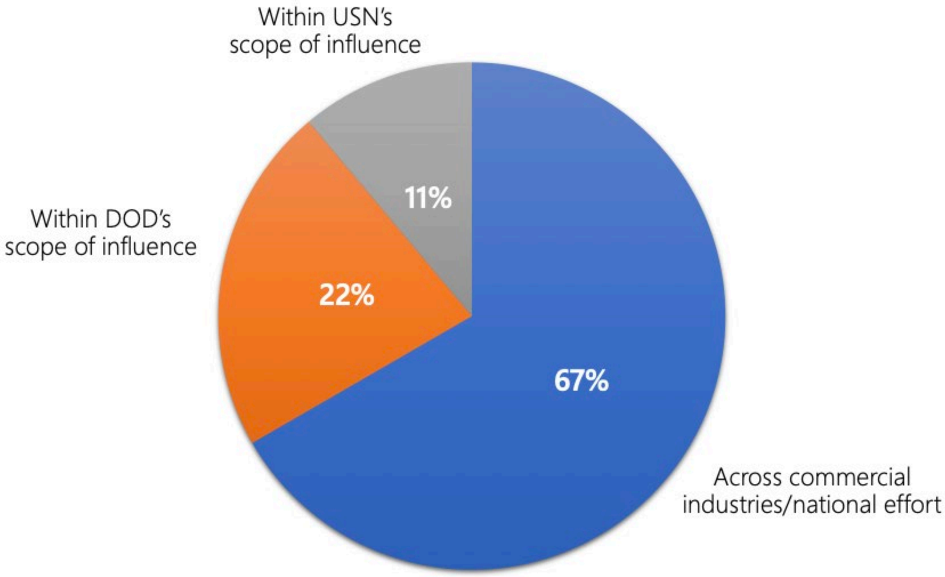

Figure 15. Stakeholder Response to Focus of Sensitivity Analysis

The final two questions used to refine our tasking statement were fundamentally linked. The impact of an adversary's control of REEs and the reliance of sectors on foreign companies was previously demonstrated in Figure 8 where China placed an embargo on REEs in 2010. This led to an increase in prices for goods that required those REEs and for countries to begin looking at other ways to acquire those REEs. The primary concern for this project is centered on the military, shown in Figure 16, and the sector most reliant on REEs is the electronics sector as shown in Figure 17.

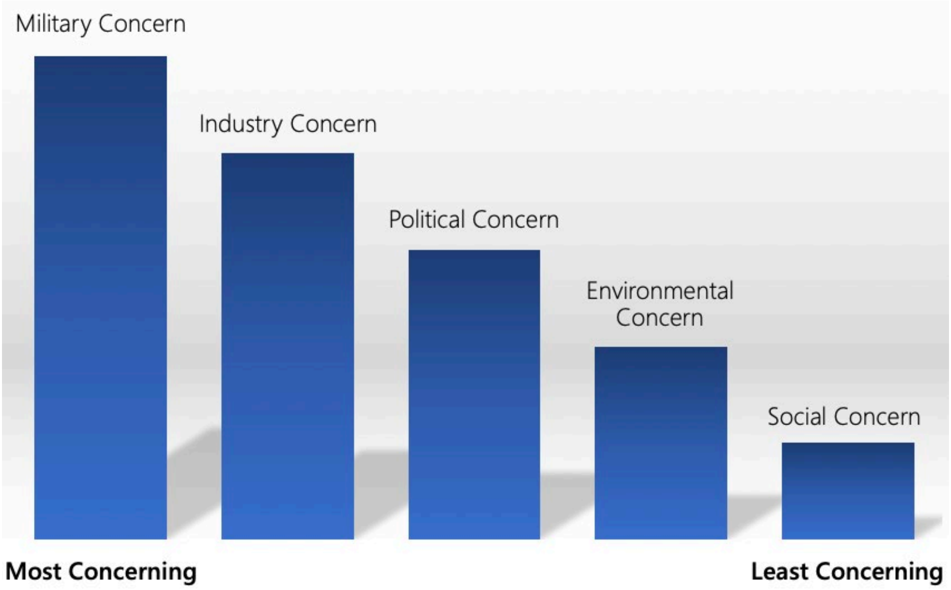

Figure 16. Stakeholder Response to Impact of Adversary's Control of REEs

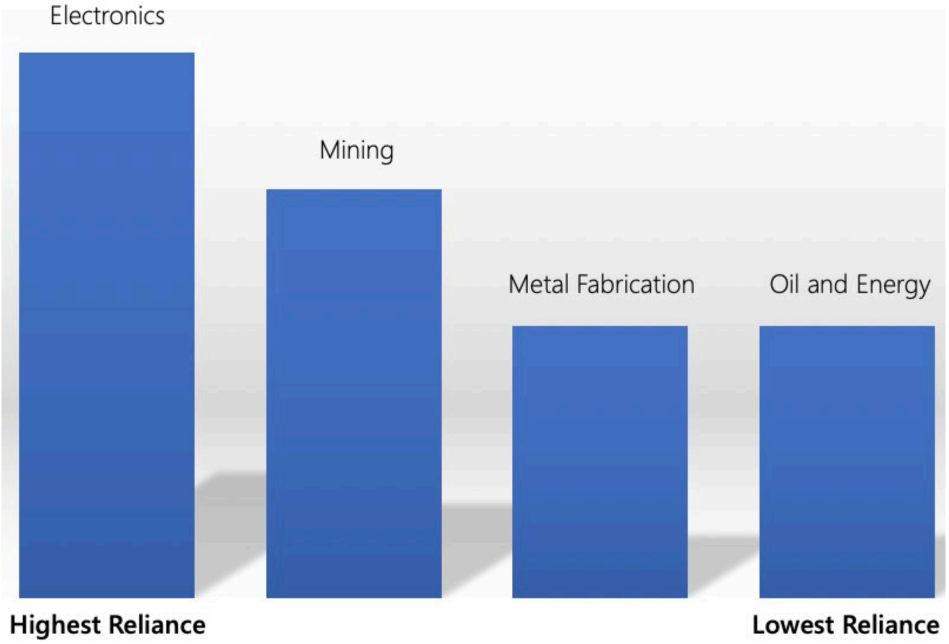

Figure 17. Stakeholder Response to Sector Reliance on Foreign Companies

D. PROBLEM STATEMENT

Taking into consideration the literature reviews, boundaries and assumptions, and feedback from the stakeholders, we were able to refine our tasking statement. We know the coming decades of global operations are not just about striking capabilities but also being able to continuously operate with limited or no resources in the face of adversarial supply chain disruptions. As such, improving our operational logistics framework by extending the kill chain to a global process capitalizing on multi-national alliances and military-industry partnerships will be a deciding factor in creating long-term resilience in our "metal-delivery" capabilities. Therefore, we aim to model ways to **increase the resilience of the operational supply chain to ensure continuous operational output in the face of an extended conflict with other global powers.**

The development of this problem statement allowed us to continue with the SE process and perform a functional decomposition, functional flow, and identification of critical operation issues (COI).

E. OPERATIONAL CONCEPT

From the problem statement we developed the high-level operational concept of the entire system that considers the stages of the mining to distribution process. In Figure 18 the system flows from right to left to signify our focus on the backside logistical architecture of obtaining, refining, and delivering Rare Earth Elements before the weapons manufacturing process. The steps of the system are defined as (1) the mining and trading or obtainment of REE; (2) the refinement, manufacturing, and assembly; and (3) the distribution or delivery of the REE. At which point our research connects with the previous capstone teams for achieving the "last mile" movement from the weapons manufacturer to the area of operation.

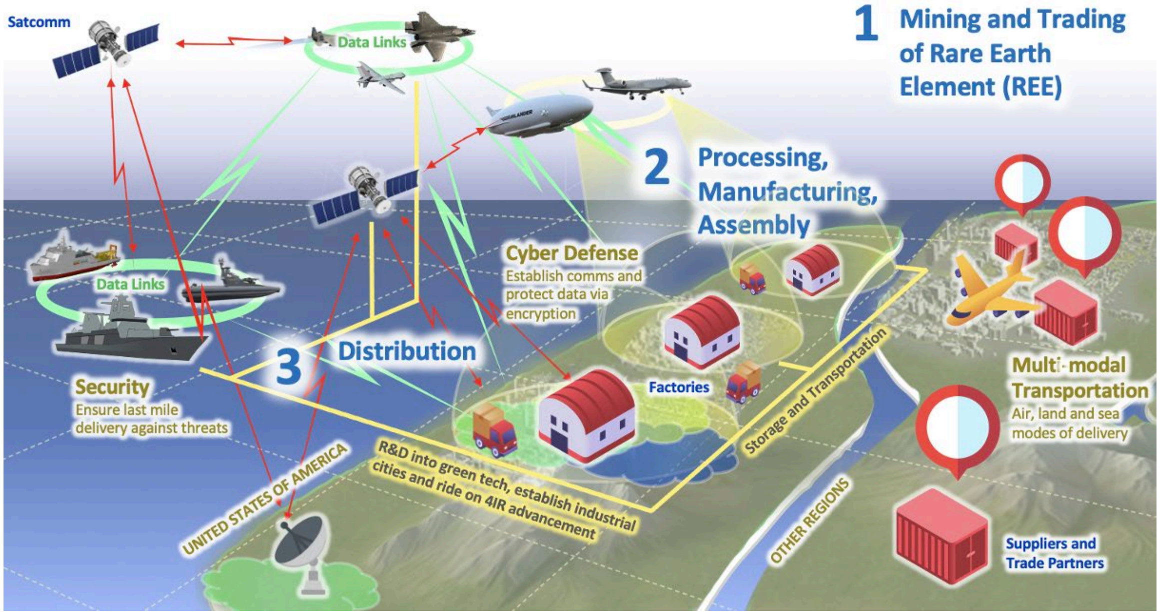

Figure 18. High-Level Operational Concept

F. FUNCTIONAL DECOMPOSITION

Within our system we have a three-level functional decomposition which includes the hierarchical relationship of subordinate functions within four major compartments of the system that generally coincide with the operational concept shown in Figure 15. This ensures the traceability of our system requirements and functions as we progress. The compartments are color-coded in Figure 19 for ease of reference and expanded as a list for readability. There you see the first compartment as performing administrative requirements, which include processing the order, selecting the mode of transportation, planning the route, and coordinating with the host nation (HN) that we might be mining in or transporting through. This process is followed by the obtainment of the REE, which includes the extraction, preparation, and delivery to the refineries where purification, packaging, and preparation occurs for the final delivery process where security is assigned, and the package is moved and defended before arriving at the destination.

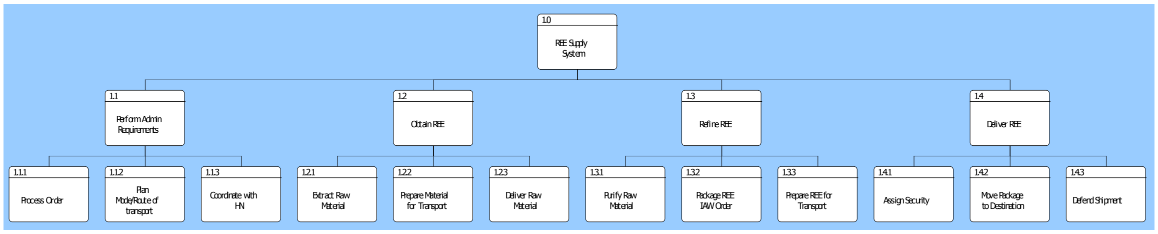

Figure 19. System Functional Decomposition

1. Perform Administrative Requirements

i) Process Order

ii) Plan Mode/Route of Transport

iii) Coordinate with HN

2. Obtain REE

i) Extract Raw Material

ii) Prepare Material for Transport

iii) Deliver Raw Material

3. Refine REE

i) Purify Raw Material

ii) Package REE in accordance with Order

iii) Prepare REE for Transport

4. Deliver REE

i) Assign Security

ii) Move Package to Destination

iii) Defend Shipment

G. FUNCTIONAL FLOW BLOCK DIAGRAM

The Functional Flow Block Diagram (FFBD) provides a time-sequenced step-by-step flow of activities derived from the same three components seen in both the operation concept and functional decomposition. The administrative requirements, however, are interspersed among those three top-level functions. In this case, the process begins with receiving the logistical request at which point we have the option to mine locally, abroad, or draw from reserves. Then after selecting the most appropriate mode of transportation, we move the material by land, sea, or air before refinement takes place via commercial, military, or allied mechanisms. Overall, this basic FFBD provides an initial framework for the modeling team to begin building the necessary models and simulations. As the project moves forward, we will develop this diagram, shown in Figure 20, to include the inputs and outputs that will act as the entities of flow throughout.

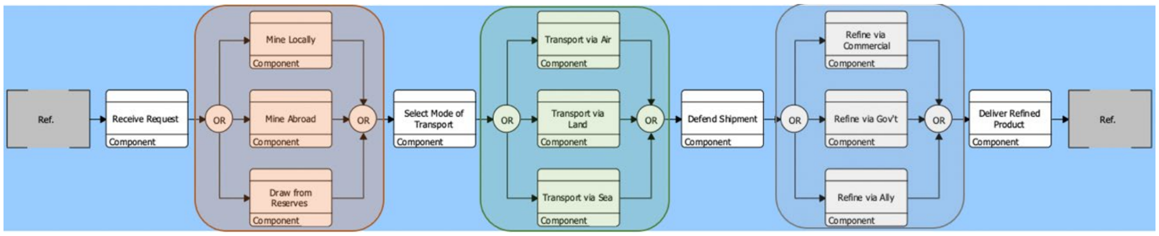

Figure 20. System Functional Flow Block Diagram

The FFBD shows the three COIs the team decomposed in the system,

1. Availability – obtaining the REE from a local, overseas, or reserve source.
2. Transportability – moving the material via land, sea, or air.
3. Producibility – refining the raw material using commercial, government, or allied factories.

This list was further decomposed into the MOEs and MOPs for the system to provide metrics the modeling team could utilize to build a representation of the system and identify areas for a sensitivity analysis.

H. MEASURES OF EFFECTIVENESS AND PERFORMANCE

The development of MOEs and MOPs is rooted in the definition of how well the system accomplishes a mission and how well the system accomplishes tasks. After COIs are defined, System Operational Requirements (SOR) are used in the next step of requirements decomposition to describe clear MOEs and MOPs. From the SORs, mission accomplishment is defined by MOEs, while task accomplishment is defined by MOPs. Finally, MOPs are described by Data Requirements (DR). These measures and requirements are used to build the model of the system, with definable parameters for analysis.

Beginning with Availability, the COI was further broken down into the SORs of operational availability, asset density, and reliability focused on the mining aspect. Operational availability was associated with the mean time between maintenance and downtime of the mining facility, as well as the percentage of REEs attainable from the source. The asset density refers to the average distance to the nearest source of REEs, i.e., how far a mine must drill or excavate to arrive at raw materials. Finally, reliability deals with the ability of the mine to consistently produce REEs, the quality of the REEs, and the yield capacity of the mine.

Next, Producibility focused on the rate of production for commercial, allied, and government manufacturing and the REE quality post-refinement. The SOR is reliant on the time needed to refine the REE and the percentage of by-product produced. These DRs in turn calculate the quality of the REEs and whether they meet purity standards.

The final COI, Transportability, decomposes into the transportation capacity, time, availability, effectiveness, asset readiness, security, and capacity. These are linked to the post-refinement process of moving the REE to the manufacturer. Therefore, we are interested in the average volume transported, the mean delivery time, and the rate of successful deliveries. We defined three avenues of transportation among land, sea, and air, with DRs to capture the most efficient assets. Finally, since we are planning for, at the least, contested logistics, the security of transportation is taken into consideration with the package damage rate. This rate is effectively the number of successful convoy deliveries between refineries and manufacturers.

The complete decomposed list of SORs is catalogued in Appendix B.

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IV. MODELING

A. OVERVIEW

In this chapter, we discuss the process of modeling a logistics supply chain in the context of our design. We note that the key functionalities of the system have already been covered and the differences between potential alternatives stem from specific data-oriented decisions, such as where to produce components. As such, our modeling approach first develops a general mathematical model that can address any of our alternatives and then proceeds to explain how the alternatives differ from each other.

The complexity of modeling the logistics supply chain for our system is evident in Figure 21. Our model must account for many elements interacting with each other across time. The dependency of our model on many data elements also requires a precise definition of the examined scenario or scenarios used for alternative analysis and performance evaluation.

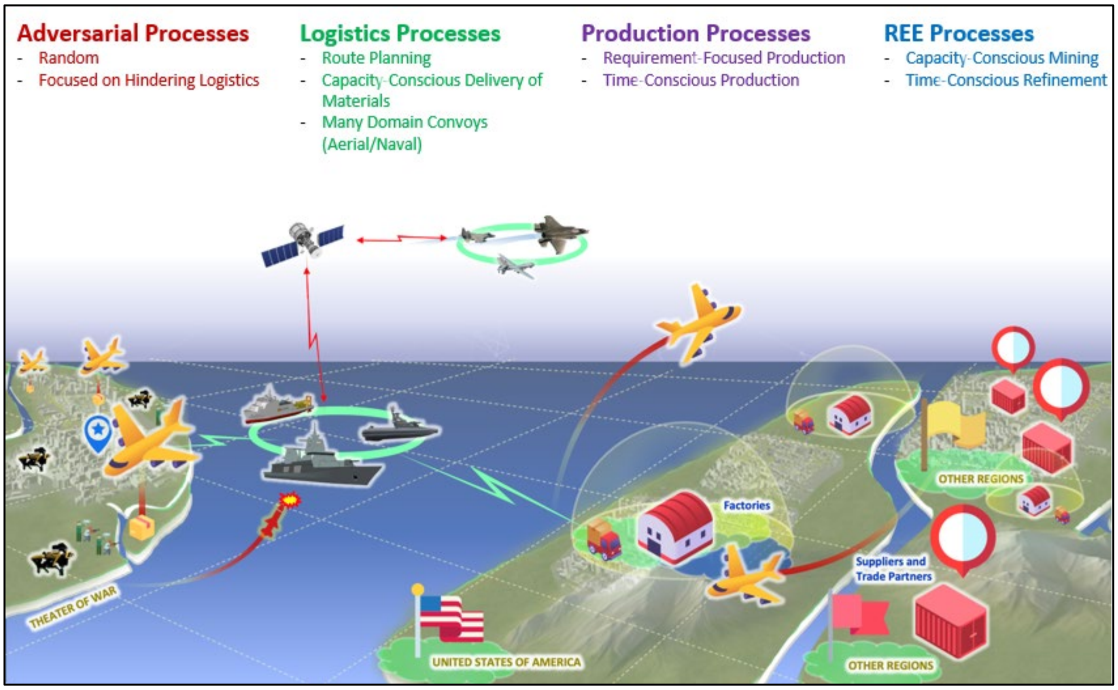


Figure 21. Processes Incorporated as Part of the Optimization Model for Simulation of Various Possible Scenarios

1. Processes Covered by the Model

The processes shown in Figure 21 are discussed in detail in the following list.

a. Adversarial Processes

- These are processes that simulate potential adversarial attacks against specific logistic targets, such as the transportation convoys, in order to hinder and disrupt the logistics supply chain of the force. These processes are stochastic in nature and were thus randomly generated as part of the various modelling scenarios explored.

b. Logistics Processes

- Various options on possible transportation convoys across different operating domains (aerial, naval) were incorporated as part of the model. The carrying capacity and velocity of the various convoy types were also accounted for within the model.
- Route planning abilities for the transportation convoys was also adopted for the shipment of REE materials from various REE mines to factories.
- Collection of materials from different locations, and delivery of those materials to their destinations.

c. Production Processes

- Requirement- focused and time- conscious production of system components by the factories, where the minimal amount of material must be met to begin production, in order to meet the desired overall demand by the force in a timely manner.

d. REE Processes

- Capacity- conscious mining and time- conscious refinement of desired REE material volume to meet overall demand by the production factories.

2. Processes Not Covered by the Model

Importantly, we note that once components have been produced, our model assumes the factory is their final destination. Consequently, we say our model is concerned with production logistics, but not operational logistics. Our system is therefore expected to be integrated with SEA29's Logistics in a Contested Environment project (Bengigi et al. 2020) such that our model essentially extends the logistics supply chain from delivery of components to their operational-oriented destination, to delivery of material from its source until it is transformed into a usable component.

An overview on the technical aspects adopted in the modeling approach is shown in Figure 22.

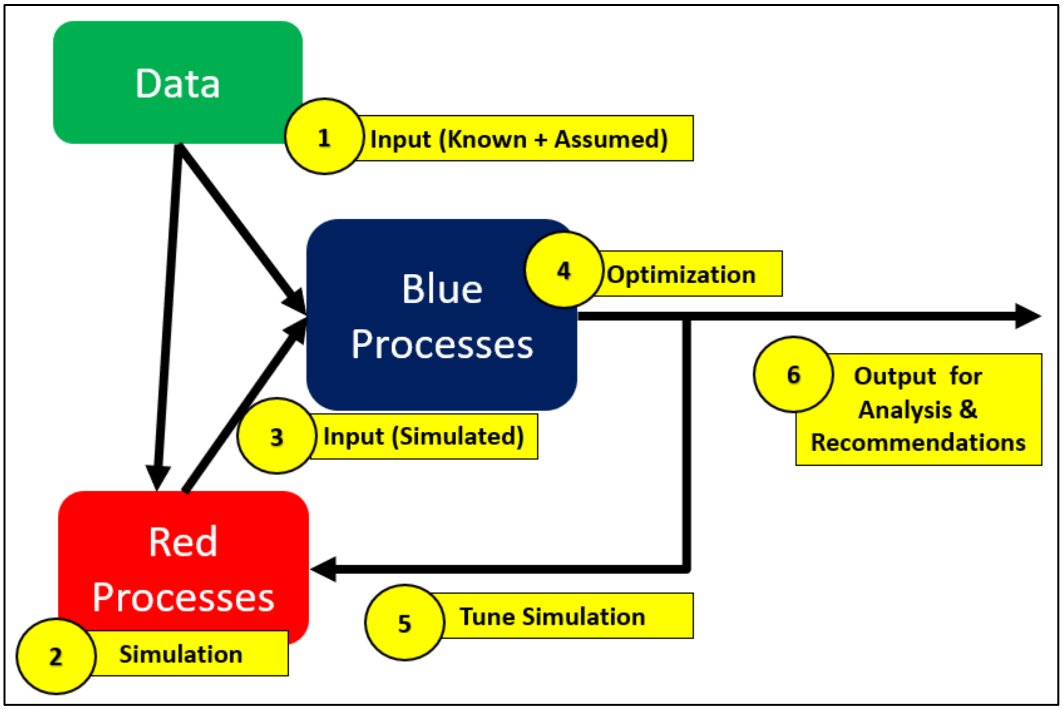


Figure 22. Technical Aspects of the Modeling Approach

Red processes represent plausible actions that might be executed by potential adversaries. Using simulation, these processes are generated as a data input that is fed into the optimization model as scheduled attacks targeting specific routes traveled by convoys at certain times along the event horizon for each scenario simulation run. Hence, by utilizing data collected from available sources or by using reasonable estimates, red processes can be simulated either by using scenario-specific behavior or via stochastic means.

Blue processes represent the operations of one's force, which encompass the movements of the various convoys along the different routes, collection of REE materials, and component production at the various production factories. These were all captured to a reasonable degree within the large-scale optimization model.

Thus, simulated red processes outputs and available data inputs are fed into the blue processes model. The model outputs are subsequently optimized using available large-scale optimization tools. In addition, the simulation model is further tuned where necessary to improve the robustness of the model design to produce reliable outputs when presented with different operational scenarios.

The goal of the large-scale optimization model would be to derive the optimal combination of factors that would maximize the weighted MOPs. The various factors encompass the movement of convoys between locations, the availability of REE materials from each REE mine, the materials collected by each respective convoy and corresponding material volume, as well as the production plan and production timing for each of the factories within the model.

Within the model, red processes are generated using a simulation model, with its outputs fed into the large-scale optimization model as scheduled attacks targeting specific routes that convoys travel along at certain times in the event time horizon as part of the respective simulation runs. Hence, if a simulated convoy happens to be traveling along a route at the same time as an adversary, an "Encounter" is determined to have occurred. Each "Encounter" is simulated using a model like the Hughes Salvo equations (Hughes 1995) that will result in the convoy sustaining some damage that is translated into the loss of carried material. Hence, convoys not transporting any materials are deemed to be most vulnerable to such attacks. In addition, the model does not account for potential shipping delays experienced by the convoys during the production of components by the various factories.

B. METHODS AND TOOLS

The optimization model developed strives to capture various elements/processes of interest, and their corresponding interaction effects over time. Thus, the scale of the model can be considered to be large in terms of overall development complexity. Various tools and techniques were thus adopted as part of the model development, in order to obtain results from the model in a time effective and efficient manner.

The various techniques and tools used to develop the simulation and large-scale optimization model used in this study are further discussed.

a. Pyomo Model

Pyomo (Hart et al. 2017) is a software package designed in the Python programming language (Van Rossum 2007) that can be used to easily build large-scale objected-oriented optimization models, and specifically, integer-programming models.

b. Data Farming

The model was also designed to be 'data farmable' (Sanchez et al. 2020) to allow for analysis using suitable statistical and visualization techniques from which to derive potentially useful insights from the model outputs. Our model can make use of a Design-of-Experiment (DOE) input that can help us test the limits of the model under various scenarios.

c. Additional Tools

The analysis accompanying the model outputs (further discussed in the next chapter) includes graphics or evaluations by JMP software (Jones 2011).

C. ASSUMPTIONS

There were several elements incorporated as part of the model, such as convoys, REE mines, factories, and production processes. These elements also potentially include various sub-types, for example convoys could possibly include aerial and naval assets. Moreover, due to the classification of this study, the amount of available data is limited in scope. Therefore, several assumptions had to made in the development of the simulation and large-scale optimization model. These assumptions can be broadly categorized into either data assumptions or model assumptions. We describe the data assumptions in the context of examined scenarios here.

a. Convoy Related Assumptions

- Routes traversed by convoys between locations are two-way routes of equal length. These routes form a connected network.
- Convoys travel with a constant speed along routes.
- Convoys can be deployed at the start of the time period from any location within the simulation model.
- A deployment period for convoys is considered in obtaining the set of feasible optimal solutions.
- Convoy entities are never destroyed by enemy attacks in the model, only the materials carried by the convoys can be 'lost'.

b. Material Related Assumptions

- Unloading/loading of materials from convoys at various locations requires a constant time period.
- The volume of materials loaded/unloaded from a convoy is limited.
- From each REE mine, a constant rate of raw material mining is assumed.
- A constant rate for material refining is also assumed.

c. Production Related Assumptions

- Factories can produce the same weapon system components with the same production procedures but differ in production time and efficiency.

d. Adversary Assumptions

- Adversaries can be detected but cannot be fended off by convoys.
- Adversaries can launch targeted attacks on routes by causing damage to convoys traversing on the same route at the same time.
- Adversarial units attack convoys with the same amount of offensive damage. The damage is equivalent across all adversarial units.

D. MATHEMATICAL MODEL DESCRIPTION

This section discusses the mathematical formulation of our model elements.

1. Optimization Model

The first part of the model is a mixed-integer programming model that aims to maximize our MOEs by using the data to decide an optimal allocation of resources. The model creates an optimal route plan for each of the convoys as well as a plan to carry materials from mines to factories for production.

The key objects in the model include:

- **Convoys**. Convoys can be aerial or naval, each independently moving between different locations of interest around the globe. The convoys can load or unload material from each location. In addition, convoys can be **damaged**, as detailed later in this chapter.
- **Location**. The locations in this model represent places around the globe of interest, usually mines or factories. We note that locations with no indicated purpose can serve as storage facilities.

- **Mines** produce a rare-earth metal that can be used to produce weapon components. The material in each mine is limited and grows with time, as more material is excavated.
- **Factories** can transform material into weapon components. The production process is shown in the sets of objects.

2. Combat Model

The combat model is inspired by Hughes' Salvo equations (Hughes, 1995). Assumptions of this model include:

- Enemies attack a convoy that traces its route along the same route as that enemy during the same time unit.
- Enemies only attack a convoy for that time unit and do not engage it otherwise.
- However, enemies will attack ALL convoys along that route.
- Enemies are indestructible. The model is centered around the damage a convoy sustains and the loss of material resulting from that damage.

3. Mixed-Integer Programming Formulation

We can now begin describing several notations to our data.

a. Sets of Objects

- $MOPS$: the set of all measures-of-performance of interest.
- LOC: the set of all locations of interest.
- $ALLIED.LOC \subset LOC$: the subset of all allied (non-U.S.) locations.
- $MINES$: the subset of all locations that are mines.
- $FACTORIES$: the subset of all locations that are factories.

- REE: the set of all rare earth elements of interest.
- $WEAPONS$: the set of all weapons of interest.
- $ROUTES \subset LOC \times LOC$: the set of all routes between locations. Note that not every pair of locations has a route between them. Routes are not necessarily symmetric.
- $CONVOYS$: the set of all convoys of interest. This is assumed to be fixed.
- $ENEMIES$: the set of all enemies.
- AFF: the set of all affiliations (countries).

b. Object Information of Interest

- $T \in \mathbb{N}_+$ is the maximum time-unit. We call $H = \{1,2, \dots, T\}$ the time horizon.
- For an $MOP_i \in MOPS$:
    - $w_i \in \mathbb{R}$ is a weight for that MOP.
- For a route $r \in ROUTES$:
    - $len_r \in \mathbb{N}_+$: is the length of the route.
    - $src_r \in LOC$: is the source location of the route.
    - $dst_r \in LOC$: is the destination location of the route.
    - Routes are not necessarily symmetric.
    - Given a convoy with a speed s_c, we let $LEG_{r,c}$ be the set of legs required for the convoy to traverse the route (rounded up). Formally, $LEG_{r,c} = \{1,2, \dots, \left\lceil \frac{len_r}{s_c} \right\rceil\}$. We also denote by $k_{r,c} \in LEG_{r,c}$ the maximal leg.

- For a location $\ell \in LOC$:
    - $SRC_\ell \subset ROUTES$: is a subset of routes starting at ℓ.
    - $DST_\ell \subset ROUTES$: is a subset of routes ending at ℓ.
    - $c_\ell \in \mathbb{R}_+$ is the capacity of the location.
    - $q_\ell \in AFF$ is the affiliation of the location.
- For a mine $m \in MINES$:
    - $e_m \in REE$ is the rare earth metal produced by that mine.
    - $v_m^0 \in \mathbb{R}_+$ is the initial volume of that material in that mine.
    - $\Delta v_m \in \mathbb{R}_+$ is the volume of that material mined at each time unit.
- For a rare earth metal $e \in REE$:
    - $\alpha_e \in (0,1)$ is the refinement rate for that material.
- For a factory $f \in FACTORIES$:
    - $f_w \subset WEAPONS$ is the subset of weapons that factory can produce.
    - $\forall w \in f_w$: $t_{f,w} \in \mathbb{N}_+$ is the number of time units required to produce a weapon w by factory f.
- For a weapon $w \in WEAPONS$:
    - $w_e \subset REE$ is the subset of rare earth elements required to produce that weapon.
    - $\forall e \in w_e$: $v_{w,e} \in \mathbb{R}_+$ is the required volume of that element to produce a single unit of the weapon.

- For a convoy $c \in CONVOYS$:
    - $s_c \in \mathbb{N}_+$: is the speed of the convoy.
    - $u_c \in \mathbb{R}$: is the capacity of the convoy.
    - $\ell_c \in LOC \cup \{\emptyset\}$: is the initial location of the convoy (can be null, so as to specify it be can anywhere in the world per our choosing).
    - $p_c \in \mathbb{R}$: is the counterfire strength of the convoy.
    - $d_c \in \mathbb{R}$: is the defense of the convoy
- For an enemy $a \in ENEMIES$:
    - $t_a \in H$: is the time unit at which the enemy attacks.
    - $r_a \in ROUTES$: is the route the enemy attacks.
    - $p_a \in \mathbb{R}$: is the strength of the enemy (see Section E.4).

c. Other Constants of Importance

- $\Delta LOAD$: is the maximal volume of a single rare earth element a convoy can load onto itself in a time unit.
- $\Delta UNLOAD$: is the maximal volume of a single rare earth element a convoy can **unload** from itself in a time unit.
- $DMG.MIN$: is the minimal **damage** per encounter (see Section E.4).
- DMG.MAX: is the maximal **damage** per encounter (see Section E.4).
- $DMG.REE$: is the volume of rare earth material lost to the sea by a single point of **damage** during an encounter.
- M_{ally}: is a constant (“Big M”) for tracking visits in allied locations.

- M_{idle}: is a constant ("Big M") for tracking factory idle times.

- M_{prod}: is a constant ("Big M") for tracking which factories produce which weapons.

d. *Decision Variables*

(1) Convoy Variables

- $\forall c \in CONVOYS, \ell \in LOC, t \in H: XL_{c,\ell,t} \in \{0,1\}$ indicates whether a convoy is at a location at that time unit.

- $\forall c \in CONVOYS, r \in ROUTES, t \in H, k \in LEG_{r,c}: XR_{c,r,k,t} \in \{0,1\}$ indicates whether a convoy is at the k^{th} leg of its journey at a route at that time unit.

- $\forall c \in CONVOYS, e \in REE, t \in H: Y_{c,e,t} \geq 0$ is the volume of a specific material carried by a convoy at that time unit.

- $\forall c \in CONVOYS, r \in ROUTES, t \in H: E_{c,r,t} \in \{0,1\}$ indicates whether a convoy is having an encounter on a route at that time unit.

- $\forall c \in CONVOYS, t \in H: D_{c,t} \geq 0$ is the damage sustained by a convoy at that time unit.

(2) Location Variables

- $\forall \ell \in LOC, e \in REE, c \in CONVOYS, t \in H: VM_{\ell,e,c,t} \in \mathbb{R}$ is the volume of a specific material *moved* from a location to a convoy at that time unit. Note that a positive quantity implies the convoy *loads* material from a location, a negative quantity implies the convoy *unloads* material from a location.

- $\forall \ell \in LOC, e \in REE, t \in H: V_{\ell,e,t} \in \mathbb{R}_{+}$ is the volume of a specific material at a certain location at that time unit.

(3) Factory Variables

- $\forall f \in FACTORIES, \forall e \in REE, \forall t \in H$: $VU_{f,e,t} \in \mathbb{R}_+$ is the volume of a specific material *consumed* for production at a factory at that time unit.
- $\forall f \in FACTORIES, \forall w \in WEAPONS, \forall t \in H$: $PS_{f,w,t} \in \mathbb{R}_+$ is the volume of a specific weapon whose production at a specific factory starts at that time unit.
- $\forall f \in FACTORIES, \forall w \in WEAPONS, \forall t \in H$: $PT_{f,w,t} \in \mathbb{R}_+$ is the total volume of a specific weapon produced by a specific factory by that time unit.
- $\forall f \in FACTORIES, , \forall t \in H$: $IDLE_{f,t} \in \{0,1\}$ indicates whether a specific factory is *idle* (not producing any weapons) at that time unit.
- $\forall f \in FACTORIES, \forall w \in WEAPONS$: $PW_{f,w} \in \{0,1\}$ indicates whether a specific factory is set to produce a specific weapon.

(4) Other Variables

- $\forall q \in AFF$: $VIS_q \in \{0,1\}$ indicates whether any convoy traveled through a location with the specified affiliation.

E. FORMULATION

The objective function which we maximized is defined as $\max \sum \mathrm{w_i MOP_i}$ with the following constraints:

1. Constraints for Convoy Movement

$\forall c \in CONVOYS, \ell_c \neq \emptyset: XL_{c,\ell_c,1} = \ell_c$
$\forall c \in CONVOYS\text{: } \sum_{\ell \in LOC} XL_{c,\ell,1} = 1$
$\forall c \in CONVOYS, t \in H\text{: } \sum_{\ell \in LOC} XL_{c,\ell,t} + \sum_{r \in ROUTES} \sum_{k \in LEG_{r,c}} XR_{c,r,k,t} = 1$
$\forall c \in CONVOYS, \ell \in LOC, t \in H \backslash \{T\}: XL_{c,\ell,t} \leq XL_{c,\ell,t+1} + \sum_{r \in SRC_\ell} \sum_{k \in LEG_{r,c}} XR_{c,r,k,t}$
$\forall c \in CONVOYS, r \in ROUTES, k, k+1 \in LEG_{r,c}, t \in H \backslash \{T\}: XR_{c,r,k,t} = XR_{c,r,k+1,t+1}$
$\forall c \in CONVOYS, r \in ROUTES, k_{r,c} \in LEG_{r,c}, t \in H \backslash \{T\}: XR_{c,r,k_{r,c},t} \leq XL_{c,dst_r,t+1}$

2. Constraints for Material Collection

$$\forall \ell \in LOC \backslash MINES, e \in REE: V_{\ell,e,1} = 0$$

$$\forall m \in MINES, e \in REE: V_{m,e,1} = v_m^0$$

$$\forall \ell \in LOC, t \in H: \sum_{e \in REE} V_{\ell,e,t} \le c_\ell$$

$$\forall c \in CONVOYS, t \in H: \sum_{e \in REE} Y_{c,e,t} \le u_\ell$$

$$\forall c \in CONVOYS, m \in MINES, e \in REE, e \neq e_m, t \in H: VM_{m,e,c,t} = 0$$

$$\forall c \in CONVOYS, m \in MINES, t \in H: VM_{m,e_m,c,t} \le \Delta LOAD \cdot XL_{c,m,t}$$

$$\forall c \in CONVOYS, f \in FACTORIES, e \in REE, t \in H: VM_{f,e,c,t} \le 0$$

$$\begin{aligned}&\forall c \in CONVOYS, \ell \in LOC \backslash (MINES \cup FACTORIES), e \in REE, t \in H: VM_{f,e,c,t} \\ &\qquad \le \Delta LOAD \cdot XL_{c,m,t}\end{aligned}$$

$$\forall c \in CONVOYS, m \in MINES, e \in REE, t \in H: VM_{m,e,c,t} \ge 0$$

$$\forall c \in CONVOYS, \ell \in LOC \backslash MINES, e \in REE, t \in H: VM_{f,e,c,t} \ge -\Delta \mathrm{UN}LOAD \cdot XL_{c,m,t}$$

$$\forall c \in CONVOYS, \ell \in LOC, e \in REE, t \in H: -VM_{\ell,e,c,t} \le Y_{c,e,t}$$

$$\begin{aligned}&\forall c \in CONVOYS, e \in REE, t \in H, t > 1: Y_{c,e,t} \\ &\qquad = Y_{c,e,t-1} - DMG.REE \cdot D_{c,t} + \sum_{\ell \in LOC} VM_{\ell,c,e,t}\end{aligned}$$

$$\begin{aligned}&\forall \ell \in LOC \backslash (MINES \cup FACTORIES), e \in REE, t \in H, t > 1: V_{\ell,e,t} \\ &\qquad = V_{\ell,e,t-1} - \sum_{c \in CONVOYS} VM_{\ell,c,e,t}\end{aligned}$$

$$\begin{aligned}&\forall m \in MINES, e \in REE, t \in H, t > 1: V_{m,e,t} \\ &\qquad = V_{m,e,t-1} - \sum_{c \in CONVOYS} VM_{m,c,e,t} + I(e = e_m)\Delta v_m\end{aligned}$$

$$\begin{aligned}&\forall f \in FACTORIES, e \in REE, t \in H, t > 1: V_{m,e,t} \\ &\qquad = V_{m,e,t-1} - \sum_{c \in CONVOYS} VM_{f,c,e,t} + (\frac{1}{\alpha_e})VU_{f,e,t}\end{aligned}$$

3. Constraints for Production

$$\forall f \in FACTORIES, e \in REE, t \in H: VU_{f,e,t} \le \alpha_e \cdot V_{f,e,t}$$

$$\forall f \in FACTORIES, t \in H: IDLE_{f,t} \ge 1 - \sum_{w \in WEAPONS} PS_{f,w,t}$$

$$\forall f \in FACTORIES, t \in H: M_{idle} \cdot IDLE_{f,t} \le M_{idle} - \sum_{w \in WEAPONS} PS_{f,w,t}$$

$$\forall f \in FACTORIES, w \in WEAPONS, t \in H: PS_{f,w,t} = 0$$

$$\forall f \in FACTORIES, w \in WEAPONS, t \in H: PT_{f,w,t} = 0$$

$$\forall f \in FACTORIES, w \in f_w, e \in w_e, t \in H: PS_{f,w,t} \le VU_{f,e,t}/v_{w,e}$$

$$\forall f \in FACTORIES, w \in f_w, t \in H \backslash \{T\}: PT_{f,w,t+1} = PT_{f,w,t} + I\big(t > t_{f,w}\big)PS_{f,w,t-t_{f,w}}$$

$$\forall f \in FACTORIES, w \in f_w\colon M_{prod} \cdot PW_{f,w} \geq \sum_{t \in H} PS_{f,w,t}$$

$$\forall f \in FACTORIES, w \in f_w\colon PW_{f,w} \leq \sum_{t \in H} PS_{f,w,t}$$

4. Combat Constraints

$$\forall c \in CONVOYS, r \in ROUTES, t \in H\colon E_{c,r,t} = I\left(\left(\sum_{\substack{a \in ENEMIES, \\ r_a = r, t_a = t}} 1\right) > 0\right) \sum_{k \in LEG_{r,c}} XR_{c,r,k,t}$$

$$\forall c \in CONVOYS, t \in H\colon D_{c,t} \geq \left(\frac{1}{d_c}\right) \cdot \left(\sum_{r \in ROUTES} \sum_{\substack{a \in ENEMIES \\ r_a = r, t_a = t}} p_a E_{c,r,t} - p_c\right)$$

$$\forall c \in CONVOYS, t \in H\colon D_{c,t} \geq DMG.MIN \cdot \left(\sum_{r \in ROUTES} E_{c,r,t}\right)$$

$$\forall c \in CONVOYS, t \in H\colon D_{c,t} \leq DMG.MAX \cdot \left(\sum_{r \in ROUTES} E_{c,r,t}\right)$$

5. Other Constraints

$$\forall q \in AFF\colon M_{ally} \cdot VIS_q \geq \sum_{c \in CONVOYS} \sum_{\ell \in LOC, q_\ell = q,} \sum_{t \in H} XL_{c,\ell,t}$$

$$\forall q \in AFF\colon VIS_q \leq \sum_{c \in CONVOYS} \sum_{\ell \in LOC, q_\ell = q,} \sum_{t \in H} XL_{c,\ell,t}$$

6. Production Process

To produce a weapon component, we define a production equation. The equation states the minimal volume of different materials required to produce a unit volume of a weapon component. Once a factory has enough material shipped by convoys, production can start. To account for the required refinement process, only a certain percentage of the material within the factory is usable for the sake of production. We also note that the time until production is completed is dependent on the specific technology and resources each factory has.

The production equation can be written explicitly using the previously presented notations (Figure 23):

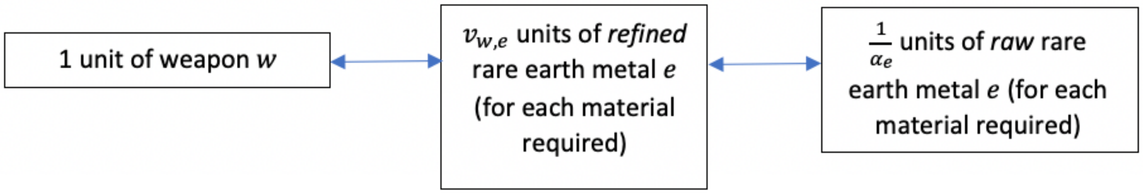


Figure 23. Production Equation

7. Damage to a Convoy During an Encounter

If a convoy $c \in \text{CONVOYS}$ encounters a set of enemies $\text{ENEMIES}_\text{c} \subset ENEMIES$, it sustains damage equal to:

$$\text{DMG}_\text{c} = \min\left\{\frac{\sum_{\text{a}\in\text{ENEMIES}_\text{c}} \text{p}_\text{a} - \text{p}_\text{c}}{\max\{\text{d}_\text{c}, \epsilon\}}, \text{DMG.MIN}\right\}$$

That is, we sum the total strength of all engaged enemies, subtract the convoy's counterfire strength, and then divide by the convoy's defense. Note that the expression $\min\{d_c, \epsilon\}$ ensures we do not divide by 0. The damage cannot be reduced below $DMG.MIN$.

For each point of damage, a fraction of each material carried by the damaged convoy is lost to the sea. That fraction is denoted by $DMG.REE$.

F. SIMULATION MODEL

The optimization model just described accounts for static data. However, when accounting for hazards such as the existence of enemies, we want to ensure our model can account for enemies of varying patterns of attack. To that end, we wrap our optimization model with a simulation-oriented approach: we randomly generate information about enemies, according to a simple model described in the following paragraphs, and then feed the results into our optimization model.

1. Enemy Metamodel

Note that we have already described the information required to generate enemies:

- $t_a \in H$: is the time unit at which the enemy attacks.

- $r_a \in ROUTES$: is the route the enemy attacks.
- $p_a \in \mathbb{R}$: is the **strength** of the enemy.

While t_a and r_a are problem data, to generate p_a we use the following technique: every simulation run, for each t_a, r_a at which an enemy should appear, we let N_a be the number of enemies to potentially attack the route at that time and P_a the probability that each independent enemy appears during that attack. N_a and P_a embed some information about any intelligence reports or wargaming analysis we may have when trying to predict enemy attacks. Observe that the actual number of enemies to appear is binomially distributed with parameters N_a and P_a. The strength of the group of enemies p_a is the sum of all enemies that appear.

2. Design of Experiment

Each run of the simulation defines a set of parameters for each group of enemies that (potentially) appear during the time horizon. This set includes t_a, r_a, N_a, P_a and the individual strength of each enemy (denoted here by $p_a{}'$). For n locations with $O(n^2)$ routes, the number of parameters is defined as $O(Tn^2)$.

We relax the requirement for full coverage of the design space by creating a designated set of routes $ROUTES.VULNERABLE \subset ROUTES$, such that the only routes at which enemies can appear must be routes from $ROUTES.VULNERABLE$. Therefore, each run of simulations requires only the four parameters shown in Table 5.

Table 5. Adversary Parameter Space for Experimentation

Parameter	Type	Range
$\boldsymbol{t_a}$	Integer	$H = \{1,2,\dots,T\}$ (time horizon)
$\boldsymbol{N_a}$	Integer	$[0, 10]$
$\boldsymbol{P_a}$	Continuous	[0,1] (probability)
$\boldsymbol{p_a{}'}$	Continuous	[1,10]

As the table suggests, the design space for each route in $ROUTES.VULNERABLE$ is still extremely large. To address this limitation, we use an NOLH (nearly orthogonal linear hypercubes) design with 113 sample points in this space, rounding down the values for t_a and N_a.

G. ALTERNATIVE DESIGN USING THE MODEL

This section discusses how one can use the model to design alternatives. We describe the specific details for each alternative in the context of our examined scenarios.

1. Fleet Design

An important aspect of alternative design using the model is the fleet design, specifically the composition and characteristics of convoys. As already explained, we can control how many convoys we have, how fast they move, what their capacity is and even their combat capabilities. However, these are not decision variables but rather input parameters that reflect a decision made by decision makers when designing the system.

2. Location Design

The second aspect of alternative design is location design. This aspect has to do with both the choices of where to extract material from as well as which factories should produce components from the extracted material. Location design entails the potential to explore both existing locations (mines) but also locations that do not necessarily exist yet (such as factories that could be established by the year 2030). In this work, we attempt to keep exact factory locations abstract and not address any specific factories in existence.

H. EXAMINED SCENARIO

The scenario we examined using the model takes place in a limited time horizon in which the United States and its allies must maximize production in accordance with the MOPs while being targeted by attacks along routes crossing the Indian Ocean and the Pacific. We specifically explore the production of stabilization magnets from Neodymium, a rare earth metal.

This scenario entails exploration of three core alternatives with three variants.

1. Alternative 1: Produce Locally

In this alternative, production of components is limited to within CONUS.

2. Alternative 2: Produce Remotely

In this alternative, production of components is limited to outside CONUS only.

3. Alternative 3: Produce "Near Me"

In this alternative, production is not limited geographically, but rather optimized according to the MOPs directly.

As mentioned, these alternatives focus on Location Design. We have three variants for each alternative that focus on Fleet Design. The variants use either small-and-fast convoys, medium-and-fast convoys, or large-and-slow convoys.

The model was also optimized on two specific areas, namely, material collection and component production. For material collection, there was no specific designation per alternative/variant and the model was programmed to choose the best source based on the problem parameters. Meanwhile, the component production was alternative-dependent as different regions have different production procedures and regulations, which translates into different production times.

I. DATA AND ASSUMPTIONS

While most of the data used in this model is based on our literature review, there are gaps in the model data requirements.

Figure 24 depicts the overview of the input data used for the model. The input data used in the model were unclassified information and can be obtained from open sources. Due to the limited information available in open sources, some assumptions had to be made for the model to run and make the necessary analysis. The input data can be classified into four broad categories: (1) mines, (2) factories, (3) convoys, and (4) distances between location nodes.

Figure 24. Overview of Input Data

In addition to this, Tables 6 through 8 summarize the data used for the mines, convoys, and distances between nodes in the model.

Table 6. Mine Data

Name	Capacity (MT)	Volume Per Time
California (Mountain Pass)	100000	216.67
India	100000	25
Myanmar	100000	183.333
Australia (Mount Weld)	100000	175

Table 7. Convoy Data

Name	Type	Speed (Normalized)	Capacity (MT)	Defense (Normalized)
Small Container	Sea	3	500	10
Medium Container	Sea	2	6000	20
Large Container	Sea	2	30000	20

Table 8. Distances between Location Nodes

Source	Destination	Distance (mi)
California (Mountain Pass)	Texas	1500
California (Mountain Pass)	Virginia	2500
California (Mountain Pass)	Australia (Melbourne)	8400
California (Mountain Pass)	Myanmar	12000
California (Mountain Pass)	India	13000
California (San Francisco)	Texas	1500
California (San Francisco)	Virginia	2500
California (San Francisco)	Australia (Melbourne)	8400
California (San Francisco)	Myanmar	12000
California (San Francisco)	India	13000
California (San Francisco)	California (Mountain Pass)	1500
Texas	Virginia	1500
Virginia	Europe	4400
Europe	Texas	6000
Europe	California (Mountain Pass)	8000
Europe	California (San Francisco)	8000
Europe	India	7700
Europe	Myanmar	8000
Australia (Mount Weld)	India	3000
Australia (Mount Weld)	Myanmar	4500
Australia (Melbourne)	India	3000
Australia (Melbourne)	Myanmar	4500
Australia (Mount Weld)	Australia (Melbourne)	1500
South America	Australia (Melbourne)	8000

In addition to these data points, we made the following modeling assumptions.

- Distances between any two points in the ‘model’ world are normalized such that 1-time unit is equivalent to three days at most.

- Time horizon used in the model optimizes over 15-time units (equivalent to a 45-day period).
- For the REE mines, the rate of REE refinement for each mine used in the model is 0.06.
- Approximately 5.37 units of permanent magnets for weapon systems can be produced per mton of REE material (Neodymium).

J. ALTERNATIVE DESIGNS

For the first alternative design, Produce Locally, the system focused on producing components only within CONUS, as shown in Figure 25. In this alternative design, the only possible factories are those within CONUS, with one on the east coast and one on the west coast. The material (neodymium) can be collected from Australia, India, or California.

Figure 25. Alternative 1: Produce Locally

For the second alternative design shown in Figure 26, Produce Remotely, the system focused on producing components only outside CONUS, exploiting the potential proximity of non-U.S. mines to factories, and the possibility to reduce costs. In this alternative design, the selected factories are outside CONUS, potentially either in Australia or in Europe while the material (neodymium) can be collected from Australia, India, or California.

Figure 26. Alternative 2: Produce Remotely

For the third alternative design shown in Figure 27, Produce "Near Me," the system is not necessarily bounded by any geographical location. It is the most extreme case, where components (before being shipped to front bases) are potentially scattered across several locations, both CONUS and non-CONUS. In this alternative design, all options are available, and the material (neodymium) can be collected from Australia, India, or California.

Figure 27. Alternative 3: Produce "Near Me"

The simulation was run by exploring a specific scenario that includes adversarial attempts. Several simulation runs were conducted with different input parameters, to explore the variability of each alternative and variant, as well as the effect of the choice of specific convoys has on the metal delivery process.

V. ANALYSIS AND RESULTS

This chapter discusses the implementation of the scenario from the previous chapter and analyzes the results of that implementation. Whereas in the previous chapter we discussed alternatives and input data, here we describe how to incorporate the system engineering process and the MOPs defined by that process into our model. We then highlight key insights and outputs resulting from running the model on our examined scenario.

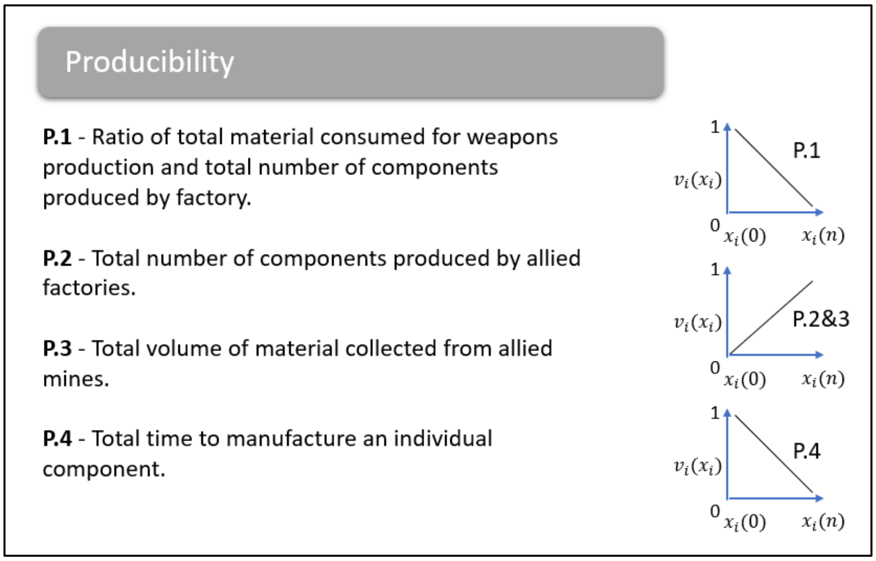
A. MEASURE OF PERFORMANCE ANALYSIS

The system engineering process has defined 14 MOPs to maximize or minimize for our examined scenario. In this section, we describe how we integrate these MOPs into our scenario modeling and analysis. We begin by discussing the associated system engineering process that transforms the MOPs for our scenario into scalars (weights) provided to our optimization model.

1. Value Functions

The value functions facilitate the conversion of raw candidate scores or data into normalized utility scores before applying a global swing weight approach for building an aggregate value score for each alterative. For instance, in the case of P.2 (total number of components produced by allied countries), among the three alternatives we find that the total number of components varies from 0 to 17. The first step is to bound the x-axis of the value curve in question based on the minimum number of components that would yield no value. Next, the analyst would fit the appropriate line or curve (in this case a negative linear function) to the assessed value. Then, one can interpolate the relative value of each alternative by finding the utility score as a function of the fitted line or curve. The result is three normalized value scores capable of comparing the candidate solutions. Lastly, the sum product of the value scores and their respective global swing weights captures the total comparable utility of each candidate solution.

For the producibility COI, three simple linear relationships exist between the raw scores and their associated utility. For P.1 (refer to Figure 28 for definition) there is an inverse relationship between the rate and its value since lower is better considering that the metric essentially describes the efficiency of productivity. For P.2 and P.3 the opposite is true; the total number of components produced, and total volume of material collected follows a positive linear trend since more is better. Finally, the time to manufacture an individual component (P.4) exhibits a negative relationship.



Producibility

P.1 - Ratio of total material consumed for weapons production and total number of components produced by factory.

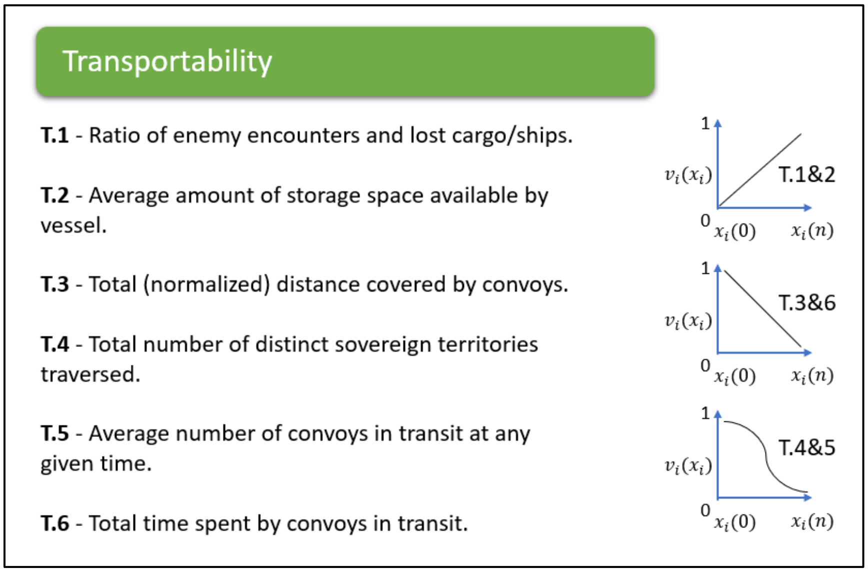
P.2 - Total number of components produced by allied factories.

P.3 - Total volume of material collected from allied mines.

P.4 - Total time to manufacture an individual component.

Figure 28. Measures of Effectiveness/Performance Value Curves for Producibility COI

For the transportability COI, the first two measures assume a positive linear relationship between the raw scores and utility, considering that the desire is to maximize survivability (which is what T.1 attempts to capture by creating a rate between enemy encounters and lost cargo) and maximize the amount of storage space per vessel. Alternatively, T.3 and T.6 follow a negative linear relationship since more distance covered and more time spent traveling equate to increased risk. Lastly, the T.4 and T.5 value measures follow a negative s-curve shape since they are influenced by a threshold of tolerance. For example, the number of sovereign territories traversed is tolerable to the extent of our ability to coordinate with allied nations. The same is true regarding the total number of convoys at any given time based on the nation’s capacity to defend multiple convoys. As result, the consequences of exceeding capacity become dramatically worse as values increase, hence the dramatic decrease in value towards the latter portion of the curve. These relationships are shown in Figure 29.



Transportability

T.1 - Ratio of enemy encounters and lost cargo/ships.

T.2 - Average amount of storage space available by vessel.

T.3 - Total (normalized) distance covered by convoys.

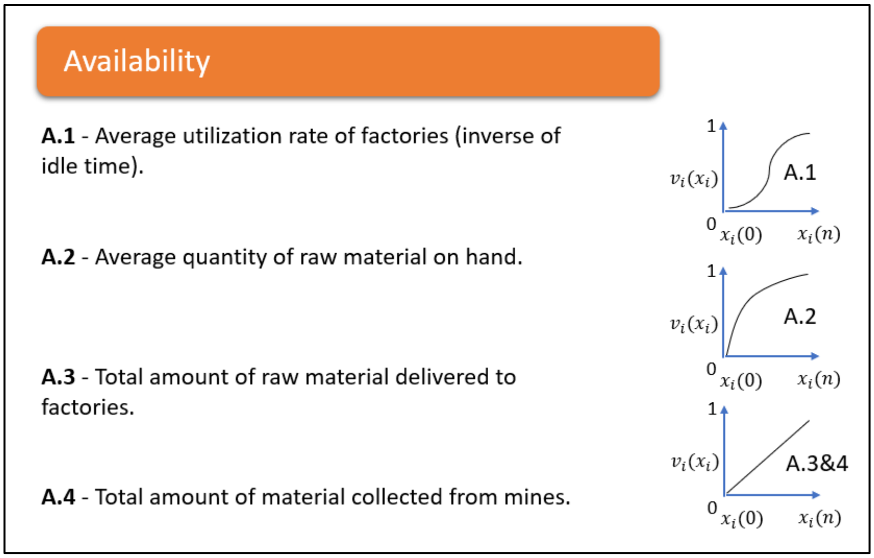
T.4 - Total number of distinct sovereign territories traversed.

T.5 - Average number of convoys in transit at any given time.

T.6 - Total time spent by convoys in transit.

Figure 29. Measure of Effectiveness/Performance Value Curves for Producibility COI

For the availability COI, a positive s-curve applies for A.1 since this measure effectively represents a factory’s utilization rate. The s-curve relationship penalizes underutilized factories while rewarding those that reach their optimal performance level before a dramatically decreasing value as factories approach their maximum utilization rates. The premise is that factories tend to experience catastrophic failures and worker fatigue at maximum capacity, but also experience extreme inefficiency at low utilization rates. The A.2 MOP, however, measures the average quantity of material on hand. This essentially represents the cached material that is readily available. In this case, the value experiences diminishing marginal returns indicative of the concave value curve seen on the middle-right side of Figure 30. In theory, the value of having additional material on-hand diminishes as the cost of storage rises. Lastly, the final two metrics (A.3 and A.4) follow a positive linear trend since more is better regarding raw materials delivered and collected.



Availability

A.1 - Average utilization rate of factories (inverse of idle time).

A.2 - Average quantity of raw material on hand.

A.3 - Total amount of raw material delivered to factories.

A.4 - Total amount of material collected from mines.

Figure 30. Measures of Effectiveness/Performance Value Curves for Availability COI

2. Global Swing Weights

In a parallel effort, this study developed swing weights based on the prioritization of MOPs and the variability within their raw scores. Of note, each preceding value measure outranks the following based on the stakeholder's analysis and expert opinion. By ranking the MOPs and measuring the variability within each measure, this research applied a multi-objective decision analysis technique known as the "swing weight matrix" (Parnell and Trainor 2009) as an objective approach to assessing each alternative's overall utility. Before constructing the matrix, however, this study measured the variability within the raw data using coefficients of variation (CV). Figure 31 illustrates the formula for calculating CV values and the corresponding criteria for categorizing the variability.

$$CV = \frac{StDev_{MOP}}{Mean_{MOP}}$$

$$Where:$$

$$CV \leq 0.33 \rightarrow LowVariation$$

$$0.33 < CV \leq 0.66 \rightarrow MediumVariation$$

$$CV > 0.66 \rightarrow HighVariation$$

Figure 31. Coefficient of Variance Calculation

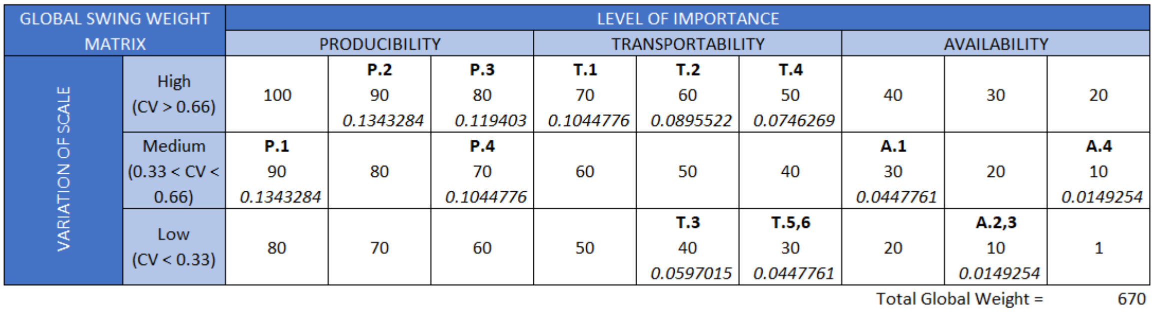
Table 9 shows the results of the CV analysis.

Table 9. Level of Variation by Measure of Performance

MOP	CV	Variation
P.1	33%	L
P.2	78%	H
P.3	77%	H
P.4	65%	M
T.1	187%	H
T.2	109%	H
T.3	14%	L
T.4	82%	H
T.5	8%	L
T.6	8%	L
A.1	46%	M
A.2	17%	L
A.3	29%	L
A.4	33%	L

To construct the global swing weight matrix, this research placed each MOP within the matrix based on its level of importance (across the top of Figure 32) and variation of scale (down the left side of Figure 32). Each block within the matrix carries a specified weight between 1 and 100 that decreases in value from top-left to bottom-right. In doing so, a measure can only achieve the highest weight if it is most important to the stakeholders and contains high variation within the MOP data. Greater variation equates to increased value based on the MOPs ability to better differentiate between alternatives (Parnell and

Trainor 2009). Figure 32 displays the complete matrix overlaid with the MOPs. Each individual box includes (from top to bottom) the MOP (bold text), individual weight (standard text), and normalized global swing weight (italicized text).



GLOBAL SWING WEIGHT MATRIX		LEVEL OF IMPORTANCE								
		PRODUCIBILITY			TRANSPORTABILITY			AVAILABILITY		
VARIATION OF SCALE	High (CV > 0.66)	100	**P.2** 90 *0.1343284*	**P.3** 80 *0.119403*	**T.1** 70 *0.1044776*	**T.2** 60 *0.0895522*	**T.4** 50 *0.0746269*	40	30	20
	Medium (0.33 < CV < 0.66)	**P.1** 90 *0.1343284*	80	**P.4** 70 *0.1044776*	60	50	40	**A.1** 30 *0.0447761*	20	**A.4** 10 *0.0149254*
	Low (CV < 0.33)	80	70	60	50	**T.3** 40 *0.0597015*	**T.5,6** 30 *0.0447761*	20	**A.2,3** 10 *0.0149254*	1

Total Global Weight = 670

Figure 32. Global Swing Weight Matrix. Adapted from Parnell and Trainor (2009).

Finally, the raw metrics from the modeling results can filter through the value functions before applying the global swing weights to determine each alternative's total utility. However, this study then returns to the modeling process to optimize results using the newly minted global swing weights.

3. Measure of Performance Weights for Optimization

The final weights are shown in Table 10.

Table 10. Optimization Model Swing Weigh Values

MOP	S/N	MOP	Swing Weights
Producibility	P.1	Ratio of total material consumed for weapons production and total number of components produced by factory	0.1343
	P.2	Total number of components produced by allied factories	0.1343
	P.3	Total volume of material collected from allied mines	0.1194
	P.4	Total time to manufacture an individual component	0.1045
Transportability	T.1	Ratio of enemy encounters and lost cargo/ships	0.1045
	T.2	Average amount of storage space available by vessel	0.0896
	T.3	Total (normalized) distance covered by convoys	0.0597
	T.4	Total number of distinct sovereign territories traversed	0.0746
	T.5	Average number of convoys in transit at any given time	0.0448
	T.6	Total time spent by convoys in transit	0.0448
Availability	A.1	Average utilization rate of factories (inverse of idle time)	0.0448
	A.2	Average quantity of raw material on hand	0.0149
	A.3	Total amount of raw material delivered to factories	0.0149
	A.4	Total amount of material collected from mines	0.0149
		Total:	1

These weights become the input to our optimization model described in the previous chapter. We note that for MOPs, with adjustment of sign (multiplied by -1) for MOPs with a decreasing or generally decreasing value function. We should also note that a ratio of functions $f(x)/g(x)$ will be maximized by our optimization scheme, in this case by maximizing the approximate value $f(x) - g(x)$.

B. SCENARIO RESULTS

This section discusses the total objective and the specific measure of performance results gathered from execution of the model.

1. Total Objective Results

The graphic in Figure 33 shows the normalized objective values separated by alternative and location of production. As evidenced by Figure 33, when components are Produced Remotely and "Near Me" they tend to perform best and are almost identical when using both medium and large convoys. The Produce Locally alternative performs the worst for all convoy variants emphasizing that, when possible, production overseas is best. Another key insight detailed by these results is that when shipping is done in small quantities, the production of weapons components will be hindered, yielding a component reduction of ~50% or more across all alternatives. Furthermore, this graph implies that load capacity is a superior characteristic in determining the efficiency of the shipping method.

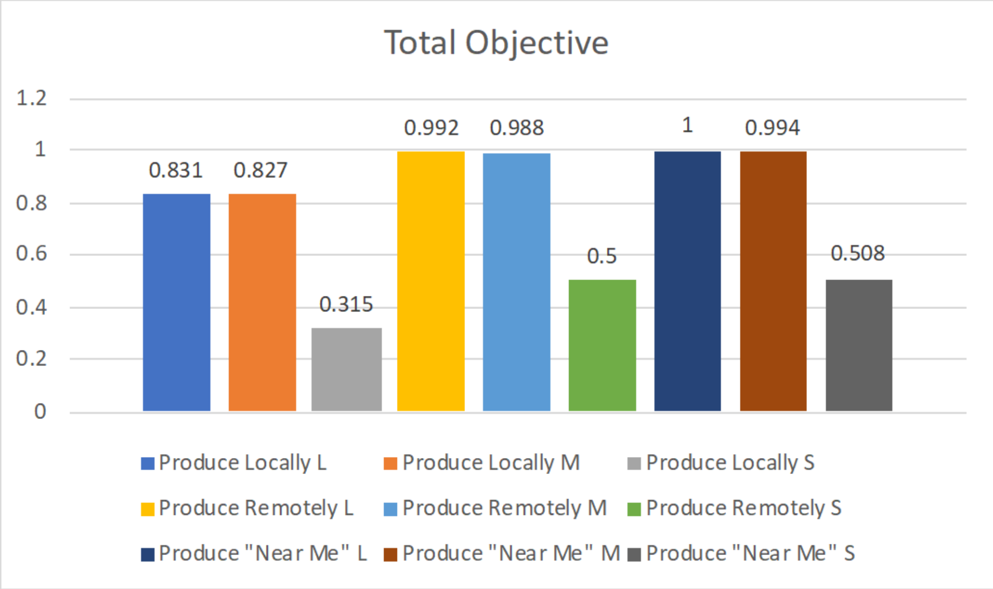
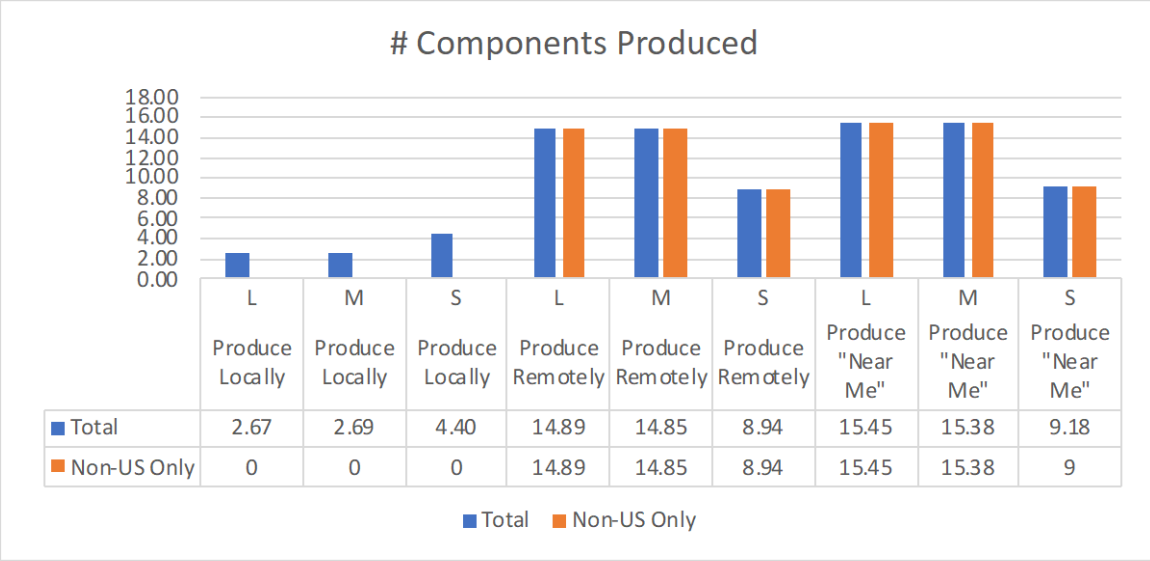


Figure 33. Normalized Objective Values by Alternative and Location of Production

Figure 33 represents an optimized solution for a 45-day period; however, projecting these same conditions over longer periods may yield a different solution. Objectively, it makes sense to manufacture the parts outside of the United States, but this output does not consider losses that could be associated with transporting the final weapon component (i.e., magnets) to the weapon system in what is referred to as the "last mile."

2. Specific Measure of Performance Results

We have noticed that the planner optimizes the production of components in accordance with the volume ratio between Neodymium and a singular stabilization magnet. Therefore, all alternatives yield the same production-consumption ratio. On the other hand, we can see differences in the raw number of components produced, shown in Figure 34.



	L Produce Locally	M Produce Locally	S Produce Locally	L Produce Remotely	M Produce Remotely	S Produce Remotely	L Produce "Near Me"	M Produce "Near Me"	S Produce "Near Me"
🟦 Total	2.67	2.69	4.40	14.89	14.85	8.94	15.45	15.38	9.18
🟧 Non-US Only	0	0	0	14.89	14.85	8.94	15.45	15.38	9

Figure 34. Raw Number of Components Produced

Weapon production is a function of the REE being refined and then manufactured into a usable component, i.e., magnets or actuators. Figure 34 indicates that the most efficient way of producing weapon components is by using medium container ships to transport raw REEs from mines located overseas. Additionally, another key insight is that using small but fast convoys is only viable when producing components locally, most likely attributed to the reduction in distance between mine and component manufacturing facility. Finally, the difference between the production of components using medium and large containers is negligible, meaning that either method would provide adequate component production.

We can also see that for the Produce Locally, the volume of material collected at non-U.S. mines is the lowest, with only 85% collected from non-U.S. mines. Other alternatives collect almost exclusively from non-U.S. mines. Figure 35 shows that Producing "Near Me" with large containers ships causes the greatest dependence on REE materials from foreign countries, with the use of medium ships just behind. Dependence on materials from foreign countries is a function of where the materials are taken to be produced. Interestingly, for Produce Locally, when using small ships, the percentage of material collected from foreign countries jumps by 10%, which brings it close to the same dependence as all other options.

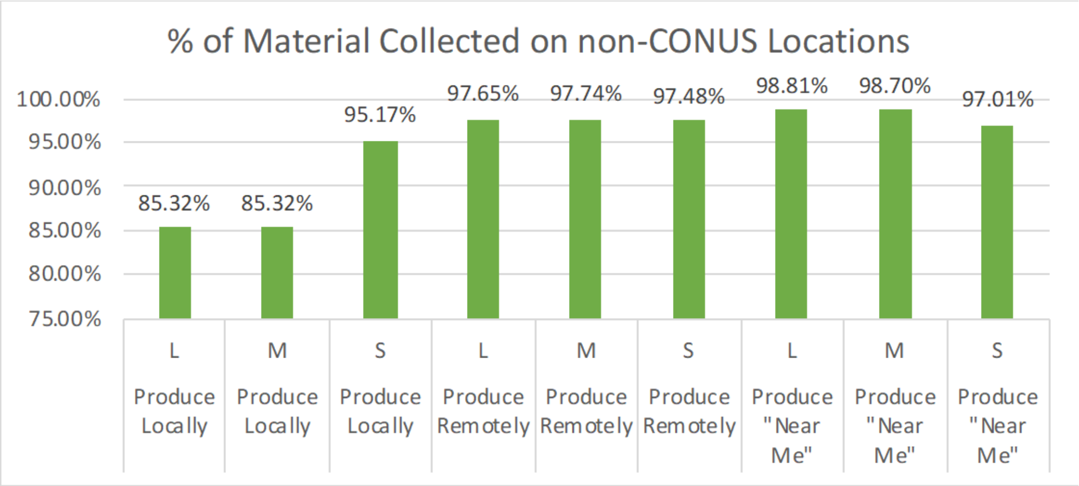


Figure 35. Volume of Material Collected in non-CONUS Locations

In terms of robustness to adversarial attacks, as shown in Figure 36, Produce Remotely is the most varied and most vulnerable option. This can be attributed to the increased distance required to transport materials to the production facilities. Production by allied forces is a viable solution to manage the resistance of potential threats. As mentioned in Chapter II (Section D.1), having a diverse supply chain network can greatly help mitigate supply chain choke points, should a conflict ensue. Insomuch, when allied forces are responsible for manufacturing weapon components there is also an increase in the potential material loses (see Figure 36).

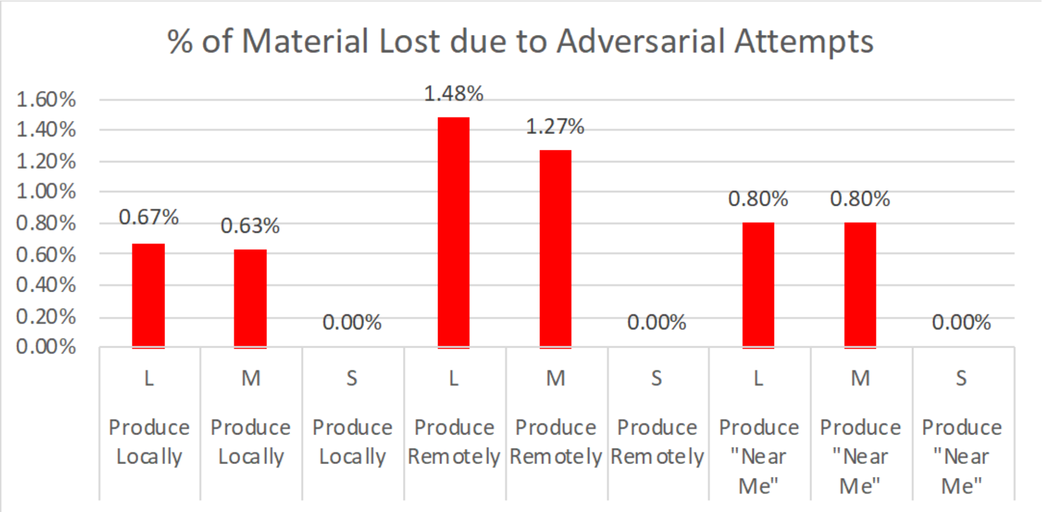


Figure 36. Material Lost to Adversarial Attempts

As expected, Produce Locally requires the least amount of time spent by convoys in transit (that is, time not spent in loading or unloading material). Due to capacity limits, we see that for the most part the small convoy variants spend less time than other variants in transit. As can be seen in Figure 37, Produce Remotely and Produce “Near Me” produce very similar results, with Produce Remotely having just slightly less time in transit. Transit time for Produce Locally did not depend on the size of container ship used as they were all about the same. When using either the Produce Remotely or Produce “Near Me” alternatives, the use of a large or medium ship significantly increased the average amount of time spent in transit.

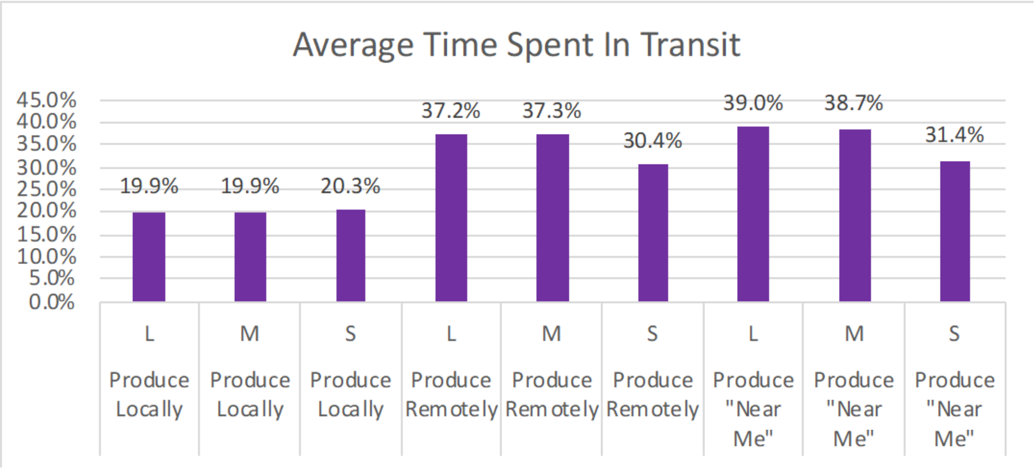


Figure 37. Average Time Spent in Transit

The utilization rate was maximized in the Produce Remotely scenario with either large, slow convoys or medium, fast convoys. Producing remotely allowed mined materials to be shipped to factories closer to the point of origin. The steady stream of materials allowed the factories to produce on a more regular schedule than any of the other scenarios. In any given alternative shown in Figure 38, the small, fast convoys minimized the utilization rate while large and medium sized convoys had nearly equal utilization rates for each alternative. This indicates that small, fast convoys are not able to match the rate at which factories can turn the raw materials into weapons. Small, fast convoys create a bottleneck in all three alternatives.

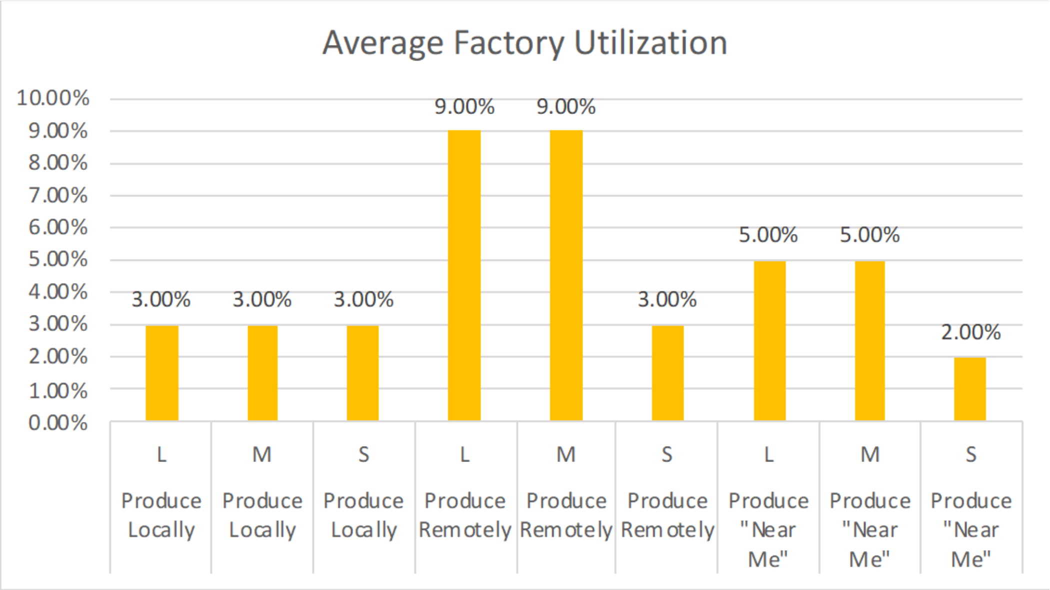


Figure 38. Average Factory Utilization

C. CONCLUSION AND RECOMMENDATION FOR FUTURE WORK

In this work, we addressed the issues of designing a supply chain in a contested environment when focused on "metal delivery". Our approach to this problem was to tackle the processes required to produce weapon components necessary to maintain long-term combat. We have identified key processes, such as the mining of rare earth metals, refinement of material, transportation of material through various locations of interest, and finally, production of components through means of transforming the material into a usable object.

Our work showed there are inherit challenges in a system designed to address the problem statement. Some of these challenges are physical in nature such as the precise geographical locations at which some rare earth metals are available or the time required to produce a component. Other challenges stem from adversarial effects of attempts to hinder our efforts. The large scale of operation across time, space, and alternative spaces add to the complexities we encountered.

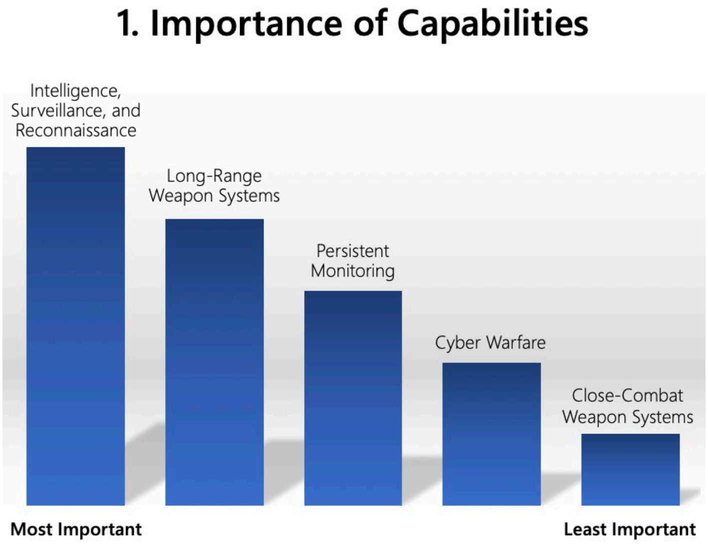
In particular, we focused our attention on a scenario in which the system operates within a 45-day window immediately and without prior warning, while being contested along the Pacific and Indian Oceans, limiting the operability of our convoys to move westward from the United States into Asia. This scenario is both relevant and captures many of the challenges and elements we identified as vital to create a robust supply chain. We used a Design-of-Experiment approach combined with large-scale optimization methods to model and analyze this scenario.

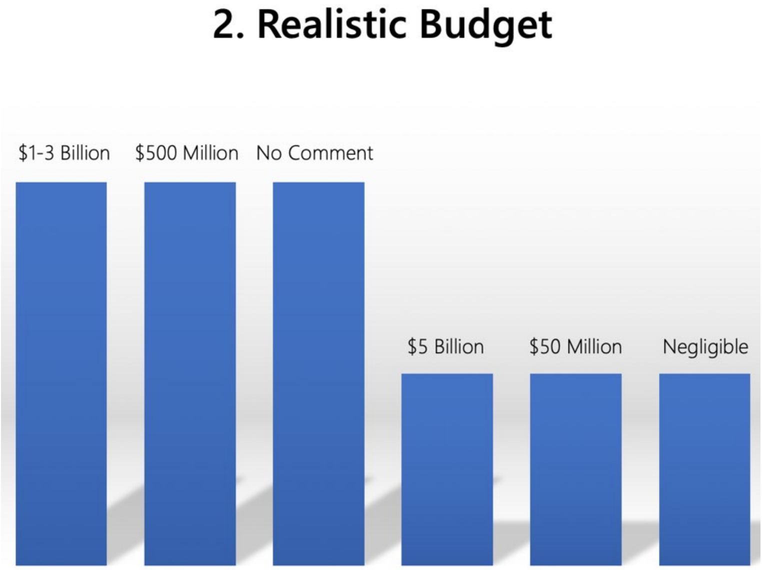
Our results show that allowing the production process to take place near the mining process alongside a sufficiently large convoy to carry material from location-to-location lead to the best results. We called this alternative Produce "Near Me" because, from the perspective of the convoy, it reflects the convoy's intent to carry collected material across the best (shortest and safest) route possible, without concerning for geopolitical constraints, such as having to produce components outside the United States.

We observed that there are some subtle differences between using an M convoy – speedy and sufficiently large in capacity – and an L convoy – slowest but largest in capacity. We deem both of these convoy designs as suitable, while noting that external factors we did not examine, such as equipment cost and maintenance, may alter our analysis. We also wish to note that for time period longer than 45 days, the increased speed of the M convoy may prove useful.

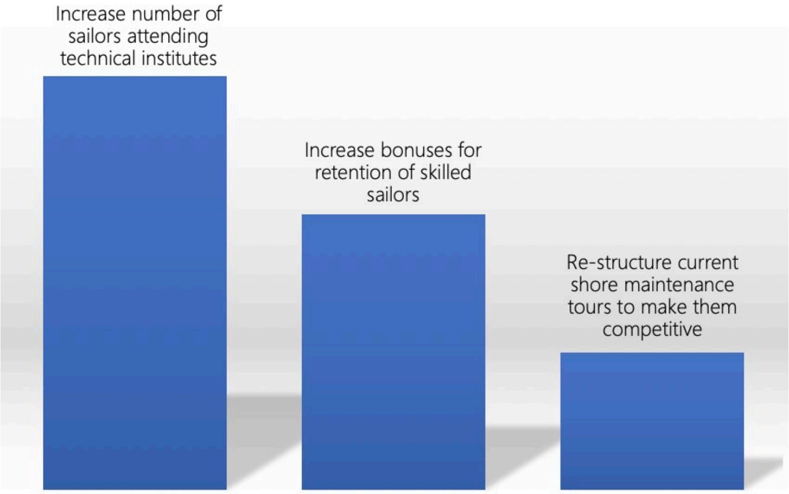
Our process was limited by the availability of data, and we highly recommend that more precise and often classified data will be employed in our designed model moving forward. We also note that exploration of more complex fleet designs and smaller and/or larger time periods may shed more light about the performance of the proposed alternatives.

APPENDIX A. STAKEHOLDER RESPONSES

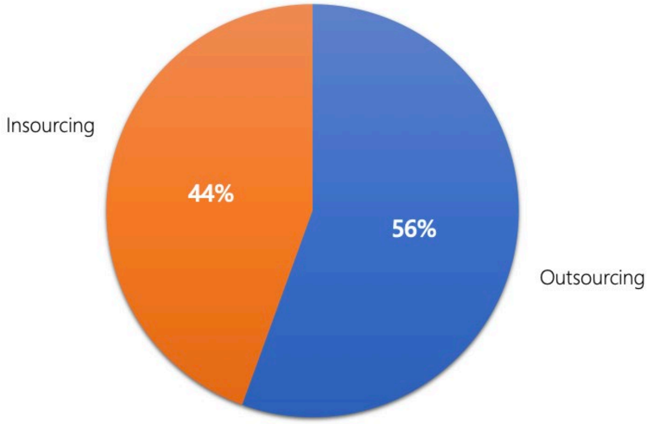




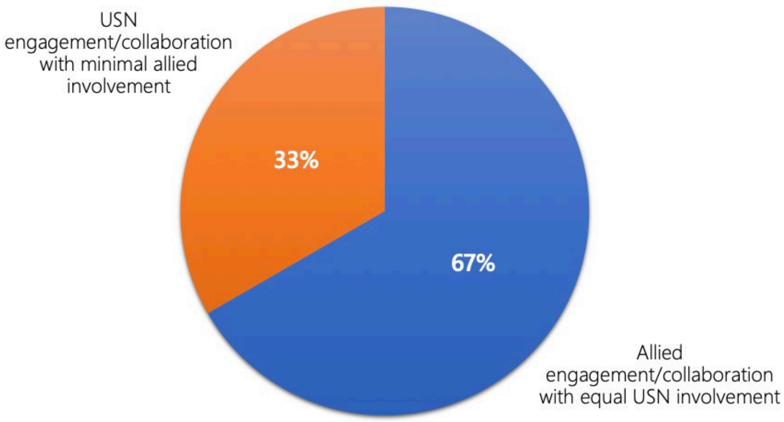
3. How to Incentivize Skilled Workforce



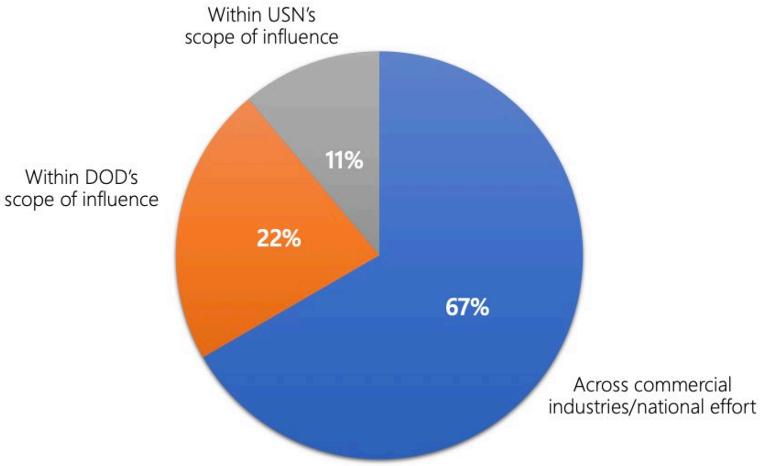
4. Preference in Sourcing Maintenance



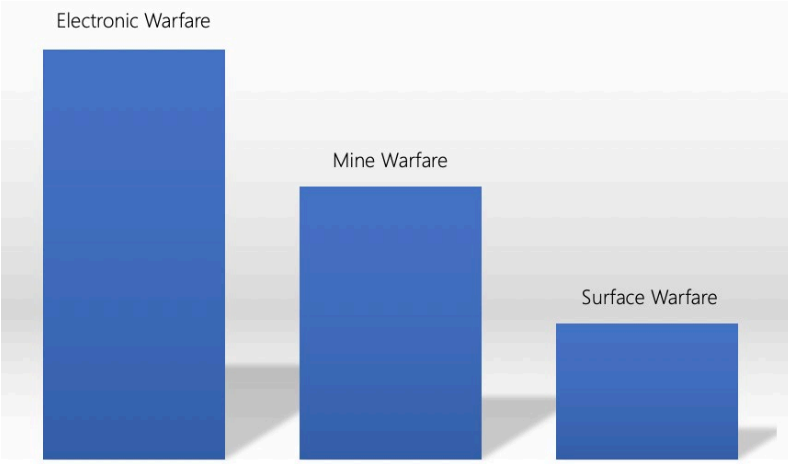
5. Role of Regional Allies and Partners



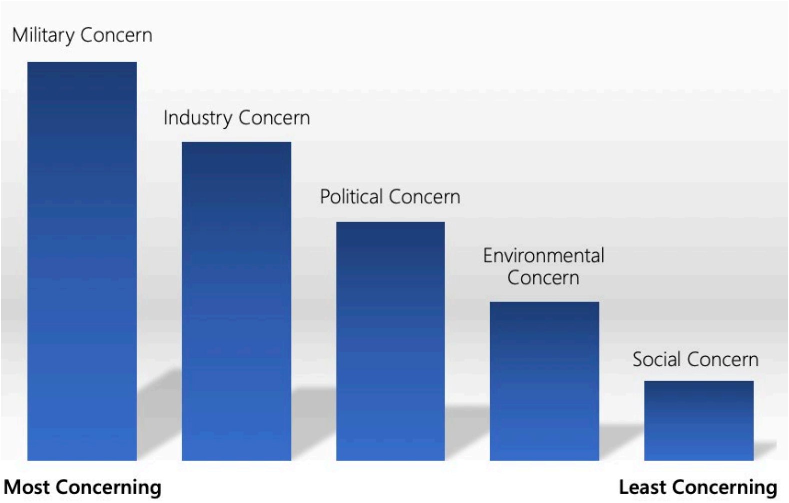
6. Focus of Sensitivity Analysis



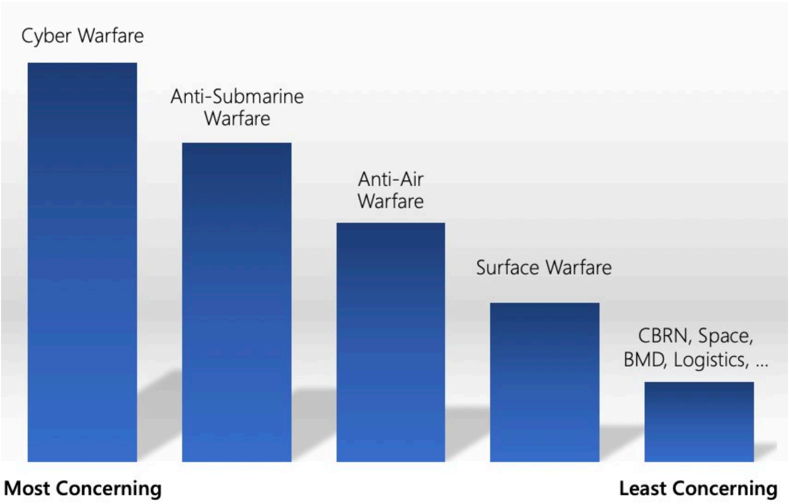
7. Best Areas for Unmanned Systems



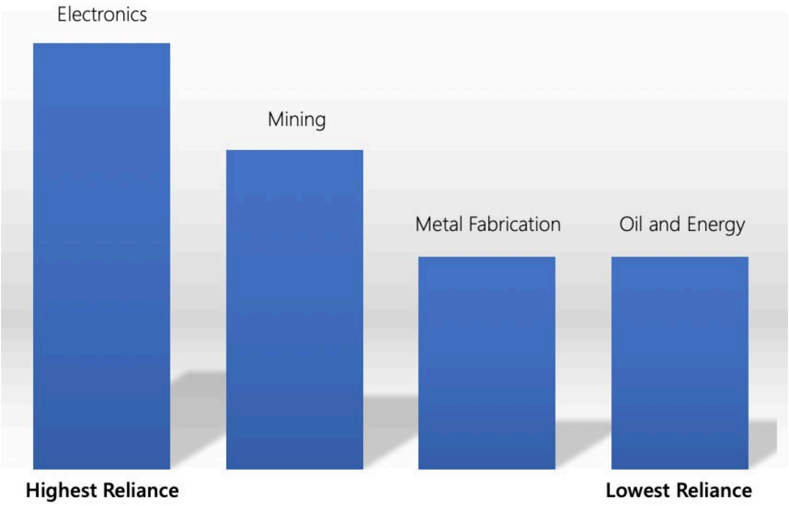
8. Impact of Adversary's Control of REEs



9. USN's Areas of Concern by 2035



10. Sector Reliance on Foreign Companies



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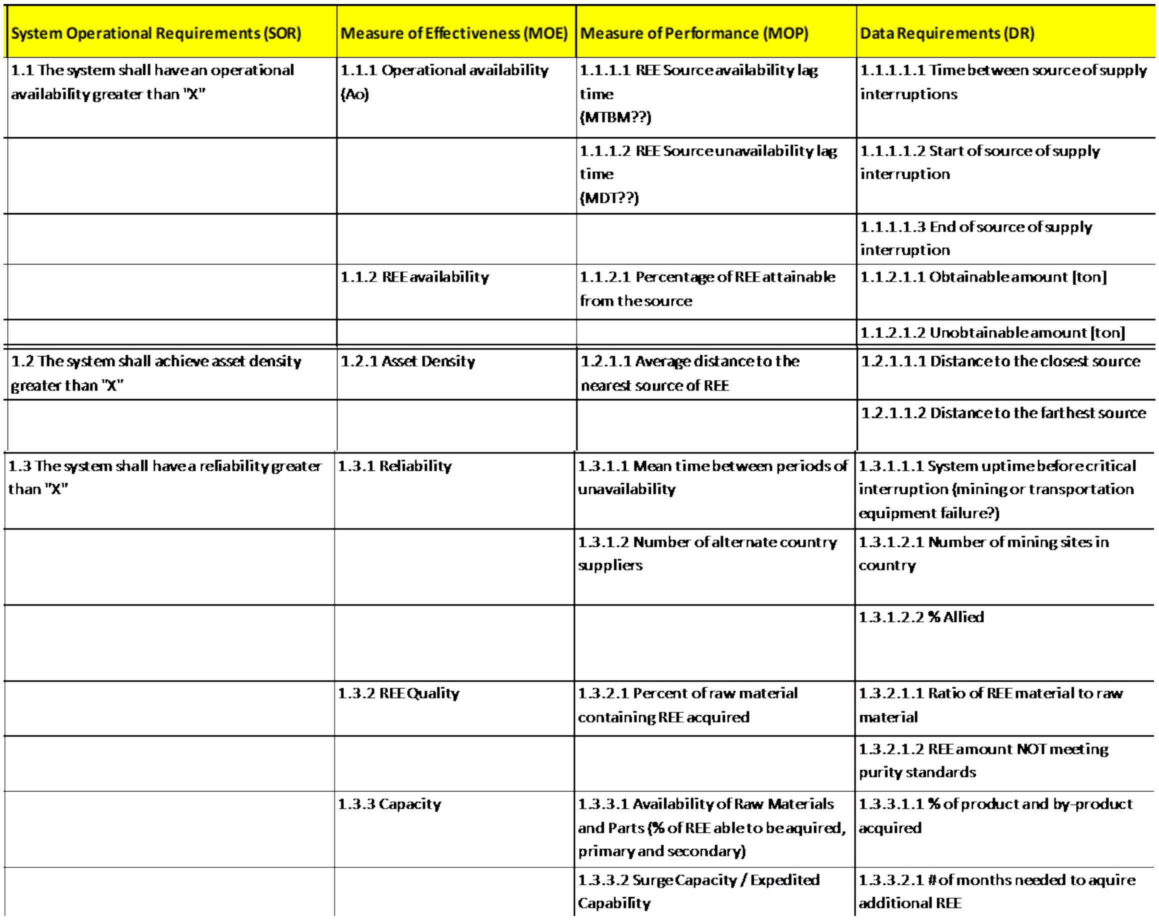
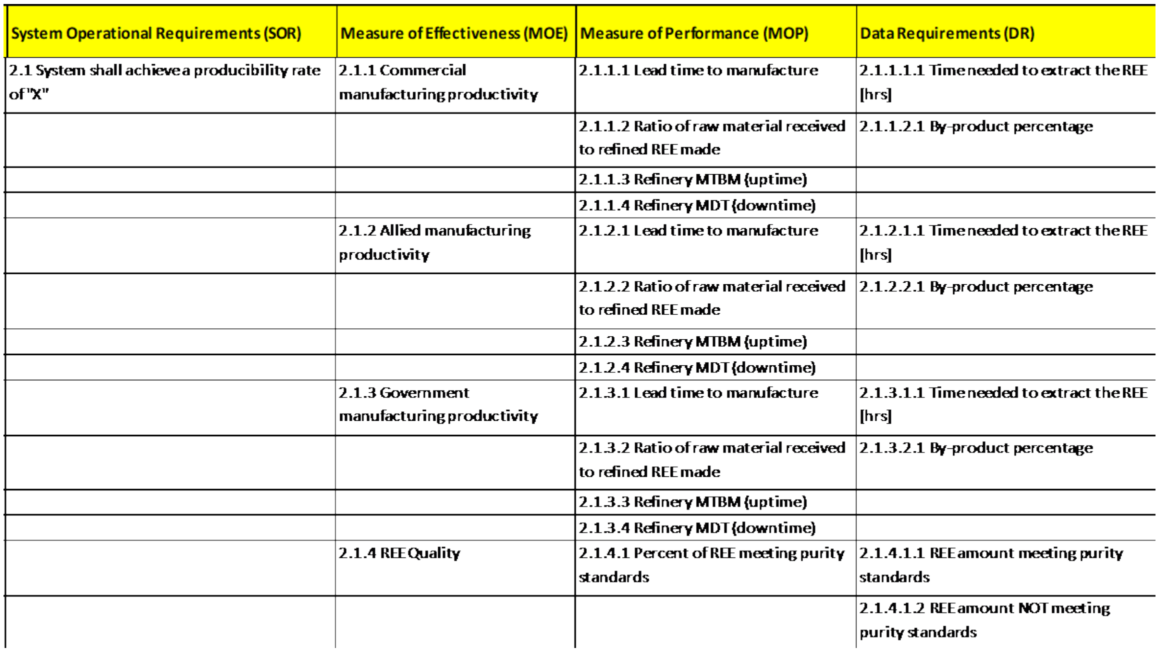
APPENDIX B. MEASURES OF EFFECTIVENESS AND PERFORMANCE

A. AVAILABILITY



System Operational Requirements (SOR)	Measure of Effectiveness (MOE)	Measure of Performance (MOP)	Data Requirements (DR)
1.1 The system shall have an operational availability greater than "X"	1.1.1 Operational availability (Ao)	1.1.1.1 REE Source availability lag time (MTBM??)	1.1.1.1.1 Time between source of supply interruptions
		1.1.1.2 REE Source unavailability lag time (MDT??)	1.1.1.1.2 Start of source of supply interruption
			1.1.1.1.3 End of source of supply interruption
	1.1.2 REE availability	1.1.2.1 Percentage of REE attainable from the source	1.1.2.1.1 Obtainable amount [ton]
			1.1.2.1.2 Unobtainable amount [ton]
1.2 The system shall achieve asset density greater than "X"	1.2.1 Asset Density	1.2.1.1 Average distance to the nearest source of REE	1.2.1.1.1 Distance to the closest source
			1.2.1.1.2 Distance to the farthest source
1.3 The system shall have a reliability greater than "X"	1.3.1 Reliability	1.3.1.1 Mean time between periods of unavailability	1.3.1.1.1 System uptime before critical interruption (mining or transportation equipment failure?)
		1.3.1.2 Number of alternate country suppliers	1.3.1.2.1 Number of mining sites in country
			1.3.1.2.2 % Allied
	1.3.2 REE Quality	1.3.2.1 Percent of raw material containing REE acquired	1.3.2.1.1 Ratio of REE material to raw material
			1.3.2.1.2 REE amount NOT meeting purity standards
	1.3.3 Capacity	1.3.3.1 Availability of Raw Materials and Parts (% of REE able to be aquired, primary and secondary)	1.3.3.1.1 % of product and by-product acquired
		1.3.3.2 Surge Capacity / Expedited Capability	1.3.3.2.1 # of months needed to aquire additional REE

B. PRODUCIBILITY



System Operational Requirements (SOR)	Measure of Effectiveness (MOE)	Measure of Performance (MOP)	Data Requirements (DR)
2.1 System shall achieve a producibility rate of "X"	2.1.1 Commercial manufacturing productivity	2.1.1.1 Lead time to manufacture	2.1.1.1.1 Time needed to extract the REE [hrs]
		2.1.1.2 Ratio of raw material received to refined REE made	2.1.1.2.1 By-product percentage
		2.1.1.3 Refinery MTBM (uptime)	
		2.1.1.4 Refinery MDT (downtime)	
	2.1.2 Allied manufacturing productivity	2.1.2.1 Lead time to manufacture	2.1.2.1.1 Time needed to extract the REE [hrs]
		2.1.2.2 Ratio of raw material received to refined REE made	2.1.2.2.1 By-product percentage
		2.1.2.3 Refinery MTBM (uptime)	
		2.1.2.4 Refinery MDT (downtime)	
	2.1.3 Government manufacturing productivity	2.1.3.1 Lead time to manufacture	2.1.3.1.1 Time needed to extract the REE [hrs]
		2.1.3.2 Ratio of raw material received to refined REE made	2.1.3.2.1 By-product percentage
		2.1.3.3 Refinery MTBM (uptime)	
		2.1.3.4 Refinery MDT (downtime)	
	2.1.4 REE Quality	2.1.4.1 Percent of REE meeting purity standards	2.1.4.1.1 REE amount meeting purity standards
			2.1.4.1.2 REE amount NOT meeting purity standards

C. TRANSPORTABILITY

System Operational Requirements (SOR)	Measure of Effectiveness (MOE)	Measure of Performance (MOP)	Data Requirements (DR)
3.1 System shall transport required REE	3.1.1 Transportation capacity	3.1.1.1 Avg Daily volume of REE transported	3.1.1.1.1 Min amount transported/day [ton]
			3.1.1.1.2 Max amount transported/day [ton]
	3.1.2 Transportation time	3.1.2.1 Mean delivery time	3.1.2.1.1 Start time
			3.1.2.1.2 End time
	3.1.3 Transportation availability	3.1.3.1 Probability that transportation will be available	3.1.3.1.1 # of full mission capable assets
	3.1.4 Transportation effectiveness	3.1.4.1 Successful Delivery Rate	3.1.4.1.1 # of orders fulfilled
			3.1.4.1.2 # of on time orders (actual/scheduled)
			3.1.4.1.3 Reasons for delay in delivery (by category)
	3.1.5 Average daily transportation asset readiness	3.1.5.1 Average Air Transportation Use	3.1.5.1.1 Route Distance, Frequency, and Time
			3.1.5.1.2 Items Shipped (Amount of inventory produced)
			3.1.5.1.3 Container Utilization Rate (Amount of containers utilized)
			3.1.5.1.4 Performance and Survivability Ratio
		3.1.5.2 Average Land Transportation Use	3.1.5.2.1 Route Distance, Frequency, and Time
			3.1.5.2.2 Items Shipped (Amount of inventory produced)
			3.1.5.2.3 Container Utilization Rate (Amount of containers utilized)
			3.1.5.2.4 Performance and Survivability Ratio
	3.1.6 Transportation Security	3.1.6.1 Average # of countries transited through	3.1.6.1.1 # of countries on shipping route
		3.1.6.2 Performance and Survivability Ratio	3.1.6.2.1 Package Damage Rate (number of inventory items damaged)
3.2 System shall store required REEs	3.2.1 Storage availability	3.2.1.1 Percentage of storage space available	3.2.1.1.1 Amount of storage space occupied
			3.2.1.1.2 Amount of storage space available
		3.2.1.2 Number of alternate country storage facilities	3.2.1.2.1 Number of effective allies
		3.2.1.3 Effectiveness of use for resources such as space and materials	3.2.1.3.1 Performance and Survivability Ratio

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