Managing Portfolios of Complex Systems with the
Portfolio-Level Epoch-Era Analysis for Affordability Framework

by

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Submitted to the Department of System Design and Management
on May 11, 2018 in Partial Fulfillment of the
Requirements for the Degree of Master of Science in
System Design and Management

ABSTRACT

The effects of Sequestration on U.S. Defense spending in the mid-2010s serve as a reminder that complex defense weapons systems are funded by a finite budget. These defense systems have become increasingly complex over time, and with that complexity has come substantial cost. The ability to afford those systems, many of whose burgeoning lifecycle costs have far exceeded initial estimates, has been strained.

The Nunn-McCurdy Act is the means of notifying Congress of cost overruns in major defense development programs, and often sets in motion program terminations. But it is, however, an incomplete means of managing a portfolio of systems. It addresses affordability, but does not assess the utility of the subject assets to the stakeholders, either as standalone assets or as part of a synergistic collection. Utility-at-cost provides a more useful figure of merit that can be evaluated objectively and unemotionally, not just in a static context, but over a range of possible future contexts—and not only for a single system, but also a collection of disparate systems and systems of systems.

The Portfolio-Level Epoch-Era Analysis for Affordability (PLEEAA) method (Vascik, Ross, and Rhodes, 2015, 2016) builds upon established analytical techniques including Multi-Attribute Tradespace Exploration, Epoch-Era Analysis, and the Responsive Systems Comparison framework. It notably introduced elements of Modern Portfolio Theory, which hitherto were constrained to portfolios of financial assets like stocks and bonds.

This research illustrates the general applicability of PLEEAA by exploring two case studies, the U.S. Air Force airborne Intelligence, Surveillance and Reconnaissance portfolio, and the U.S. space-based geospatial intelligence portfolio inclusive of both government-owned and commercial assets.

On the whole, these case studies are “top-down” in nature, levying emerging and potentially disruptive technologies on the asset mix. A more rigorous analytical method would be to conduct the “bottom-up” or “as-is” case using only established assets, and compare the two results. Such an approach could illustrate the incremental and potentially synergistic behavior of new assets introduced to the portfolio design problem.

Thesis Supervisor: Dr. Adam M. Ross
Title: Research Scientist, Engineering Systems

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Acknowledgments

This thesis marks the end of my time at the Massachusetts Institute of Technology (MIT), and I would like to take this opportunity to thank several people and organizations for helping me get to this point.

First, a sincere thanks for my wife, Nicole, who was patient and supportive throughout, bore more than her fair share of parenting when I needed to do homework. The workload at times felt overwhelming, but your support was amazing.

For my dear boys, Jacob and Joshua, I wanted to complete this degree before you reached school age to help instill in you the value of education at all stages of life. Some of my favorite memories at MIT were bringing you to campus to see "where daddy goes to school."

I'm grateful to my parents, Wayne and Susan, for the sacrifices you made in your own lives to raise my brother, Jeremy, and me. You gave up your own college aspirations to have a family. But despite that, you gave us the passion for knowledge that we carry with us to this day. MIT's motto, *Mens et Manus*—Mind and Hand, perfectly conveys that spirit.

Jeremy, thank you for the friendly, brotherly competition in life. Unquestionably my successes would have been significantly diminished if I did not have to keep up with you.

Dr. Adam Ross, from the bottom of my heart, thank you so very much for all the feedback you have given me in this research endeavor, and helping me to shape a topic. Without you this thesis would have been infinitely more difficult. Your brilliance has been an inspiration. I look forward to following your contributions to human knowledge in the years ahead.

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To the countless many I have derived inspiration from—coworkers, friends, and of course, MIT colleagues—thank you. Everybody has their own unique gifts and strengths, and you drive me to push myself harder, to demand better, to learn more, to live life intensely.

I would like to extend my thanks to my employer who helped me financially through my time here, for being patient and understanding when the extreme rigor of MIT's curriculum got in the way of work hours, and for giving me the professional opportunities that set into motion

my decision to attend MIT. United Technologies Corporation, forever Goodrich in my heart, I am in your debt.

And last but far from least, I want to thank the men and women who put on a uniform in service to their country, far from home, who defend the freedoms that we enjoy. I have had the privilege of visiting some of you in your deployed locations, and your professionalism and sacrifices have given immense purpose to my career. My Uncle Dean gave his life for this country in WWII, my Uncle Arnold saw fierce combat and was forever changed, and my college friend, Lisa Frost, was aboard Flight 175 on September 11, 2001. I have a passion for trying to keep young people safe, and that passion spurred me on to complete this research.

Biographical Note

Jason Dieffenbacher has more than 15 years of experience in the Aerospace and Defense industry in engineering and program management roles. He has overseen the development of space-based telescopes at L3 SSG, the development and sustainment of U.S. Air Force high-altitude electro-optical / infrared and wet film camera systems and ground stations for United Technologies Corp, served as a Department of Defense acquisition program manager and systems engineer at Jacobs Technology, oversaw early stage engineered coatings research at Triton Systems, and designed a number of aircraft engine sensors at AMETEK Aerospace and Defense.

Jason has entrepreneurship experience in the form of the company he founded, Pegasus Performance, LLC. Inspired by severe injuries from a bicycle racing crash, he developed a line of cycling apparel intended to reduce "road rash" abrasions. Unlike prior companies' efforts to add padding or abrasion-resistant textiles, Pegasus' intellectual property was based on strategically placed sliding layers of conventional sports textiles to reduce friction at the human / pavement interface. Pegasus participated in the highly competitive MassChallenge startup accelerator in 2012. Jason ceased operations to focus on his demanding role at United Technologies.

Jason holds an M.B.A. from Babson College, which he attended from 2006-2008; an M.S. of Electrical Engineering from Boston University, which he attended from 2005-2007; and a B.S. of Mechanical Engineering from Boston University, which he attended from 1997-2001.

He holds the Project Management Professional (PMP) and Risk Management Professional (PMI-RMP) credentials from the Project Management Institute (PMI).

Jason is a member of the Institute of Electrical and Electronics Engineers (IEEE), PMI, and the International Council on Systems Engineering (INCOSE).

He rang the NASDAQ closing bell on May 2, 2008, as part of the CFA Society Global Investment Research Challenge.

An unabashed "math nerd," he was fascinated by Fermat's Last Theorem (no three positive integers satisfy $a^n + b^n = c^n$ for $n > 2$), and sought simpler solutions than Andrew Wiles' beguiling 129-page proof. As a teenager he discovered an interesting property of prime numbers, reproduced in Appendix C, which still has not been explained by professional mathematicians he shared his findings with.

Jason currently lives in New Hampshire with his wife, Nicole, and boys, Jacob and Joshua. He is an avid competitive cyclist and runner. His intellectual curiosity is insatiable, and his only regret is best summed up by Tim Rice's lyrics for the "Circle of Life," featured in Disney's The Lion King: "There's more to be seen than can ever be seen, more to do than can ever be done." Echoing Ted Kennedy's eulogy for his brother Robert, "he loved life completely and live it intensely."[1]

[1] Edward M. Kennedy, Address at the Public Memorial Service for Robert F. Kennedy, http://www.americanrhetoric.com/speeches/ekennedytributetorfk.html, accessed 1/18/2018.

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In Memoriam

This work is dedicated to John Helferich, a remarkable Teaching Assistant here at the Massachusetts Institute of Technology. He was a fixture of the System Design and Management curriculum, and he touched the lives of all who knew him. John brought a touch of humor to his teaching style, which was so very welcome when the workload felt insurmountable. He was also a profoundly interesting person, with a diverse background including being an executive at Mars and running a brewery.

One of my favorite light-hearted quotes John said in the first few weeks of the SDM program, speaking of the strain the workload could place on a student, went something like, "This program has never broken up a marriage. (pausing) Well, maybe a couple…but they were on the rocks already anyway." Moments like those helped buoy my spirits and made learning fun.

As part of a class survey, we were asked to guess what John had in his wallet. Remarkably, I correctly guessed a €10 note. Perhaps it was dumb luck, or perhaps it was, knowing that we were in many ways kindred spirits, because I myself at that moment had a (South) Korean ₩10,000 note in my wallet—a souvenir from prior travel.

Thank you, John, for leaving your mark upon many, many scholars, faculty, and all who knew you.

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Acronyms

A2/AD	Anti-Access / Area Denial
AFDD	Air Force Doctrine Document
AI	Artificial Intelligence
AIAA	American Institute of Aeronautics and Astronautics
AoA	Analysis of Alternatives
ARI	Available Rank Index
ASARS	Advanced Synthetic Aperture Radar System
ASM	Air-to-Surface Missile
BBP	Better Buying Power
C2	Command and Control
CAL	Capital Allocation Line
CAP	Combat Air Patrol
CAPM	Capital Asset Pricing Model
CFA	Chartered Financial Analyst
CID	Combat Identification
COIN	Counter Insurgency
CONOPS	Concept of Operations
COTS	Commercial Off The Shelf
CSG	Carrier Strike Group
DNI	Director of National Intelligence
DoD	Department of Defense

DSM	Design Structure Matrix
DVM	Design-Value Matrix
EEA	Epoch-Era Analysis
EEI	Essential Elements of Information
efNPT	Effective Fuzzy Normalized Pareto Trace
eNPT	Effective Normalized Pareto Trace
EISS	Enhanced Integrated Sensor Suite
EOIR	Electro-Optical Infrared
F2T2EA	Fix, Fix, Track, Target, Engage, Assess
FAR	Federal Acquisition Regulations
FFRDC	Federally-Funded Research and Development Center
FMV	Full Motion Video
FPS	Fuzzy Pareto Shift
FY	Fiscal Year
GAO	Government Accountability Office
GEOINT	Geospatial Intelligence
GDP	Gross Domestic Product
HALE	High Altitude Long Endurance
IC	Intelligence Community
ICBM	Intercontinental Ballistic Missile
IEEE	Institute of Electrical and Electronics Engineers
ISR	Intelligence, Surveillance and Reconnaissance

ITAR	International Traffic in Arms Regulations
JP	Joint Publication
LASE	Low Altitude Short Endurance
MAE	Multi-Attribute Expense
MALE	Medium Altitude Long Endurance
MATE	Multi Attribute Tradespace Exploration
MAU	Multi-Attribute Utility
MAUA	Multi-Attribute Utility Analysis
MAUT	Multi-Attribute Utility Theory
MDAP	Major Defense Acquisition Program
MP-RTIP	Multi-Platform Radar Technology Insertion Program
MPT	Modern Portfolio Theory
MTS-B	Multispectral Targeting System - B
NASA	National Aeronautics and Space Administration
NERC	North American Electric Reliability Council
NFPT	Normalized Fuzzy Pareto Trace
NGA	National Geospatial-Intelligence Agency
NIIRS	National Imagery Interpretability Rating Scale
NIP	National Intelligence Program
NPT	Normalized Pareto Trace
NSPD	National Security Presidential Directive
NRO	National Reconnaissance Office

NTM	National Technical Means
O&M	Operations & Maintenance
OAS	Office of Aerospace Studies
ODNI	Office of the Director of National Intelligence
PDM	Programmed Depot Maintenance
PED	Processing, Exploitation, and Dissemination
PLEEAA	Portfolio-Level Epoch-Era Analysis for Affordability
PMI	Project Management Institute
PMPT	Post-Modern Portfolio Theory
PPD	Presidential Policy Directive
PRAN	Probability Risk Assessment Number
QFD	Quality Functional Deployment
RCS	Radar Cross Section
RPA	Remotely Piloted Aircraft
RSC	Responsive Systems Comparison
S&T	Science & Technology
SAM	Surface-to-Air Missile
SAR	Selected Acquisition Report (Nunn-McCurdy Act term)
SAR	Synthetic Aperture Radar (sensor technology term)
SoS	System of Systems
SoSTEM	System of Systems Tradespace Exploration Method
SUAS	Small Unmanned Aerial Systems

SYERS	Senior Year Electro-Optical Reconnaissance System
SWOT	Strengths, Weaknesses, Opportunities, and Threats
TCPED	Tasking, Collection, Processing, Exploitation, and Dissemination
TPED	Tasking, Processing, Exploitation, and Dissemination
TSE	Tradespace Exploration
TTP	Tactics, Techniques and Procedures
UAS	Unmanned Aircraft System / Unmanned Aerial System
USAF	United States Air Force
USC	United States Code
VASC	Valuation Approach for Strategic Changeability

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1. Introduction

1.1. Background and Motivation

The effects of Sequestration on U.S. Defense spending in the mid-2010s serve as a reminder that complex defense weapons systems are developed, procured, and sustained by the government's budget, and that budget is finite. These defense systems have become increasingly complex over time, and with that complexity has come substantial cost. The ability to afford those systems, many of whose burgeoning lifecycle costs have far exceeded initial estimates, has been strained. In 2010, Under Secretary of Defense for Acquisition, Technology and Logistics, Dr. Ashton Carter, penned a memo initiating Better Buying Power (BBP), strategic guidance that made it clear that cost control across the Department of Defense (DoD) was an imperative. The DoD said of its Fiscal Year (FY) 2017 budget that, "It reflects Administration-wide efforts to make tough program choices." (Defense Budget Overview, 2016). These "tough program choices" translate to cuts of various forms—terminations, divestitures, mothballed assets, etc. The military thus manages its collection of systems as a portfolio, making tailored decisions each year about the types and quantities of assets it will develop, hold, and divest based on the national security threats it predicts for several decades into the future.

The Nunn-McCurdy Act (10 U.S.C. §2433) is one of the primary means of notifying Congress of cost overruns in Major Defense Acquisition Programs (MDAP). Under the Act, there are two tiers of breaches: Significant and Critical. The figures of merit are the Program Acquisition Unit Cost, which is the total cost of development, procurement, and construction divided by the number of units purchased; and Procurement Unit Cost, which is the total

procurement cost divided by the number of units purchased. Significant Unit Cost Breaches are triggered when an MDAP's cost grows by 15% from its current baseline or 30% from its original baseline. Critical Unit Cost Breaches are triggered when an MDAP's cost growth grows 25% from its current baseline or 50% from its original baseline. Critical breaches set in motion a program's termination, unless the Secretary of Defense certifies the program as essential to national security. (Schwartz, 2010)

Thinking of weapon systems as constituents of a portfolio is evident in the way Nunn-McCurdy breaches are reported to Congress. When the DoD wishes to continue the development and procurement of a breached program, the funds to cover the cost overrun are allocated by reducing other, lower priority programs in the portfolio. In the parlance of game theory, this is a zero sum game, in which the "gain" of a breached program is offset by an equal-sized "loss" elsewhere in the portfolio. This budget reality underscores the need for decision makers to look at the assets under their control against the backdrop of their best guess of tomorrow's national security threats to make asset allocation choices.

From 1997 through 2016, there were 91 significant and critical Nunn-McCurdy breaches according to the Government Accountability Office (GAO). Upticks in breaches during 2001, 2005, 2006, and 2009 are at least partly explained by changes in presidential administration and new statutory requirements. The GAO estimated that almost 40% of the breaches followed production decisions such as quantity reductions. (GAO, 2011) Production cuts are often the result of unit cost growth, but can also stem from changing requirements and / or strategic priorities—the result of an evolving contextual backdrop.

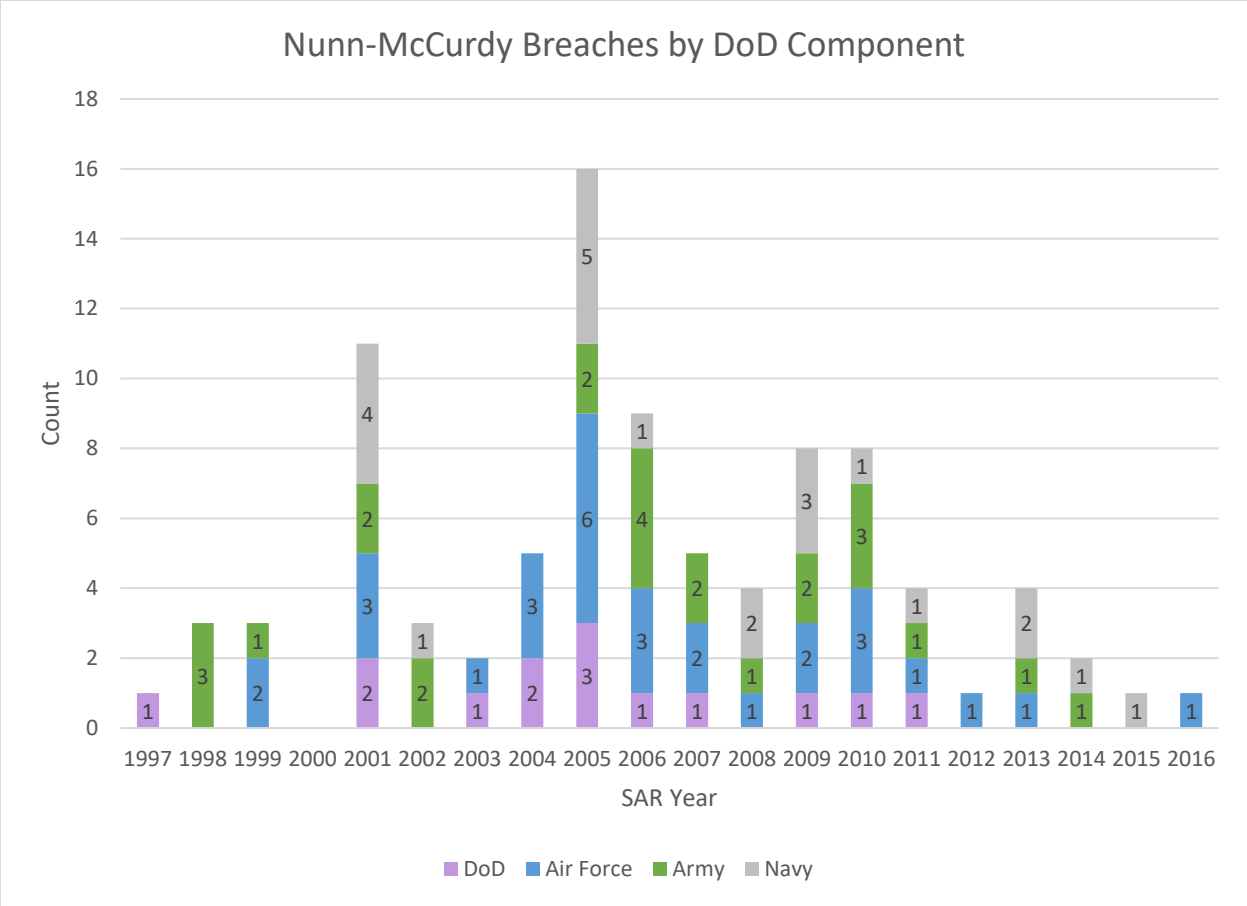

Figure 1. Nunn-McCurdy Breaches by DoD Component, 1997-2016
(Reproduced from "Performance of the Defense Acquisition System: 2016 Annual Report", Figure 2-34, page. 64.)

Nunn-McCurdy is, however, an incomplete means of managing a portfolio of systems or systems of systems (SoS). First, it only addresses the affordability constraint—it does not assess the utility of the subject assets to the stakeholders, either as standalone assets or as part of a synergistic collection. Utility-at-cost is a more meaningful figure of merit.

Second, technology has long been cited as a "force multiplier," so a smaller number of technologically superior assets may, under certain circumstances, outperform a larger number of less capable assets. Determining the appropriate mix of inexpensive and

expensive or “exquisite” capabilities is not addressed in a Concept of Operations (CONOPS) or any other way for that matter when evaluating Nunn-McCurdy breaches.

Third, it does not include some lifecycle cost elements such as Operations & Maintenance (O&M) or disposal costs, which can be very significant. In fact, the O&M cost typically exceeds the up-front cost by a large amount. An oft-cited heuristic by the Office of the Secretary of Defense Cost Analysis Improvement Group in 1992 suggests a ratio of 70:30, sustainment cost to development and procurement cost (Jones et al, 2014). Therefore, Nunn-McCurdy ignores a large swath of the budget—the part dedicated to sustaining existing capabilities.

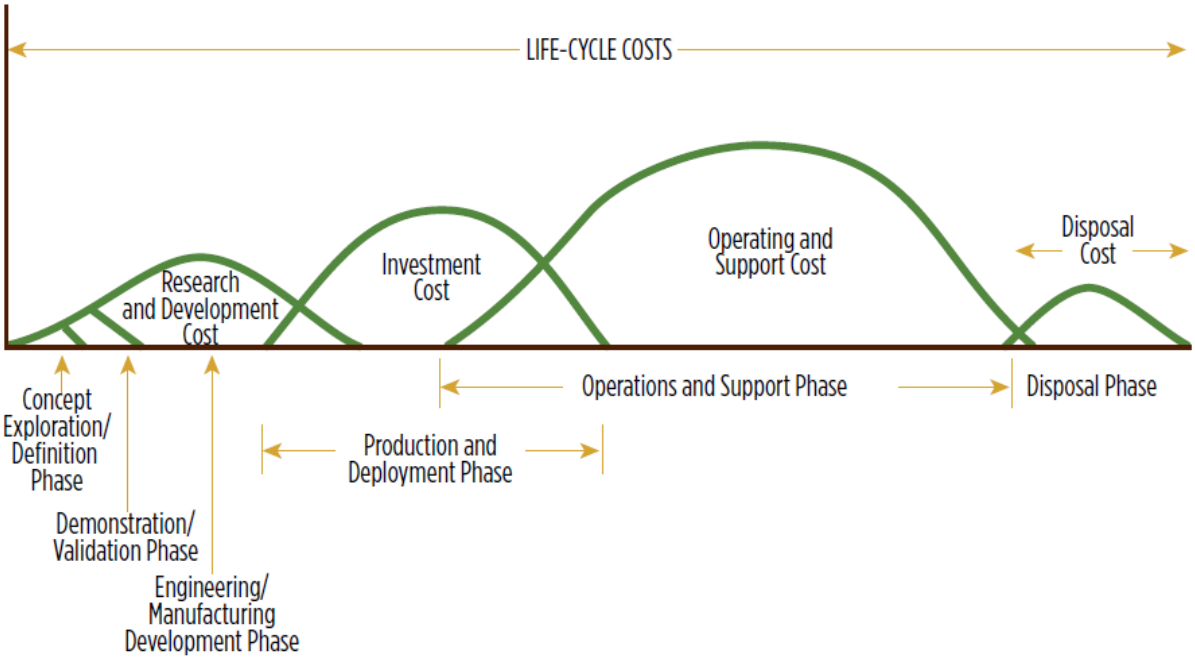

Figure 2. Notional Lifecycle Costs for a DoD Weapon System (Jones et al, 2014)

The relatively slow pace of weapon system development has prompted DoD Decision makers to look to the commercial world for alternative or complementary technologies. In 1994, then-Secretary of Defense William Perry penned a memo to the Chairman of the Joint Chiefs of Staff and others, articulating the need to increase the use of commercial products

in use by the military. "To meet future needs, the Department of Defense must increase access to commercial state-of-the-art technology and must facilitate the adoption by its suppliers of business processes characteristic of world class suppliers. In addition, integration of commercial and military development and manufacturing facilitates the development of dual-use processes and products and contributes to an expanded industrial base that is capable of meeting defense needs at lower costs. I have repeatedly stated that moving to greater use of performance and commercial specifications and standards is one of the most important actions that DoD must take to ensure we are able to meet our military, economic, and policy objectives in the future." In the time since, portfolio managers have had to explore not only the mix of DoD assets in operation and in development, but also to scan the horizon for commercial products that can help meet its objectives faster and / or at lower cost. This is especially evident by the rise of commercial geospatial intelligence satellite industry, which is the study of the second case study herein. Backed by a plurality of Presidential directives, the United States Intelligence Community (IC) has been embracing the use of commercial imagery to augment its own constellations. How best to balance the mix of commercial and military with concern for affordability is the domain of multi-attribute tradespace exploration and portfolio theory.

The work of Vascik, Ross, and Rhodes (2015, 2016) merged elements of financial Modern Portfolio Theory (MPT) with Multi-Attribute Tradespace Exploration (MATE) and Epoch-Era Analysis (EEA) in their development of the Portfolio-Level Epoch-Era Analysis for Affordability (PLEEAA) framework. They noted some key differences between MPT as applied to portfolios of financial assets like stocks and bonds, and portfolios constructed of complex engineering

systems and systems of systems. These differences prevent the wholesale application of MPT to systems portfolios, but nevertheless the PLEEAA framework is a significant advance that will be explored in more detail in this thesis.

1.2. Research Scope

In this thesis, the author uses the Portfolio-Level Epoch-Era Analysis for Affordability (PLEEAA) framework, a domain of Multi-Attribute Tradespace Exploration (MATE), to analyze two U.S. defense-based case studies—the Air Force airborne Intelligence, Surveillance and Reconnaissance (ISR) fleet, and the space-based satellite portfolio comprised of both U.S. funded assets and commercial sensor constellations. Recognizing that ISR brackets a number of distinct types, such as Geospatial Intelligence and Signals Intelligence, this thesis focuses only on Geospatial Intelligence in order to constrain the scope to a manageable size.

This thesis builds upon roughly two decades of work in systems engineering tradespace exploration (TSE), and proposes an expanded toolbox of techniques and a framework for strategists and decision makers who are charged with oversight of portfolios of complex engineering systems. It demonstrates applicability of existing methods through two case studies, and notes areas where biases, either conscious or unconscious, may anchor the outcomes.

The work herein is applicable to early stage concept development, analyses of alternatives, strategic planning and war gaming. It may also be used when making portfolio level investment and divestment decisions.

The author discusses the benefits and limitations of the approach and the research to aid future researchers and decision makers interested in the method.

Finally, the author gives recommendations for future research that may be useful in expanding the usefulness of the approach.

1.3. Research Questions

This work seeks to extend the Portfolio-Level Epoch-Era Analysis for Affordability (PLEEAA) framework (Vascik, Ross, and Rhodes, 2015, 2016) to large system of systems portfolios to aid strategists and decision makers in refining their universe of assets in the face of changing needs.

Portfolio mix decisions are constrained in part by the budgets of the organizations that control those portfolios. When budgets are reasonably stable, with modest annual expansion or contraction, portfolio change decisions amount to a *zero sum game*. That is, an increase in one area of the portfolio necessarily is offset by a decrease in one or more areas elsewhere in the portfolio. Given an uncertain future and the lengthy development, procurement and sustainment lifecycles for many of the Government's weapon systems, decision makers must assess portfolio decisions against the backdrop of the consensus future national security picture. The stakes are understandably high—the nation's ability to deter armed conflict, or, when the alternatives to war have been exhausted, the nation's ability to fight in any domain on any scale with favorable, lopsided outcomes depends in no small part on its portfolio decisions made earlier.

The author sought to answer whether portfolios of complex engineering systems could be analogous to portfolios of financial assets. Specifically:

Guiding Questions:

1. Can principles of Modern Portfolio Theory from financial asset management be extended to portfolios of engineering systems?
2. Is there a mix of higher cost, capably exquisite and lower cost, less capable systems that exhibits efficient frontier stability across a range of possible futures or epochs?
3. How objective is the PLEEAA framework? In other words, what sources of bias and other errors can affect the inputs and outputs?
4. Can the PLEEAA framework be used to make objective system asset investment and divestment decisions?
5. Can asset covariance analysis across epochs help inform key system interoperability decisions?
6. Can the finance concept of investor risk tolerance, in establishing the optimal location on the efficient frontier, be extended to systems of systems portfolios?
7. If so, what are the constituent elements that determine the system analog for "investor risk tolerance"?

1.4. Thesis Organization

This thesis is organized as follows:

Section 1 provides introductory and background material describing the motivation and scope of the research.

Section 2 summarizes a literature review and includes definitions of terms used herein as well as the Multi-Attribute Tradespace Exploration, Epoch-Era Analysis, Responsive Systems Comparison frameworks that build upon one another to support this research.

Section 3 introduces the Portfolio-Level Epoch-Era Analysis for Affordability framework in detail.

Section 4 presents a case study analysis of the U.S. Air Force Intelligence, Surveillance and Reconnaissance (ISR) portfolio using the Portfolio-Level Epoch-Era Analysis for Affordability (PLEEAA).

Section 5 uses PLEEAA for a case study analysis of the U.S. geospatial intelligence satellite portfolio, comprised of both government-owned and commercially-owned assets.

Section 6 discusses the findings and provides recommendations for future research.

Section 7 summarizes the findings from this research against the backdrop of the guiding questions.

1.5. Thesis Data

Given the fact that the two case studies explored in this thesis are military intelligence system portfolios, the author used only open source data and market research published primarily by United States government sources (i.e., from unclassified .mil and .gov domains). Due to a number of high profile leaks of sensitive classified information in recent years, the author wishes to underscore that if the data provenance could not be traced clearly back to a U.S. Government program office or agency, it was not included herein. The author is acutely aware of the need to protect sensitive military capabilities, so the analysis performed in this thesis derived from open sources, and is surely a simplified version of what appropriately cleared strategists and decision makers would perform for the system portfolios in question.

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2. Literature Review

This section begins with the definitions for some key concepts used in this research. It then outlines a number of the main concepts that this thesis builds upon by summarizing the frameworks and methods. Finally, it includes case studies applicable to the work.

2.1. Definitions

This research advances a niche of systems engineering, which has developed its own lexicon of precise terminology. The reader is therefore better served with some up-front definitions for terms used in this text. When terms are used interchangeably the definition includes the alternative titles. And when terms are subtly different, the definitions are meant to clarify the nuances.

i. System: The National Aeronautics and Space Administration (NASA) defines a system as: "(1) the combination of elements that function together to produce the capability to meet a need. The elements include all hardware, software, equipment, facilities, personnel, processes, and procedures needed for this purpose. (2) The end product (which performs operational functions) and enabling products (which provide life-cycle support services to the operational end products) that make up a system." (NASA, 2007)

ii. Engineering System: recognizing that the natural world can fit into the above interpretation of a system, it is useful to be more precise in this research. An engineering system is "a system designed / evolved by humans having some purpose; large-scale and complex engineering systems will have a management or social dimension as well as a technical one." Hereafter in this paper, the term

"system" and "engineering system" will be used interchangeably but are meant to mean "engineering system." (de Weck et al, 2011)

iii. System of Systems (SoS): Maier provided a useful SoS definition as, "an assemblage of components which individually may be regarded as systems, and which possesses two additional properties:

Operational Independence of the Components: If the system-of-systems is disassembled into its component systems the component systems must be able to usefully operate independently. That is, the components fulfill customer-operator purposes on their own.

Managerial Independence of the Components: The component systems not only can operate independently, they do operate independently. The component systems are separately acquired and integrated but maintain a continuing operational existence independent of the system-of-systems." (Maier, 1998)

iv. Portfolio: a term that on the surface appears semantically congruent to SoS, but has a more nuanced meaning for the purpose of this research. Vascik and Ross defined a portfolio as "a construct that describes a collection of assets simultaneously invested in to exploit qualities of the set, regardless of whether the assets are operationalized independently or as participants in a SoS." (Vascik, Ross, and Rhodes, 2016)

v. Affordability: In Dr. Carter's Better Buying Power (BBP) memorandum for acquisition professionals, he defined affordability as "conducting a program at the

cost constrained by the maximum resources the Department can allocate for that capability." (Carter, 2010)

vi. Epoch: Vascik et al (2016) define an epoch as a "time period of static contexts and stakeholder expectations, like a snapshot of a potential future."

vii. Era: Vascik et al (2016) define an era as "an ordered sequence of epochs with finite time durations; a potential progression of contexts over the portfolio lifecycle." It is important to note that order may matter; the identical epochs ordered differently could yield different non-dominated portfolios.

viii. Efficient frontier, Pareto frontier: These terms are used interchangeably to mean the "non-dominated" portfolios plotted in the cost-utility plane. Non-dominated means the maximum utility at a given cost. A related concept is the "fuzzy" Pareto frontier, which allows some tolerance beneath the Pareto frontier to include additional portfolios that are nearly non-dominated.

2.2. Systems, Systems of Systems, and Portfolios

It is useful to expand on the above definitions for systems, systems of systems, and portfolios will illustrative examples and some historical background. The first two together and the last two together can appear closely related, but for the purpose of this research it is important to establish that they are not semantically equivalent.

2.2.1. Systems

First, a discussion of systems, the basal constituent element of a portfolio of systems, is given.

2.2.1.1. Systems Overview

de Weck et al (2011) suggest a system is "a set of interacting components having well-defined (although possibly poorly understood) behavior or purpose; the concept is subjective in that what is a system to one person may not appear to be a system to another." Indeed, in today's world it can be challenging to identify whether something is a system, and if so, where its boundary is. Consider the example of a smart phone.

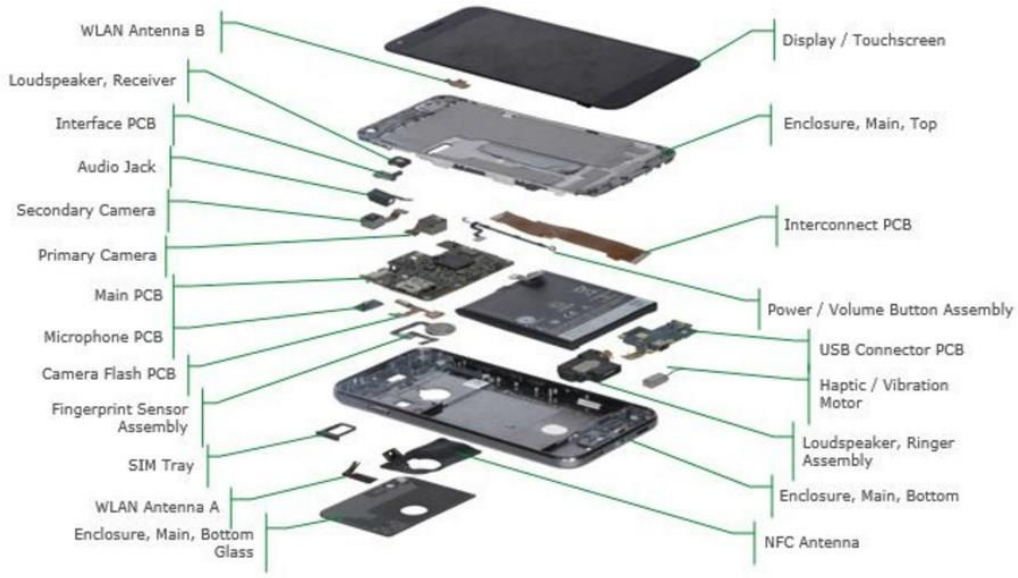

Figure 3. Smart Phone Exploded View.[2]

Shown in Figure 3 is an exploded view of a typical smart phone. One could reasonably argue that this is a system. It is made up of a number of constituent components that act in

[2] http://cdn.telecomtv.com/assets/telecomtv/pixel-bom-exploded-view-3090.jpg?w=970, accessed 1/8/2018

concert to deliver emergent function—the ability to make telephone calls, navigate on the earth, use the internet, etc. But while one could draw a system boundary around everything in the figure, it requires inputs such as electrical energy, which can be conveyed by a cable or in some cases wirelessly to the battery where the energy is stored. One could therefore argue that the system boundary encompasses the phone and the means to charge it, because without power the device will not function, and particularly if the charging interface uses a proprietary or uncommon connection. Beyond power, the device needs other things to deliver emergent function—a wireless cellular signal to make phone calls, a data signal to connect to the internet, and others. These inputs are arguably outside the system boundary, because these elements exist when the consumer purchases a cellular phone.

2.2.1.2. Systems: A Short History

Systems and systems thinking does not trace its roots to any single person, product or event, but rather took form from the ether generally coincident with World War II. The world's arsenals looked at war's end in 1945 vastly different than they did as the clouds of conflict gathered in the 1930s. At least 27 different models of biplane were in use at the start of the war[3]. By war's end, vastly more complex technologies including the rocket-powered Messerschmitt Me 163 Komet aircraft, the V-2 guided ballistic rocket, and weapons of mass destruction like the atomic bomb had been developed and operationalized.

[3] https://en.wikipedia.org/wiki/List_of_aircraft_of_World_War_II#Biplane_fighters, accessed 1/8/2018

Figure 4. Me 163 Komet.[4]

The ensuing Cold War accelerated systems engineering tradecraft, as work on Intercontinental Ballistic Missiles (ICBMs), missile early warning and defense, and the Space Race reshaped how the U.S. Government acquired capabilities and set its strategic goals.

Jared Diamond theorized in *Guns, Germs and Steel* (Diamond, 1997) that the faster rise of some civilizations relative to others was influenced by the move from being hunter-gatherers to farmers. Once civilizations were able to subsist on stable food sources, they had resources to advance technologies like metalcraft. Opportunities and threats among neighboring civilizations gave rise to innovative competition. Technology served as an enabler of societal growth—and conflict. The Industrial Revolution paved the way for the Machine Age of the late nineteenth and early twentieth centuries. Each technological innovation cumulatively advanced humanity. What bronze was to ancient peoples, systems

[4] https://upload.wikimedia.org/wikipedia/commons/b/b3/Me_163_at_Melbourne_c1950.jpg, accessed 1/8/2018

like the computer became to modern ones. The technological atomic unit has, one could argue, moved up the complexity scale to systems.

Making sense of that complexity for the average user is often not required; the driver of a car need not understand how antilock brakes work or even care that she has antilock brakes. Rather, the ability to brake hard is an at least occasional need, and the complex mechanics behind that emergent behavior is of no concern to the driver. By distilling engineering systems down into their emergent functions, the system is simplified in one's mental model to a "black box," and can potentially become a building block in a more complex system—a system of systems.

2.2.2. Systems of Systems

The next higher layer of abstraction is systems of systems, which is discussed now.

2.2.2.1. Systems of Systems Overview

A concise, universal definition of systems of systems is more elusive. Work by Boardman et al (2006) sifted through approximately 40 definitions from the research. Maier's definition is widely cited. As defined in Section 2.1 above, a system of systems is an aggregation of elements that are themselves systems, demonstrate emergent functions—that is, the output is greater than the sum of the parts, and exhibits both operational and managerial independence of components.

Operational independence means that the constituent elements, if broken out separately, must be able to operate independently. Under this definition, an automobile is a system, not a system of systems. Separating the wheels from the car provides no useful

purpose in isolation. Conversely, a naval submarine and its ICBMs satisfy this requirement, as the ICBM will fly to its target when launched from the submarine.

Managerial independence deals primarily with how elements are procured. The term means that the constituent elements are separately acquired and integrated, and can exist separate from one another. Using the prior examples for illustration, an automobile does not satisfy managerial independence. While tires or complete wheel assemblies can be separately procured (e.g. snow tires), a consumer usually buys a complete automobile in one sitting to satisfy her transportation needs. Conversely, naval submarines and their complement of ICBMs do satisfy this requirement. The overarching buyer of these capabilities typically has separate procurement offices to buy submarines and ICBMs, and each element is on a unique lifecycle. The same submarine may be capable of carrying various families of ordnance, and conversely, the same ICBM may be used in various classes of submarine.

The Institute of Electrical and Electronics Engineers (IEEE) identifies a key attribute of SoS as the "interconnection between otherwise independent systems" (2014) and cites a number of characteristics of SoS, including nonlinear correlations, scale-free phenomena, and chaotic behavior. Clearly, the demarcation between systems and systems of systems is more ambiguous. It is also evident that systems may belong in certain circumstances simultaneously to multiple systems of systems. In other words, there is no exclusivity requirement that a system belongs to only one systems of systems architecture. The U.S. Air Force (USAF) B-52 Stratofortress, for example, is a system that belongs to multiple systems of systems. It is a member of the strategic "nuclear triad" that comprises bombers,

submarines and ICBMs. It is also used for non-strategic tasks, like dropping conventional ordnance like its sister, the B-1 Lancer, and tactical fighters such as the F-15 Eagle and F-16 Fighting Falcon. While both assemblages could be systems of systems, the finite number of operational B-52s are not apportioned to only one construct or the other, or at least not permanently.

2.2.3. Programs

Vascik, Ross and Rhodes (2015) introduced another layer of systems stratification, that of programs. A program is a means of grouping systems by the common threads of capabilities and / or missions. These systems can by semi-independent or completely independent of one another. Finally, they classify two types of programs, Type I and Type II.

Type I programs are characterized by homogeneous elements. An example of this type of program is the Boeing 787 Dreamliner. There are 3 variants of record at the time of this writing, the 787-8, 787-9, and 787-10. All have similar construction and body width, and differ primarily in the number of passengers they are able to carry.[5]

Type II programs on the other hand involve heterogeneous elements that serve similar missions and are measured against a common set of performance metrics. An example of a Type II program is the Lockheed Martin U-2 Dragon Lady and the Northrop Grumman RQ-4 Global Hawk. Both systems serve an intelligence, surveillance and reconnaissance (ISR) purpose, fly at relatively similar altitudes, and carry similar types of sensors. Incidentally, these two systems are discussed in more detail in Case Study 1 below.

[5] Wikipedia, Boeing 787 Dreamliner, https://en.wikipedia.org/wiki/Boeing_787_Dreamliner, accessed 1/30/2018

2.2.4. Portfolios

Finally, a portfolio is a concept that may involve systems, systems of systems or both. The set of chosen constituents act in concert to provide a set of capabilities. (Vascik, Ross, and Rhodes, 2015). A well-designed portfolio considers both the capabilities of the standalone elements, and the emergent functions that may arise when these elements interact as systems of systems.

A portfolio is a useful abstraction for at least two reasons. First, the emergent behavior that comes from mixing disparate systems and systems of systems provides transcendental performance that may not exist when simply looking at standalone systems, systems of systems or programs. Second, how these elements are managed often varies at the different layers of abstraction. For instance, a single program manager might be responsible for all elements of a homogeneous program, but a portfolio manager may or may not have ultimate budget authority for all elements of the portfolio. In Case Study 1, the author explores the USAF airborne geospatial intelligence, surveillance and reconnaissance portfolio. All of these systems ultimately fall under the power of one portfolio manager, the Deputy Chief of Staff for Intelligence, Surveillance and Reconnaissance (referred to as “HAF/A2”). Conversely, in Case Study 2, the author considers the U.S. geospatial intelligence satellite constellation including a mix of both U.S.-owned and commercially-owned assets. In this situation, the Government portfolio manager has decision authority about how to structure the portfolio, but does not have ultimate authority over all the assets in question.

2.2.5. Modern Portfolio Theory

At this stage it is important to introduce the idea of financial asset portfolio management in order to discuss the elements that translate to the systems portfolios discussed in this research.

In financial asset management, a portfolio is typically a subset of financial assets selected from the universe of available assets—for example, companies comprising the Standard & Poor's 500 index (portfolio) as compared to the universe of all equities listed on U.S. exchanges (universe).

Harry Markowitz and William Sharpe, along with Merton Miller, went on to share the 1990 Nobel Prize in Economics for their contributions to what became known as Modern Portfolio Theory (MPT) and the Capital Asset Pricing Model (CAPM).[6]

In his 1952 essay in The Journal of Finance, "Portfolio Selection," and subsequent 1959 book, "*Portfolio Selection: Efficient Diversification of Investments*", Markowitz suggested that a rational investor seeks to maximize return on investment for a given level of risk, or seeks to minimize risk for given level of return. Moreover, by carefully constructing a portfolio of assets rather than a single asset, the astonishing mathematics of diversification showed that the portfolio of multiple assets could have less variance than holding any single asset. Not all risk can be diversified away, as some overarching risk applies to all assets in the portfolio, which is called systematic or nondiversifiable risk. In a well-designed portfolio, this systematic risk is the only risk that affects the assets' price.

[6] The Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel 1990, https://www.nobelprize.org/nobel_prizes/economic-sciences/laureates/1990/press.html, accessed 2/3/2018

MPT, also called mean-variance analysis, introduced some elegant mathematics to the profession of financial portfolio management.

The expected portfolio return is a simple weighted sum of the expected return of the assets multiplied by their respective contributions to the portfolio is given by:

$$E(R_P) = \sum_{i=1}^{N} w_i \, E(R_i) \tag{1}$$

The portfolio variance, σ_P^2, is given by:

$$\sigma_P^2 = \sum_{i=1}^{N} \sum_{j=1}^{N} w_i w_j \sigma_i \sigma_j \rho_{ij} \tag{2}$$

Where ρ_{ij} is the covariance of the two assets, denoted with subscripts *i* and *j*. Covariance is the measure of how two assets move relative to one another.

Finally, the portfolio volatility, as measured by the standard deviation of returns, is given by:

$$\sigma_P = \sqrt{\sigma_P^2} \tag{3}$$

Given a collection of constituent assets, the portfolio manager can adjust the quantity of those assets relative to the whole portfolio. The expected returns and variance of each asset plus a covariance matrix which indicates how each asset behaves relative to other assets in the portfolio are inserted into the aforementioned equations and a scatterplot similar to what is depicted in Figure 5 is generated. Each point is a hypothetical portfolio. The collection of

non-dominated points, i.e. those that maximize return for each measure of risk, is called the efficient frontier, or Pareto frontier, as defined in Section 2.1(viii). A portfolio manager might permit some tolerance on the efficient frontier to include additional near-non-dominated portfolios to allow for errors in the estimate of input factors. This is called a "fuzzy efficient frontier" or "fuzzy Pareto front." Note that in the figure, an upward-sloping line called the Capital Allocation Line (CAL). The slope of the line is known as the Sharpe Ratio, named after William Sharpe, who introduced the concept as part of his 1964 work in the Capital Asset Pricing Model (CAPM).[7] This has implications for financial portfolio management, but its usefulness in portfolios of systems and systems of systems is questionable, due to the fact that, as with MPT, it relies on the assumption that asset returns are normally distributed.

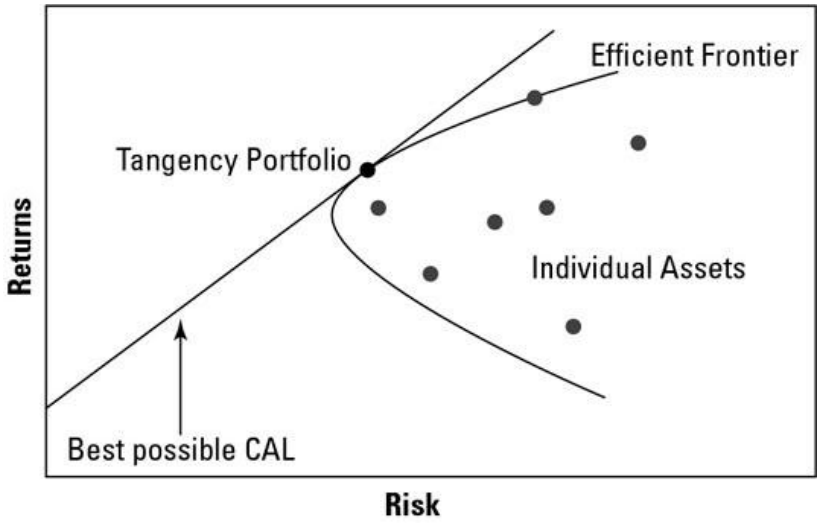

Figure 5. Portfolio Efficient Frontier[8]

Underlying modern portfolio theory and the CAPM are several assumptions, such as that investors are risk averse and seek to maximize returns, and that the constituent assets in a

[7] http://www.investopedia.com/terms/c/cal.asp, accessed 2/14/2018
[8] http://www.dummies.com/business/accounting/auditing/how-to-optimize-portfolio-risk/, accessed 2/14/2018

portfolio have normally distributed returns. As will be discussed in more detail later, some assumptions of MPT are not always applicable when extended to portfolios of systems and systems of systems.

2.2.6. Post-Modern Portfolio Theory

Post-Modern Portfolio Theory (PMPT) addresses some of the limitations of MPT (Swisher and Kasten, 2005). These include non-normal distributions of expected returns and minimizing downside risk. Instead of using the standard deviation of returns as in traditional mean-variance analysis, which considers both upside and downside variation, some possible measures of downside risk are semivariance, as was suggested by Walton in his 2002 PhD thesis, or value-at-risk. (Elton et al, 2014)

The analog to minimizing downside risk in portfolios of systems is minimizing the chance of not satisfying one of the fundamental portfolio objectives. Indeed, if the ultimate objective of any military is to win its nation's wars, then downside risk is to be minimized or avoided. And conversely, upside risk, often referred to as "opportunity," should be exploited to the maximum extent practical weighed against the affordability constraint.

While others such as Vascik, Ross and Rhodes (2016) have identified PMPT as a potential avenue to overcome some of the weak or invalid assumption of MPT for portfolios of systems, it is still an area to be researched further.

2.2.7. Financial Asset Portfolios Compared to Systems Portfolios

At the time of this writing, the work to develop tools for managing portfolios of complex engineering systems and systems of systems is still in the early stages. Walton's PhD thesis (2002) predated some of the seminal works in multi-attribute tradespace analysis (MATE) and

epoch-era analysis (EEA), but included elements of financial portfolio theory to evaluate space system architectures. Research by Ricci and Ross (2012), and Vascik, Ross, and Rhodes (2015, 2016) explored the topic further by introducing the MATE, EEA, Responsive System Comparison (RSC), and Portfolio-Level Epoch-Era Analysis for Affordability (PLEEAA) frameworks. Those researchers cited some important differences from traditional modern portfolio theory, such as the possibility for non-normally distributed behavior, and the fact that emergent functions arising from constituent portfolio systems may render the concept of covariance meaningless.

Perhaps most significantly, and the whole underlying premise for this research thesis, is the idea that forecasting the expected returns or performance-in-context of a portfolio of systems and SoS is fundamentally different than with financial asset management. Whereas in finance there are common frameworks for forecasting expected returns and variance based in part on their prior actual behavior, the requirements context for systems evolves over time, and the manner in which the constituents interact with each other is simultaneously mathematically nontrivial and context-dependent. Additionally, systems can be maintained and upgraded over time in the face of changing requirements to restore their performance-in-context and thus utility to the stakeholders. Thus, a forecasting engine needs to be inserted into the design of systems portfolios to enable analysis of the complex interactions, not only at one instant in time but over the period of interest for the portfolio designer. This forecasting engine comes in the form of the Multi-Attribute Tradespace Exploration (MATE), Epoch-Era Analysis (EEA), and the enhanced Responsive Systems Comparison (RSC) frameworks, packaged by Vascik, Ross and Rhodes (2015, 2016) in the

Portfolio-Level Epoch-Era Analysis for Affordability (PLEEAA) framework. MATE, EEA and RSC are introduced in this chapter, and the unified framework, PLEEAA, is introduced in the next to set the stage for the case studies.

Differences aside, the aforementioned researchers have successfully demonstrated applicability of several aspects of financial portfolio theory.

The CFA Institute describes a "portfolio approach" as the process of evaluating financial assets in relation to their contribution to the entire portfolio rather than in isolation. (CFA, Ch. 4, pp. 140-142). Certainly this high level concept has applicability to the architecture of systems of systems (SoS) and portfolios of systems and SoS.

Moreover, the CFA Institute lists the steps in the portfolio management process as "planning," which is understand the client's needs; "execution," which is determining the appropriate mix of assets (e.g. fixed income and equity instruments), security analysis (choosing the portfolio's constituent elements), and portfolio construction (optimizing the quantity of elements to achieve performance in line with the client's risk and reward preferences; and "feedback," which consists of monitoring and portfolio rebalancing, performance measurement and reporting. (CFA, Ch. 4, pp. 156-159). The phases of this process is also applicable to systems portfolios. Planning is fundamentally a matter of understanding the customer's overarching needs, objectives and risk tolerance. Execution is about translating that customer information into a portfolio architecture. And feedback implies a dimension of time; namely, that the portfolio manager evaluates the portfolio's ability to satisfy the customer's needs, objectives and risk tolerances through the passage of

time, making decisions to maintain the portfolio status quo or to invest or divest to bring performance back into tolerance.

2.2.8. Introduction to the Systems Trade Space Evaluation Frameworks

As discussed in Section 2.2.7, Modern Portfolio Theory cannot easily be applied to portfolios of systems because forecasting expected returns and variance is highly context-dependent, and the interactions and synergies of the constituent elements are not nontrivial. Fortunately, a tool called Trade Space Exploration (TSE) has been developed to analyze the performance of systems, systems of systems, and portfolios of those elements against the backdrop of stakeholder objectives and requirements. TSE goes beyond "point solution" design tradeoffs by building models based on how the stakeholders' values are satisfied in potential designs. (Ross, 2003)

The frameworks of Multi-Attribute Tradespace Analysis (MATE), Epoch-Era Analysis (EEA) and the enhanced Responsive Systems Comparison (RSC) are cumulative, and provide stakeholders powerful tools to analyze systems, systems of systems, and portfolios of those constituent elements in their anticipated context as a function of time. They are flexible enough to permit changes to the elements through maintenance and upgrades, as well as investments of new elements or divestments of ones no longer sufficiently useful to warrant their continued inclusion. Each of these frameworks is introduced below.

2.2.9. Multi-Attribute Tradespace Analysis

2.2.9.1. Value-Focused Thinking Compared to Alternatives-Focused Thinking

At their core, the frameworks discussed herein are designed to help decision makers make objective choices, particularly when the universe of options is complex and nontrivial.

While the multi-attribute tradespace exploration methods discussed herein are flexible enough to permit a variety of methods to articulate stakeholder preferences, such as Analytic Hierarchy Process, the Multi-Attribute Utility Analysis (MAUA) technique has been the defacto standard for many theses referenced herein. MAUA, as will be discussed below, is a powerful analytical tool that allows the decision maker to evaluate a broader universe of options and minimize biases that may be inherent by choosing among identified alternatives.

In "Value-Focused Thinking" (Keeney, 1992), the author argues that in the context of decision making, there are two types of thinking: alternatives-focused and value-focused thinking.

Alternatives-focused thinking, Keeney argues, is a five step process:

1. Recognize a decision problem: a decision maker identifies a problem that needs resolution.
2. Identify alternatives: the universe of alternative options is enumerated.
3. Specify values: criteria by which the alternatives will be evaluated are identified.
4. Evaluate alternatives: the alternatives are each evaluated against the criteria specified.
5. Select an alternative: the decision maker picks the alternative based on the analysis.

Value-focused thinking, he suggests, differ somewhat by the type of decision needed. For decision problems, there are five steps as with alternatives-focused thinking, but the order is slightly different and the operations are subtly different:

1. Recognize a decision problem.
2. Specify values. Qualitatively, and, if possible, quantitatively articulate the values. The intent here is to expand the universe of alternatives by reducing preconceived notions about the solution set.
3. Create alternatives.
4. Evaluate alternatives.
5. Select an alternative.

Decision opportunities, as compared to decision problems, can be done before or after the decision maker has identified the strategic objectives.

After strategic objectives have been set, the value-focused decision approach is to:

1. Specify values.
2. Create a decision opportunity.
3. Create alternatives.
4. Evaluate alternatives.
5. Select an alternative.

In this scenario the strategic objectives serve as a backdrop from the decision. But the decision need not follow the strategic objectives. In the scenario where the decision opportunity precedes the strategic objectives, the process is:

1. Identify a decision opportunity.

2. Specify values.
3. Create alternatives.
4. Evaluate alternatives.
5. Select an alternative.

Reflecting on the merits of this approach, value-focused thinking may help shape strategic objectives. A decision opportunity may open a new strategic front that may not have been brought to light had the analysis occurred after the strategic objectives were established.

2.2.9.2. Multi-Attribute Tradespace Analysis

Multi-Attribute Tradespace Analysis (MATE) is a powerful tool for making complex decisions. The process consists of three phases: (1) need identification, (2a) architecture-level exploration and (2b) evaluation, and (3a) design-level exploration and (3b) evaluation. (Ross and Hastings, 2005)

A complex decision analysis, according to Keeney (1992), begins with the decision makers articulating their values, which form the mission statement, the problem to be solved or opportunity to be explored. By starting with an articulation of values, the decision makers are able to minimize the effect of "anchoring" that can occur when using alternatives-based thinking. The United States Air Force (USAF) states that its mission "is to fly, fight and win in air, space and cyberspace."[9]

It is important to distinguish between stakeholders and decision makers. All decision makers are stakeholders, but not all stakeholders are decision makers. Stakeholders have their

[9] United States Air Force Mission Statement, https://www.airforce.com/mission, accessed 2/2/2018.

own value propositions. The Project Management Institute (PMI) defines a stakeholder as "an individual, group, or organization, who may affect, be affected by, or perceive itself to be affected by a decision, activity, or outcome of the project, program, or portfolio." (Project Management Institute, 2017). The distinction between stakeholders and decision makers is shown in Figure 6.

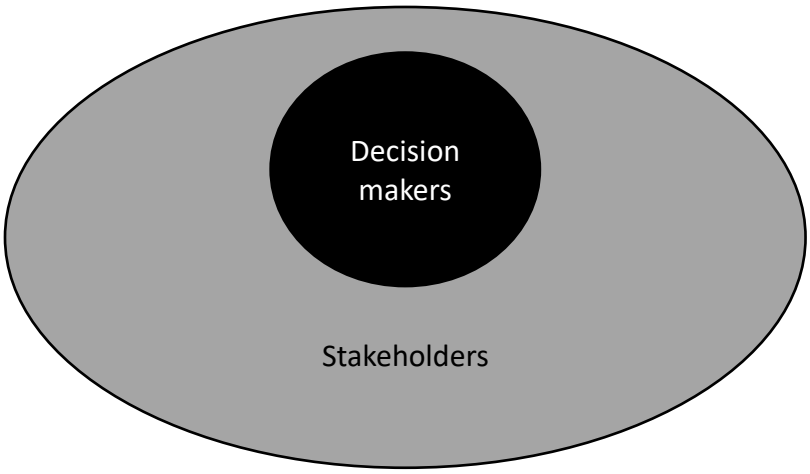

Figure 6. Stakeholders and Decision Makers

The stakeholders' values are translated into attributes. Attributes are quantifiable measures of how well the stakeholders' objectives are met. Attributes, according to Keeney and Raiffa (1976), are complete, functional, decomposable, non-redundant, and minimal. The attribute set is the collection of attributes gathered from the stakeholders. While any number of attributes may be elucidated, Miller's cognitively-based heuristic of 7 ± 2 (1956) poses a practical range to bound the analysis. Ross asserted Miller's heuristic as an appropriate target in his 2003 MIT thesis.

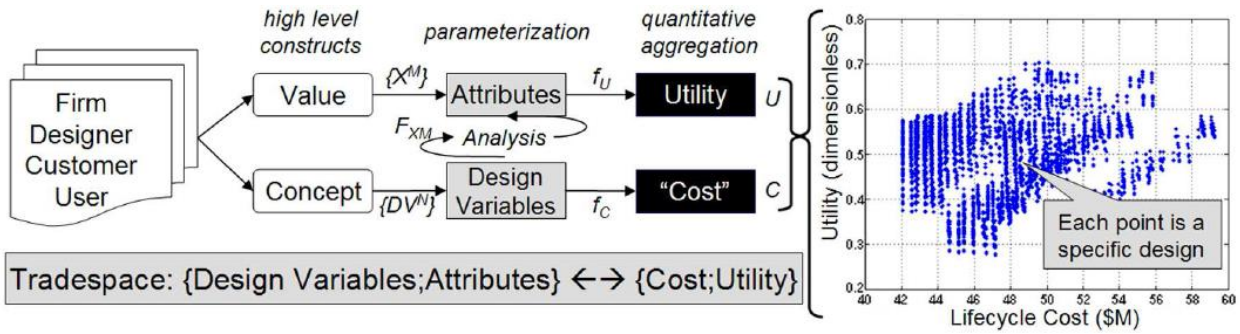

Figure 7. Tradespace designed as shorthand representations of designer controlled technical parameters and stakeholder perceived value parameters executed in terms of utility and cost (Ross, Rhodes and Hastings, 2008)

Utility curves are developed to translate the range of attributes to a user's "satisfaction." These curves can have different shapes depending on the situation—linear increasing, linear decreasing, step change up, step change down, nonlinear, etc. Utility ranges from zero to one, meaning that the stakeholder is indifferent to outcomes that exceed a utility of one. For example, to the owner of a cell phone, the thinness of the device matters to a degree, such that it is comfortable to hold and fit in a pocket, but there likely exists a point where a thinner device has no additional utility for the user.

Several mathematical techniques have been developed to allow the combination of multi-attribute utility functions. Underpinning these techniques are assumptions about the independence of the attributes. Keeney (1992) suggests that there are four main independence conditions—preferential, weak-difference, utility and additive independence. Those conditions are discussed briefly below.

Preferential Independence

A "pair of attributes $\{X_1, X_2\}$ is preferentially independent of attributes $X_3, \ldots, X_N$ if the preference order for consequences involving only changes in the levels of X_1 and X_2 does not

depend on the levels at which attributes X_3, …, X_N are fixed. This condition implies that a stakeholder's indifference curves over X_1 and X_2 do not depend on the other attributes." (Keeney 1992) Preferential independence therefore suggests that the preference order for consequences is static despite changes in the levels of the attributes.

Weak-Difference Independence

"Attribute X_1 is weak-difference independent of attributes X_2, …, X_N if the order of preference differences between pairs of X_1 levels does not depend on the levels at which attributes X_2, …, X_N are fixed." (Keeney 1992)

Utility Independence

"Attribute X_1 is utility independent of attributes X_2, …, X_N if the preference order for lotteries involving only changes in the level of X_1 does not depend on the levels at which attributes X_2, …, X_N are fixed." (Keeney 1992) He states that in this context a lottery is characterized by "a mutually exclusive and collectively exhaustive set of possible consequences and the probabilities associated with the occurrence of each."

Additive Independence

Finally, "attributes X_1, …, X_N are additive independent if the preference order for lotteries does not depend on the joint probability distributions of these lotteries, but depends only on their marginal probability distributions." (Keeney 1992) This concept is illustrated below in Figure 8, which was adapted from Figure 5.3 of Kenney. A stakeholder is presented with two lotteries, L_1 and L_2, and in each there are two outcomes of equal probability of occurrence. By inspection, it is clear that in both lotteries L_1 and L_2 that there is a 50% chance of x_1 and x_2, and of course, a 50% chance of y_1 and y_2. The marginal probability distributions on each of

attributes *X* and *Y* are equal in both lotteries, and therefore, the stakeholder would be indifferent between the two lotteries.

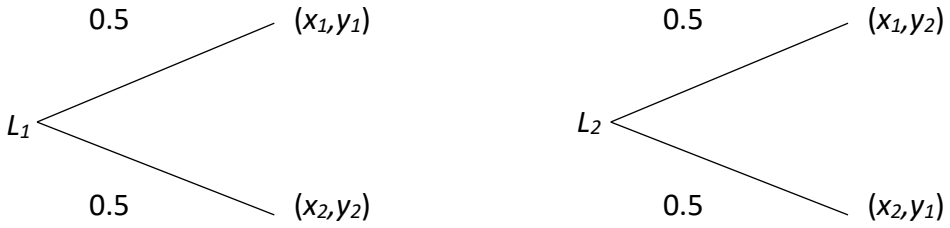

Figure 8. Additive independence illustrated through Lotteries L_1 and L_2

The additive independent utility function, given attributes $X_1,\ldots,X_N$, can be mathematically expressed as:

$$u(x_1, \ldots, x_N) = \sum_{i=1}^{N} k_i u_i(x_i) \tag{4}$$

Where,

$u_i(x_i)$ is the utility function over attribute X_i.

k_i is the set of scaling constants on the utility function

Note that a stakeholder's utility is bounded as $0 \leq u_i(x_i) \leq 1$, which means that at zero utility that stakeholder is completely unsatisfied and at unity the stakeholder is completely satisfied.

The scaling constants are bounded as $0 \leq k_i \leq 1$, which serves to weight the constituent elements of the utility function such that the multi-attribute utility $u(x_1, \ldots, x_N)$ is also bounded by zero and one. Or, said differently by Ross (2003), k_i is the multi-attribute utility value for that attribute, X_i at its best value with all other attributes are their worst value. The relative values of k_i serve to illustrate the relative importance of the attributes under consideration. Finally, the scaling constants are sum to one:

$$\sum_{i=1}^{N} k_i = 1$$

(5)

The additive independence method would be appropriate in scenarios where the stakeholder is indifferent to the outcomes of lotteries with the same marginal utility distributions that span the attributes' ranges. While the simplicity of the math makes this method fairly quick, its applicability to the analysis of complex systems and systems of systems as discussed herein is somewhat limited. It could be employed, for instance, as a first-pass analysis before a more robust analysis. The additive independence method assumes that the attributes are uncorrelated. Given the properties of emergent functional behavior inherent in complex systems and systems of systems, this lack of correlation is not always a valid assumption. The nontrivial interactions of system elements may result in unexpected changes in system behavior when one or more attributes are changed.

In their discussion of Multi-Attribute Utility Analysis (MAUA), Keeney and Raiffa (1976) provide the detailed derivation of the following multi-attribute utility function.

Given attributes $X_1,\ldots,X_N$, $N \geq 3$, the utility function

$$u(x_1, \ldots, x_N) = \sum_{i=1}^{N} k_i u_i(x_i) + k \sum_{i=1}^{N} \sum_{j>1}^{N} k_i k_j u_i(x_i) u_j(x_j)$$

$$+k^2 \sum_{i=1}^{N} \sum_{j>1}^{N} \sum_{j>h}^{N} k_i k_j k_h u_i(x_i) u_j(x_j) u_h(x_h)$$

$$+ \cdots + k^{N-1} k_1 \cdots k_N u_1(x_1) \cdots u_N(x_N) \quad (6)$$

exists if and only if {X_1,X_i}, i = 2,…, N, is preferentially independent of the other attributes and if X_1 is utility independent of the other attributes. (Keeney 1992)

As before, u_i is bound by zero and one, and scaling constants k_i are selected to determine the overall utility u. The constant k is calculated from k_i, with i = 1,…,N. When $\sum_{i=1}^{N} k_i = 1$, then k is zero, and when $\sum_{i=1}^{N} k_i \neq 1$ k is not equal to zero. By inspection, when k is zero, the equation simplifies to the additive utility function.

When $k \neq 0$, the multiplicative utility function can be derived by multiplying both sides of the above equation by a normalization constant, k, adding one and factoring, which yields:

$$ku(x_1, \ldots, x_N) + 1 = \prod_{i=1}^{N} [kk_i u_i(x_i) + 1] \tag{7}$$

When the normalization constant is negative, x_1 and x_2 can be thought of as substitutes. When positive, they complement each other, and when zero, there is no preference between them.

The scaling constants, k_i, are not an indication of the relative importance of the attributes, but rather, represent the level of stakeholder satisfaction when the given attribute is at its best value when all other attributes are at their worst value.

Once the attributes and their associated utility profiles have been specified, the next step is to define the design variables and, subsequently, the design vector. The design variables set establishes the degrees of freedom for the architecture. They represent the tradeable parameters in the design problem. The design variables are enumerated, and the range of each is defined. For example, a satellite architecture might consider design variables such as

propulsion type, power type, reliability, and altitude. A main battle tank might evaluate design variables such as crew size, cannon bore, rate of fire, maximum speed, and armor type.

The decision maker then evaluates each of the identified design variables against each of the attributes, typically using qualitative strength-of-correlation numbers such as 0, 1, 3, and 9, with the endpoints indicating no correlation and significant correlation, and the middle numbers representing, obviously, something in between. A tool such as the Design-Value Matrix (DVM) (Ross, 2006), or the Quality Functional Deployment (QFD), sometimes called the "House of Quality," is used, with design variables displayed in rows and the attributes in the columns. This methodology is useful for determining which design variables are most significant. (Ross, 2006)

The design vector is the set of design variables, and all permutations of design variables yields the number of architectures under evaluation. (Ross, Rhodes, and Hastings, 2008) The set of all design vectors bounds the design space.

A model is then built to analyze the design space. The models are typically physic-based to provide a realistic tie to environment in which the system will operate. They transform each design vector into attributes, which enable utility functions to be applied. Architecture design cost and attribute utility are calculated.[10] The architectures are plotted in the tradespace, with expense shown on the *x*-axis, and utility on the *y*-axis. An example is shown below in Figure 9. "Utopia" then would constitute zero expense and perfect utility.

[10] Multi-Attribute Tradespace Exploration, http://seari.mit.edu/mate.php, accessed 2/22/2018.

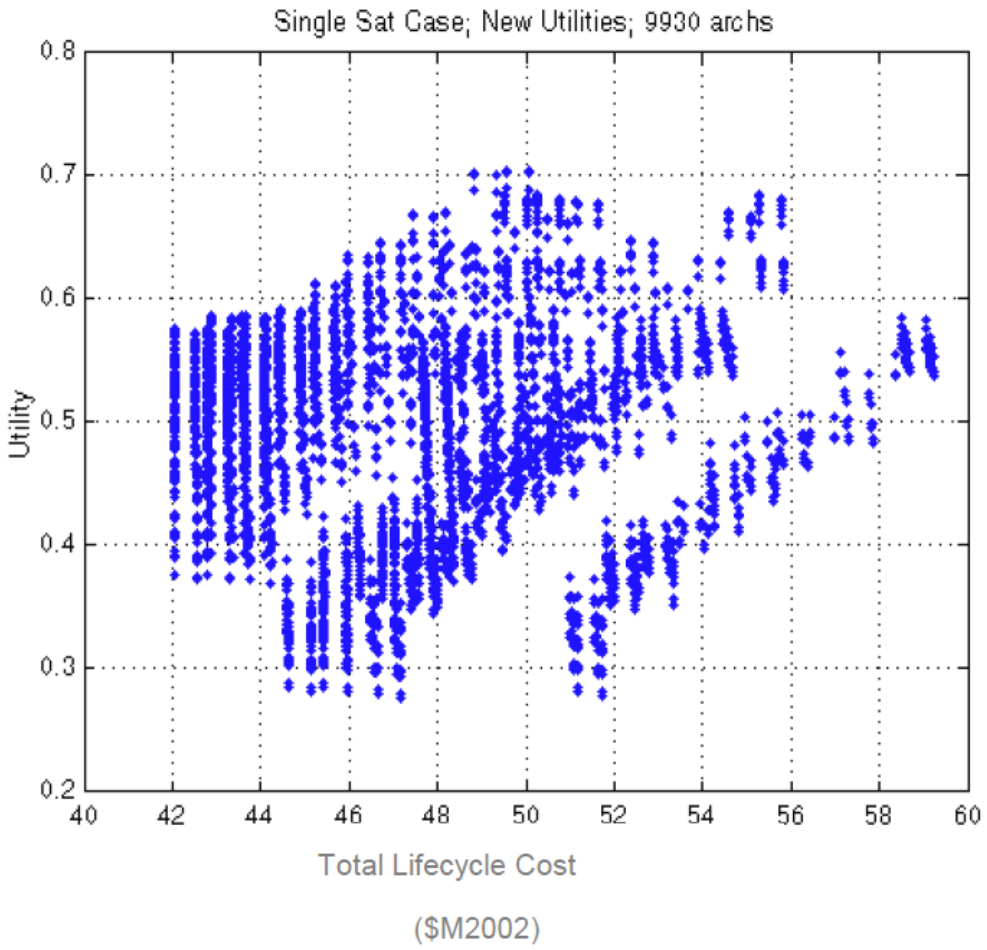

Figure 9. Example Tradespace Plot (Ross and Hastings, 2005)

The final step is to explore the tradespace. This methodology does not yield a single, deterministic answer to the design problem. Rather, the range of outcomes on or near the Pareto front will be of most interest to the decision maker. In a hypothetical example of a satellite system, the source of power helps inform mission life, amount of power available to drive subsystems, and many of the system's capabilities. On one end of the spectrum may be electrical power derived from solar, and at the other end, nuclear power. Relative to nuclear power, electrical power would have lower cost. But it is possible that the amount of energy available from each source would be different, which would drive a difference in utility

between the two choices. The decision maker then faces a choice between the two, trading cost and utility in the context of the unique mission requirements.

2.2.10. Epoch-Era Analysis

The dynamic nature of modern times mean that the contextual backdrop in which systems operate change over time. A system that provides very high utility when it is deployed may see that utility decline over time as the stakeholder needs evolve. Ross and Rhodes (2008) termed this property "value robustness"—the "ability of a system to continue to deliver stakeholder value in the face of changing contexts and needs."

Examples of value robustness derive from the lifecycle properties, the "ilities," including system modularity, such that systems can be modified or upgraded to address evolving requirements; maintainability, so that systems can be serviced and kept operational for longer; and interoperability, for example by using well-defined and controlled interfaces and open standards, so that other systems can interact and provide added value through network effects. (de Weck et al, 2011) Survivability, Ross and Rhodes (2008) suggest, is the "ability of a system to minimize the impact of a finite disturbance on value delivery."

Figure 10 below illustrates the concept behind the epoch-era analysis framework. In the first epoch, the system is operational in Context 1, and has performance capabilities that exceed expectations. In the figure, stakeholder expectations are represented by the range from the minimal "threshold" requirements to the maximum "objective" requirements. In the second epoch, the context changes to Context 2, and its performance is somewhat degraded relative to expectations. In the third epoch, the context remains the same as in the second epoch, but the stakeholder's expectations have increased. In the fourth epoch, a new

need is introduced in a new context, shifting the stakeholder expectations up. Yet the system continues to satisfy, illustrating versatility in the face of evolving need. While it does not exceed all expectations, it still outperforms the threshold level. In the fifth epoch, evolving context and rising expectations mean that the system is no longer able to meet the need without an upgrade.

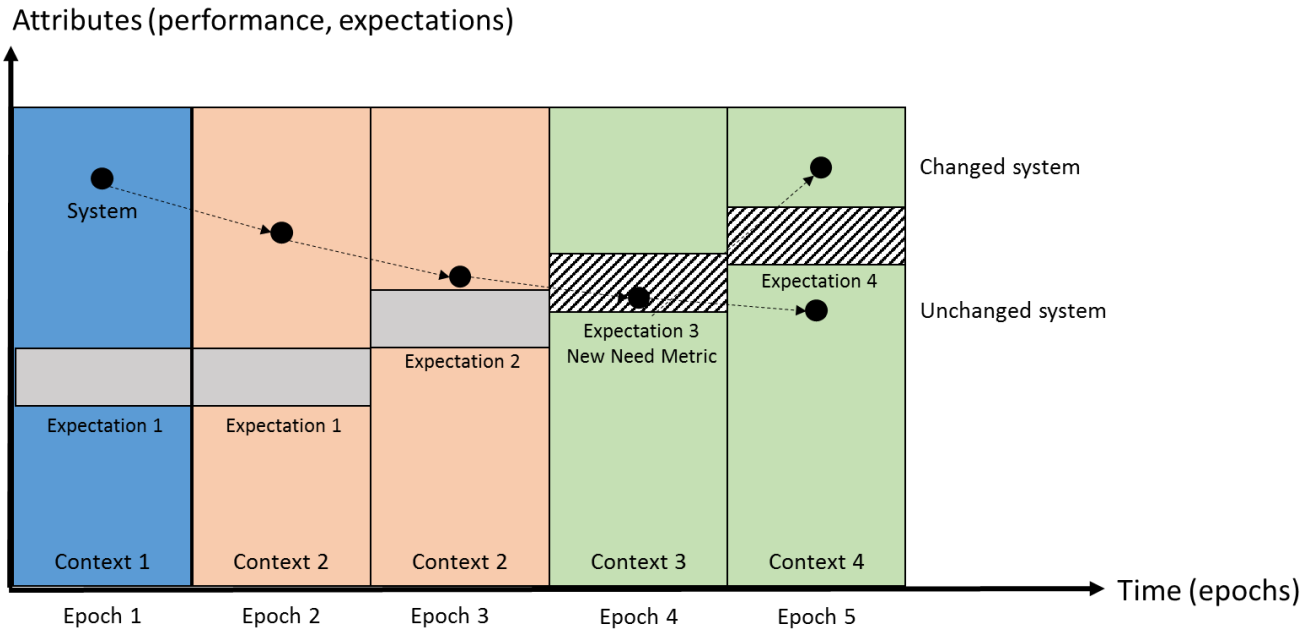

Figure 10. Epoch-Era Analysis (Adapted from Ross and Rhodes, 2008)

As defined earlier in Section 2.1(vi), and epoch is a period of time for which the requirements context is, for all intents and purposes, static. And per Section 2.1(vii), an era is an ordered sequence of epochs, each with their own unique requirements contexts. The intent of this construct is to model the changing contexts of the "real world" that result, at least in the case studies discussed herein, changes in Presidential administrations, Defense budgets, evolving technologies, adversary threats and conflict, etc.

The B-52 Stratofortress design dates to 1946, flew for the first time in 1952, and has been in continuous operation since 1955.[11] The platform's original context has changed, and so to have countless technologies that affect the aircraft. Had the design been immune to change, it would surely have been retired decades ago. But the system was periodically upgraded to address changing needs and rapidly evolving technologies, and it continues to operate well into the 21st century.

Fitzgerald, in his MIT masters thesis (2012), introduced the Valuation Approach for Strategic Changeability (VASC) based on EEA, and introduced a number of useful metrics. Among these are the Fuzzy Pareto Number (FPN), effective Normalized Pareto Trace (eNPT), effective fuzzy Normalized Pareto Trace (efNPT), Fuzzy Pareto Shift (FPS), and Available Rank Index (ARI).

The Fuzzy Pareto Number indicates a portfolio's relative value in an epoch under investigation. It has a range of zero to 100, and reflects the percent deviation from the efficient frontier. The FPN can also be used to compare portfolios across epochs to determine effectiveness. (Fitzgerald and Ross, 2012) i.e., a portfolio with an FPN equal to 100 across all epochs comprising an era would be superior.

The Normalized Pareto Trace (NPT) is calculated as the percentage of epochs for which an architecture is on the Pareto frontier. It can be calculated by counting the number of epochs in which an architecture has an FPN of zero, and dividing by the number of epochs under analysis. Similarly, fuzzy Normalized Pareto Trace (fNPT) utilizes the same methodology,

[11] Boeing B-52 Stratofortress, https://en.wikipedia.org/wiki/Boeing_B-52_Stratofortress, accessed 2/15/2018.

albeit by including a tolerance below the efficient frontier to include near-Pareto-optimal architectures. When the tolerance is equal to zero, fNPT simplifies to NPT. (Fitzgerald and Ross, 2012).

The effective Normalized Pareto Trace (eNPT) and effective fuzzy Normalized Pareto Trace (efNPT) metrics grade architectures on their "changeability-enhanced performance" rather than their baseline performance. These metrics are useful when architectures are agile enough to be changed in response to changing contexts. eNPT is calculated on Pareto-optimal architectures, whereas efNPT is calculated on the fuzzy Pareto-optimal architectures. Fitzgerald noted that these metrics consider both active and passive architecture robustness simultaneously.

The Fuzzy Pareto Shift represents the difference between the Fuzzy Pareto Number before and after changes for a particular architecture in an epoch under analysis. Its magnitude can be positive or negative, and represents an increase (+) or decrease (-) in cost efficiency associated with the changeability. Mathematically, FPS is given by:

$$FPS(d) = FPN(d) - FPN(d^*) \tag{8}$$

By inspection it is clear that a shift closer to the efficient frontier, which corresponds to the FPN decreasing, would give a positive FPS.

The Available Rank Improvement metric is a measure of the maximum utility rank-order improvement possible by considering each design change in isolation. Fitzgerald noted that ARI is dependent on the enumeration of designs, but has some utility in evaluating how much value could potentially be realized by using a particular design change. (2012)

It is worth noting that EEA is not confined to trade space exploration. It can be used for point-design analysis. (Fitzgerald and Ross, 2012) For the purpose of this research, however, EEA will be used in tandem with MATE.

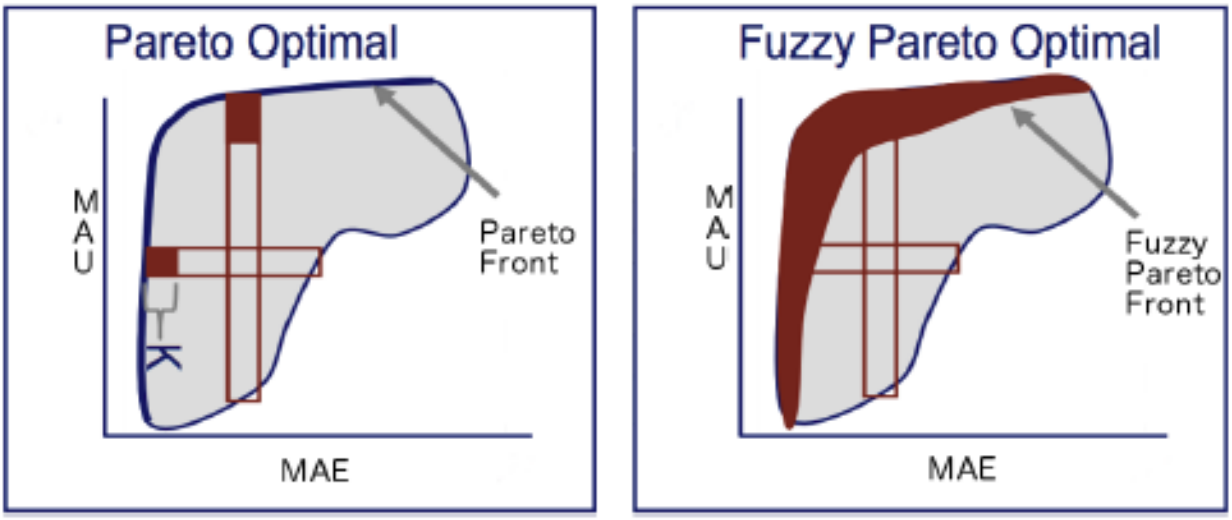

Figure 11. The Pareto Frontier and the "Fuzzy" Pareto Frontier Compared (Schaffner, Ross, and Rhodes, 2014)

2.2.11. Responsive Systems Comparison

The original Responsive Systems Comparison method was introduced by Ross et al in 2008 as an extension of the MATE and EEA frameworks, intended to better capture the evolving context in which systems would be used operationally over time, and identify how the system under investigation adds value in the face of changing context. The RSC method was meant to objectively model the lifecycle of the deployed system. It was validated in multiple case studies (Ross et al, 2008, 2009).

The enhanced RSC process, modified by Schaffner (2014), consists of six processes, which have some overlap with MATE and EEA, and are grouped into three phases: (1) Information Gathering, (2) Alternatives Evaluation, and (3) Alternatives Analysis. The processes in the

Information Gathering phase are: value-driving context definition, value-driven design formulation, and epoch characterization. The Alternatives Evaluation phase includes the design-epoch tradespace evaluation process. And the Alternatives Analysis phase includes single epoch analyses, multi-epoch analysis, era construction, single-era analyses and multi-era analysis. An overview of the process flow is shown in Figure 12.

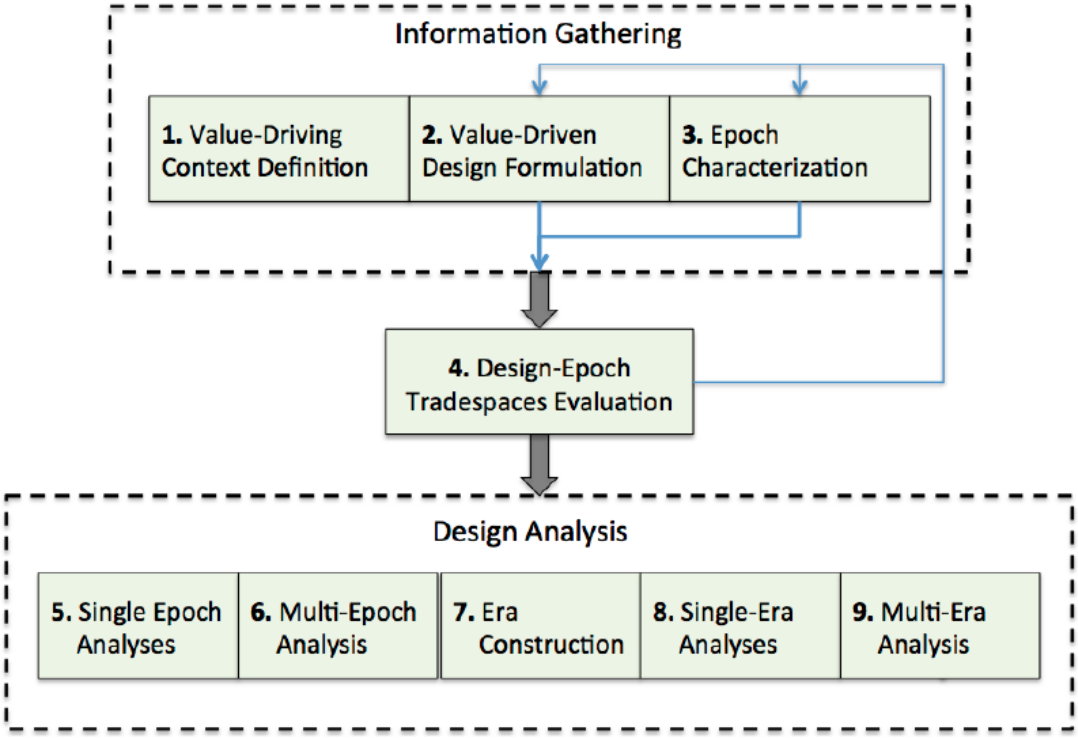

Figure 12. Overview of Enhanced Responsive System Comparison Method. (Schaffner, 2014)

Process 1, Value-Driving Context Definition, involves developing the basic problem statement, as well as identifying the stakeholders and external uncertainties. Finally, the resources available to the stakeholders are enumerated.

Process 2, Value-Driven Design Formulation, takes articulated stakeholder needs and restates them as system performance attributes. Utility functions pertaining to each stakeholder's preference relative to the performance attributes are created. System cost

functions are generated. System concepts are developed and subsequently decomposed to their basal design variables.

In Process 3, Epoch Characterization, contextual uncertainties are stated as epoch variables and given potential ranges. The complete enumeration of epoch variables constitutes all possible "futures" to be analyzed. Any changes to resource supply and availability are identified.

In Process 4, Design-Epoch Tradespaces Evaluation, the design and epoch variables are translated into Multi-Attribute Utility (MAU) and Multi-Attribute Expense (MAE) measures for each design in each epoch.

Process 5, Single Epoch Analysis, compares the system concepts in single epochs by plotting MAE and MAU in X-Y space. The "utopia" point is MAU equal to 1 and MAE = 0. Non-dominated or nearly-non-dominated designs are highlighted for further analysis in subsequent processes.

Process 6, Multi-Epoch Analysis, extends Process 5 by looking across multiple epochs. Designs that show promise across multiple epochs are more robust than those that show robustness in only a subset or none at all. The designer can evaluate the impacts of active and passive strategies to determine whether prudent investments, properly scoped and timed, can improve the MAU and MAE across, epochs.

Process 7, Era Construction, compiles ordered sequences of epochs which represent a possible future context in which the system will be used. The duration of the epochs need not be constant, nor is there a standard duration for the era. Thus, it is possible that an era may have only a small number of epochs, and the epochs may have differing durations. Or similarly, an era

could have many epochs. The overall era length would typically coincide with the system's lifecycle, though it could examine other overall durations, such as a subset of the desired system lifecycle.

Single Era Analysis is the theme of Process 8. The system is analyzed against an ordered sequence of epochs that form a single era. Focusing on a single era, such as the period spanning the system's lifecycle, enables system designers to examine, for example, whether certain designs outperform in niche contexts but underperform others in the broader context of the era. Path dependencies may also become evident in this analysis. A cycling "Grand Tour" such as the Tour de France serves as a useful metaphor. It is possible for a rider to win the Tour de France without having won a single stage. The overall victor of the multi-stage event need only be the most consistently high finisher among all other competitors. Deepening the analogy to path dependence, the path to overall victory could involve a strong early showing, followed by defending the lead for the balance of the Tour, or the ultimate victor may conserve energy by allowing others to win stages early, securing the overall lead late in the race once cumulative fatigue has worn down the early leaders.

In Multi-Era Analysis, the ninth and final process of RSC, the designer evaluates the system across multiple eras, and identifies strategies that provide a satisfactory measure of affordability over multiple possible futures. This helps to guard against systems that perform very well in one era but that may perform poorly in others. This process is most valuable when the future is highly uncertain. Calling upon Process 8's metaphor of a cycling Grand Tour race, Process 9 helps to identify versatile "General Contender" riders who can persevere and win across a variety of Grand Tours dominated by mountains, time trials, or other terrain and formats.

2.2.12. Systems Portfolio Construction as a Complex Decision

The problem of portfolio design and management is made more complicated by the fact that constituent systems may not add serially to the performance of the portfolio. Some of the elements may participate in systems of systems, in which emergent functions are realized from the synergistic behavior of the elements.

The Portfolio-Level Epoch-Era Analysis for Affordability framework which is the subject of this research included some consideration for system of systems. Chattopadhyay developed a System of Systems Tradespace Exploration Method (SoSTEM) that identified three types of combinations that arise in SoS design problem, and were subsequently leveraged for PLEEAA. How these systems of systems interact to provide value is important, as it can affect complexity and cost, but can also provide clever means to satisfy stakeholder needs with fewer unique systems. (2009) The three types of system of systems combination complexity are depicted in Figure 13.

The simplest type is in which systems act independently to satisfy system of systems attributes. An example of this type is an air traffic control system and a weather radar. Both systems are used to manage the airspace, and at least in early manifestations of air traffic control, the systems act independently.

The next level is medium combination complexity. In this scenario, two or more systems collaborate to fulfill system of systems attributes, such as through handoffs. Interoperability is a significant concern with this type of combination. One such example of a medium combination complexity system of systems is an ISR asset detecting an adversary target, and the target is engaged by a nearby fighter jet. It should be noted that this is an

oversimplification of current operations, as the "Kill Chain" (discussed in Case Study 1) involves a human decision and approval to engage the target, rather than a pure machine-to-machine handoff.

Finally, high combination complexity is covered by the third level. In this case, two or more systems merge capability simultaneously to deliver system of systems performance attributes. Chattopadhyay cites data fusion as one such example. Fusion is increasingly common in ISR processing, exploitation and dissemination (PED). In that context, fusion of intelligence products—for example, concurrent collection of signals intelligence and geospatial intelligence—helps increase the intelligence fidelity, in effect boosting the signal-to-noise ratio and reducing the risk of false positives.

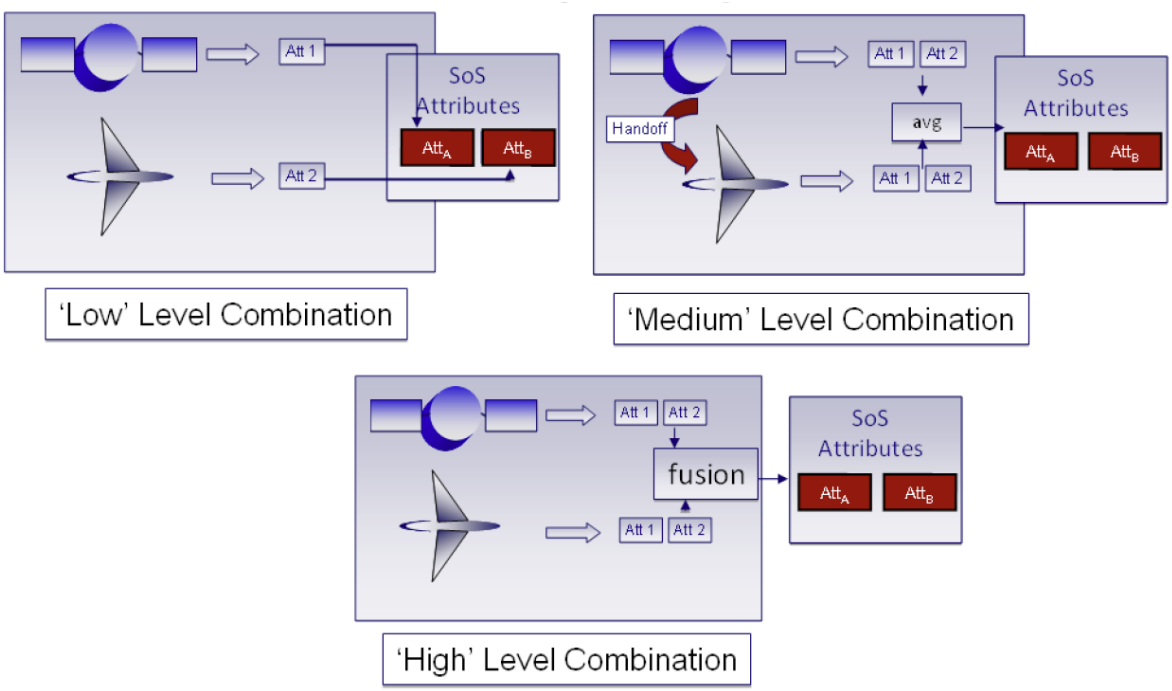

Figure 13. System of Systems Combination Complexity (Chattopadhyay, 2009)

The complexity of combination concept, as applied to portfolios of systems, is discussed briefly in the overview of the Portfolio-Level Epoch-Era Analysis for Affordability chapter.

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3. Portfolio-Level Epoch-Era Analysis for Affordability

The preceding frameworks discussed in Chapter 2 established the cumulative foundation that set the stage for Vascik, Ross and Rhodes' portfolio-level work (2015, 2016). A graphical overview of the so-called Portfolio-Level Epoch-Era Analysis for Affordability (PLEEAA) is shown below in Figure 14, and a detailed discussion of the novel elements follows.

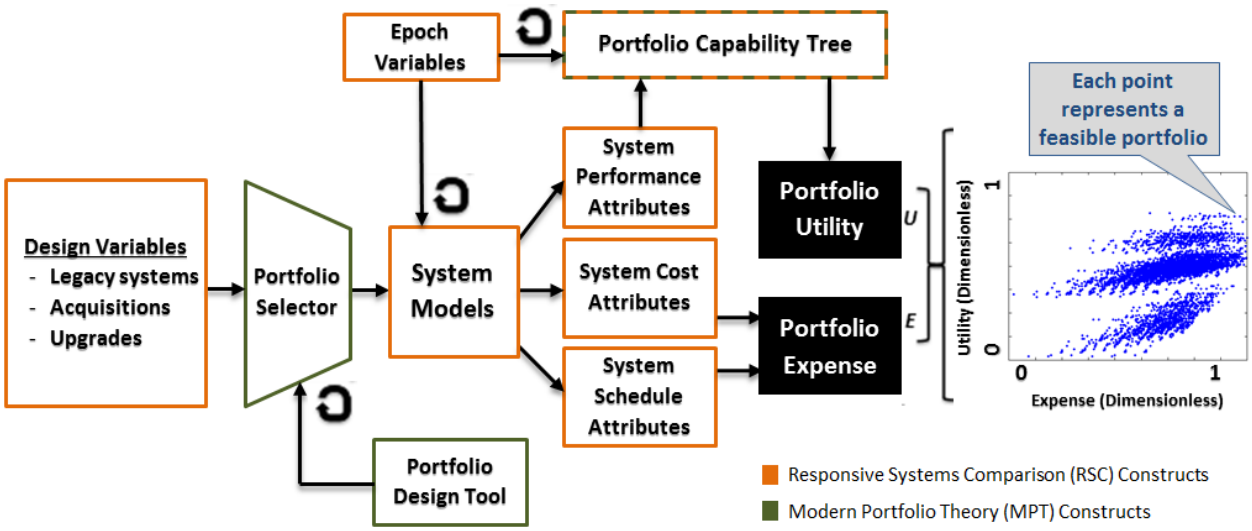

Figure 14. PLEEAA framework overview (Vascik, Ross, and Rhodes, 2015, 2016)

3.1. Portfolio Design Tool

As discussed in Section 2.2.7 earlier, the financial portfolio design problem includes choices about asset allocation—the choice, for example, of equities and fixed income instruments that coincide with the client's risk tolerance and desired return.

When translated to portfolios of complex systems, the asset allocation decision involves decisions about what types of assets will be considered. Since this hints at alternatives-centric thinking, portfolio stakeholders may wish to conduct the analysis at least two ways: once with known assets, and again with values-based thinking where new asset types may

better realize the stated objectives. Given the lead time associated with new system development and acquisition, portfolio timelines may make the "clean sheet of paper" analysis a nonstarter.

The portfolio designer may also make decisions about what Vascik calls "class constraints"—boundaries on the minimum and/or maximum quantities of costs allocated to particular assets in the portfolio.

Intuitively the Portfolio Design Tool has substantial sway over the outcome, both in terms of utility and cost. Incremental, linear thinking versus "blue sky thinking" may yield wildly different portfolios.

With the allocation decisions and constraints established, the Portfolio Design Tool enumerates all possible portfolios to be analyzed, while serving to limit the computational complexity. (Vascik, Ross and Rhodes, 2015)

3.2. Portfolio Selector

The Portfolio Selector compiles specific portfolios for modeling, by screening portfolios for that meet the constraints imposed.

3.3. Portfolio Capability Tree

PLEEAA uses a Portfolio Capability Tree as a means of mapping portfolio constituent performance attributes up to portfolio-level capabilities, and conversely, aggregating constituent system capabilities into a cogent portfolio capable of satisfying its stated objectives.

The portfolio capability tree derives from Keeney's (1992) means-ends objectives network (Vascik, Ross, and Rhodes, 2015). The means-end objectives network eventually terminates

at alternatives or classes of alternatives. This hierarchical mapping of objectives to alternatives enables quantitative methods and analysis. The Portfolio Capability tree uses the same methodology to link constituent assets at the lowest level to overall portfolio utility at the highest level.

As is common with the MATE framework, the portfolio designer leads into the capability tree creation with a statement of stakeholder values. The fundamental objectives are articulated, and subsequently decomposed into portfolio-level performance attributes.

The portfolio designer shares each top-level performance attribute with the program manager with authority over programs which contribute to that attribute. Then the process is recursively repeated, with the program manager decomposing her values into program-level performance attributes. These attributes are either shared with another program mangaer or mapped to the systems under their authority. Each level of decomposition may have its own performance attributes and utility models.

Vascik et al (2015, 2016) discuss the process of progressively amalgamating the responses back up the hierarchy from the bottom up. The “in-level” program manager conveys his utility metrics to the level-above manager. This interface is referred to as a “node.” Recognizing that less-than-objective biases may be present in this process, the portfolio designer may seek methods to normalize the responses. Vascik noted a similar but different issue in the form of multi-party negotiation methods, noting an opportunity for future research. The author asserts that one tactic for minimizing or eliminating bias is to instead outsource the utility assessments to entities without the inherent conflict of interest, namely budget authority. In the case of the U.S. Government, utility measures could be sought from

the user community, or from third party consultants such as Federally-Funded Research and Development Centers (FFRDC).

An overview of the portfolio capability tree creation process is shown in Figure 15. The flow as described above is top-down, followed by bottom-up. Note that the multi-document symbols shown at each level of decomposition depicts a program manager who uses their own value and performance models in the assessment of utility in their branch of the tree. (Vascik, Ross, and Rhodes, 2015).

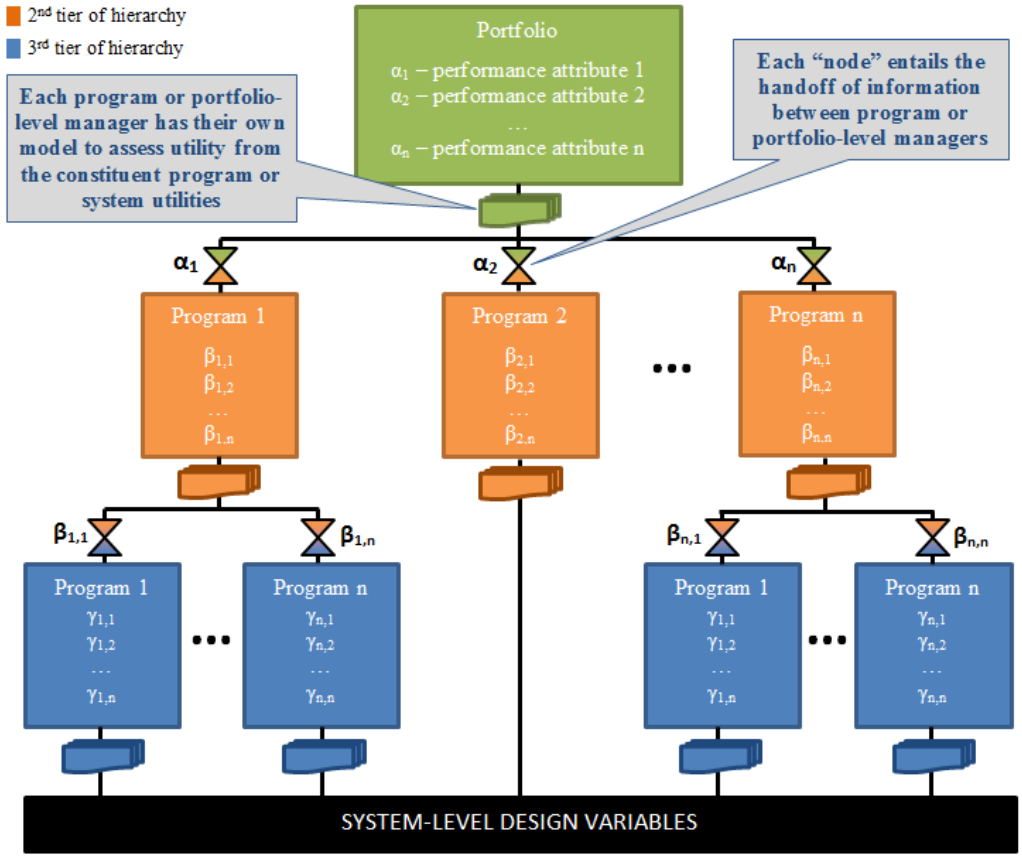

Figure 15. PLEEAA Capability Tree breakdown structure (Vascik, Ross and Rhodes, 2015)

Figure 16 shows a truncated portfolio capability tree from the Carrier Strike Group case study presented by Vascik, Ross, and Rhodes. Some branches terminated after only one level, while others branched several times. There are no firm rules about the number of

hierarchical layers necessary. The decomposition process is complete when the performance attribute at the lowest-level node, the "leaf node" as Vascik calls it, is described by a constituent system metric. Qualitatively, the more hierarchical layers there are in the portfolio tree, the more complex, nuanced, and computationally intensive the analysis may become. A potentially intriguing area of future investigation would be to extend PLEEAA to the domain of "big data," where novel patterns and insights may be gleaned from datasets of a size beyond the cognitive capability human analysts.

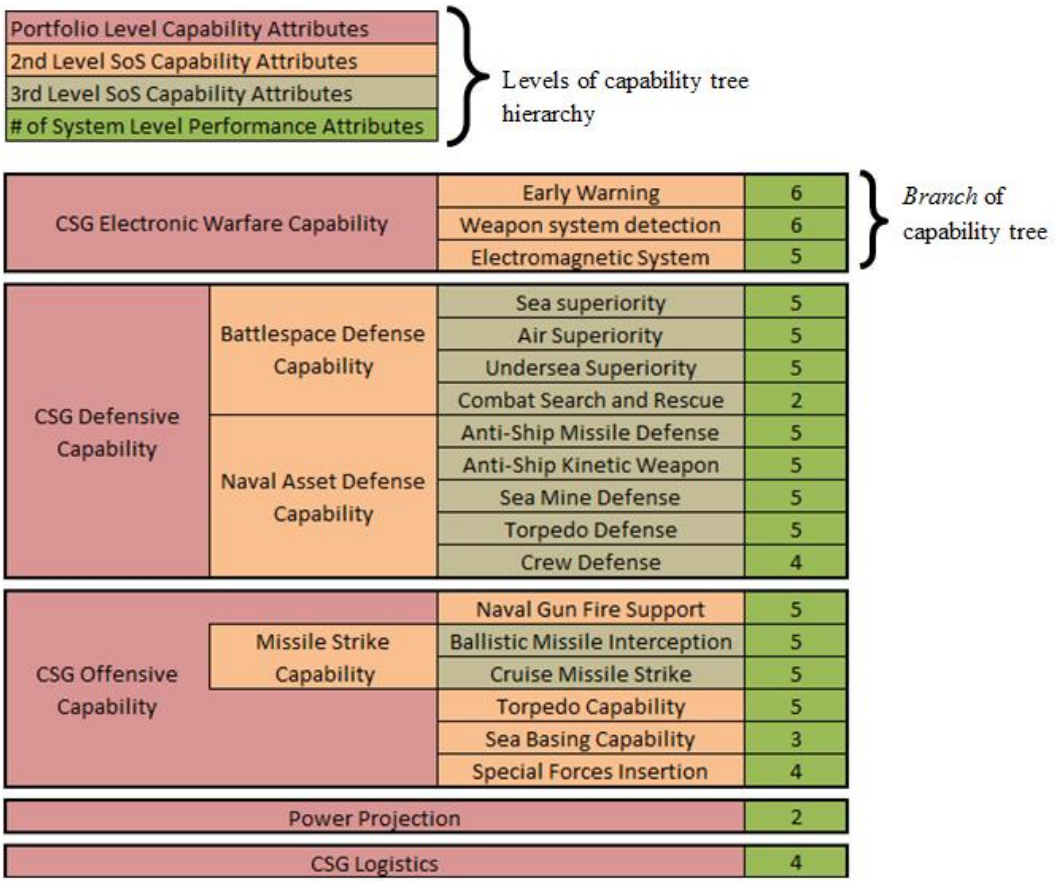

Figure 16. Example Portfolio Capability Tree (Vascik and Ross, 2015)

3.3.1. Complementary and Substitute Capabilities

Systems and systems of systems combined in a portfolio experience emergent functional behavior. Both complementary and substitute capabilities may be identified through the Portfolio Capability Tree. These are discussed briefly here.

3.3.1.1. Complementary Capability

Complementary systems are two or more constituent elements that combine in a system of systems or portfolio and either change in value delivery against existing performance attributes or add capability in new performance attributes. The magnitude and direction of change depends on the unique circumstance. The changes may stem from a change in the Concept of Operations (CONOPS). (Vascik, Ross, and Rhodes, 2015)

The Portfolio Capability Tree aids the identification of complementary capabilities. The lowest-level managers, having a high degree of knowledge of their systems, combined with visibility into the other systems under evaluation in the portfolio, may be able to identify pairings that provide complementary behavior. This may be limited in military systems where some capabilities are classified or compartmented in such a way that the low-level stakeholders may not have sufficient, or any, knowledge of systems beyond their immediate control. Also of note is that emergent function is often not trivial to identify, so attempts to identify complementary systems may not be completely fruitful.

3.3.1.2. Substitute Capability

Substitute capabilities occur when two or more constituent elements combine in a system of systems or portfolio and provide overlapping capability in a CONOPS. (Vascik, Ross, and Rhodes, 2015) It is worth noting that substitute capabilities are not necessarily a bad thing.

Redundancy can provide continuity of operation when one element fails. For instance, substitute capabilities are useful for military command, control and communications. It is also worth noting that context matters, because systems may be substitutes in one use case or context and not in others.

The process of creating the Portfolio Capability Tree can help identify substitutes. As discussed above, the lowest-level program managers evaluate each system in terms of the attributes. Of course, this says nothing of the organizational behavior matters that arise in such an exercise. Programs and budgets are controlled by people, and the motivations of those people are not always altruistic.

3.3.2. Multiple Stakeholders

The case studies examined in this research focus on portfolio design problems where there is typically a primary stakeholder, and that person is effectively the Chief Executive Officer of the portfolio with a high degree of control over the constituent elements. This need not be the case.

In a hypothetical example of a next-generation Air Traffic Control portfolio, different potential constituents may belong to a host of Government departments and agencies, such as the Federal Aviation Administration, the National Oceanic and Atmospheric Administration (for weather), the Department of Defense (for the Global Positioning System), and others. Coming to a consensus about the portfolio objectives and attributes may be more complicated in an example like this, potentially requiring negotiation between multiple stakeholders.

No further novelty is advanced in this paper to incorporate the works of Fitzgerald and Ross (2015, 2016). This could be the subject of future research.

3.4. PLEEAA Process

The PLEEAA process flow is adapted from the works of Schaffner (2014) and Ross et al (2009). For reference, the Responsive System Comparison framework was discussed above, and its process flow is illustrated in Figure 12.

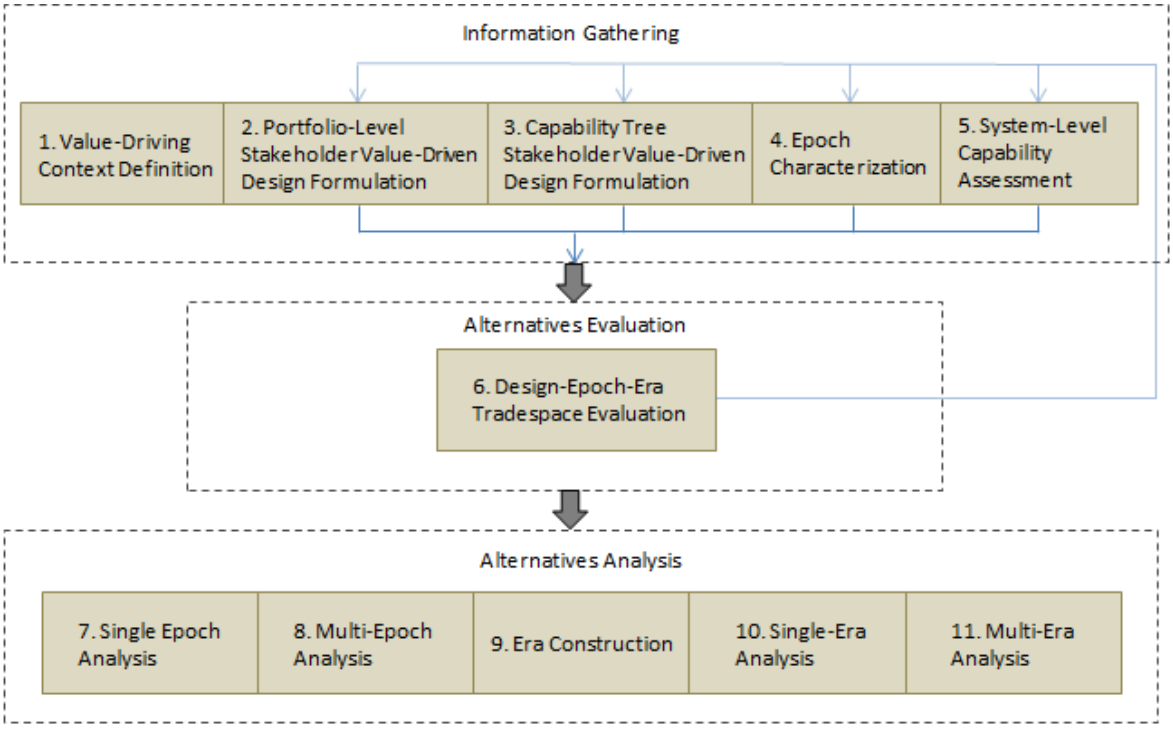

Figure 17. PLEEAA Process Adapted from RSC Method (Vascik, Ross, and Rhodes, 2015)

PLEEAA builds upon the nine processes of the enhanced Responsive Systems Comparison framework discussed earlier, comprising eleven steps spread over three phases. Processes one through five make up the "Information Gathering" phase, process six is the "Alternatives Evaluation," and processes seven through eleven make up the "Alternatives Analysis" phase. These are elaborated on below, as defined by Vascik, Ross and Rhodes (2015).

3.4.1. Process 1: Value-Driving Context Definition

Process 1 is concerned with developing the basic problem statement for which the proposed portfolio is being assembled, and portfolio-level stakeholders are identified and interviewed. It is at this stage that the initial value proposition is articulated, and threats and risks are identified. A tentative set of candidate assets is created, and the portfolio designer's level of control over those assets is identified.

3.4.2. Process 2: Stakeholder Value-Driven Design Formulation

Process 2 requires that the portfolio designer solicits information from the portfolio-level stakeholders to generate the highest level of the capability tree, as well as identify constraints that bound the portfolio.

Two types of attributes are identified: performance and expense. The former gives the top-level capabilities which the portfolio much achieve to meet the stated strategic objectives. Weights are assigned to these based on stakeholder preferences and a utility function is developed. The expense attributes are specific types of costs applicable to the portfolio. Thresholds are identified and cost functions are derived.

The constraints establish the boundaries for the portfolio. They might include the type and quantity of constituent elements, the total budget and / or the amount of money that can be allocated to particular elements or categories of cost.

3.4.3. Process 3: Capability Tree Stakeholder Value-Driven Design Formulation

In Process 3, the portfolio designer synthesizes the information gathered and creates a notional capability tree. Program managers are identified at each node. The program

managers provide information about the systems under their control that help the portfolio manager decompose the Capability Tree from its highest-level attributes to the lowest-level system-level attributes. Figure 16 shows a truncated example of a capability tree for the Carrier Strike Group case study performed by Vascik et al.

The process of building the capability tree yields a novel tool that can aid the portfolio designer in the subsequent analysis. The decomposition of portfolio-level performance (and cost) attributes into program- and system-level attributes is mirrored by the decomposition of utility down through the layers of the hierarchy. It is thus possible to visualize which constituent elements contribute most—or least—to the performance and cost attributes. This gives the portfolio designer a tangible measure of the sensitivity of each constituent on the overall portfolio utility, and similarly, where upgrades, investments and divestments have the greatest impact.

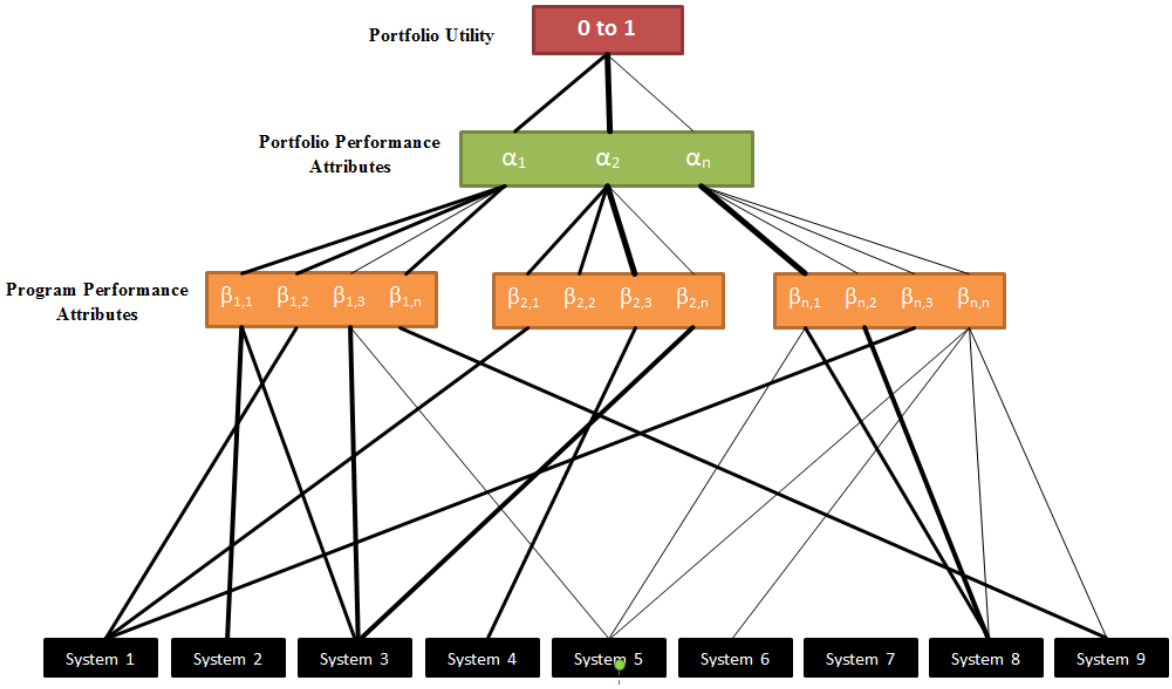

Figure 18. Portfolio Value Trace (Vascik, Ross, and Rhodes, 2015)

3.4.4. Process 4: Epoch Characterization

Process 4 involves eliciting information from the portfolio stakeholders about what possible future contexts in which the portfolio will operate.

The sources of information need not come purely from the low-level program managers and stakeholders. Rather, professional market research, expert opinion of futurists, commercial market trends, and wargaming may all yield insights about potential future contexts and risks that may impact the portfolio.

Epoch variables are derived from the contextual uncertainties. If any stakeholder preferences change as a result of this process, updates are made to the earlier processes.

3.4.5. Process 5: System-Level Capability Assessment

Vascik explains that in the fifth process, each potential portfolio constituent element is "evaluated for its performance in each system-level performance attribute." The means to the end may vary based on the unique circumstances of the situation, but the lowest-level program managers assess the potential elements' performance either qualitatively or quantitatively.

The Carrier Strike Group case study analyzed by Vascik, Ross, and Rhodes used a qualitative means to measure each of the system-level performance attributes in each of the epochs identified. Discrete values of 0, 1, 3, and 9 were used, where 0 was no performance, 1 was minimal performance, 3 was moderate and 9 was "performance sufficient to meet the desired portfolio capability."

The PLEEAA framework attempts to give consideration to the value-added behavior of systems of systems participating in a portfolio. It does so by developing "Complexity of Combination" coefficients which figure into the multi-attribute utility and multi-attribute cost calculation. Mechanically, the process involves constructing a Design Structure Matrix (DSM), and evaluating the interaction of each system relative to one another in terms of delivering value in a system performance attribute. The CSG example (Vascik et al, 2015, 2016) focused on the high complexity of combination, though in theory all three levels of combination complexity could be accounted for with enough time and expertise into the low-level interaction of the constituent systems.

3.4.6. Process 6: Design Epoch-Era Tradespace Evaluation

PLEEAA recommended the use of Multi-Attribute Utility Theory (MAUT) to visualize portfolio performance in the tradespace, plotting Multi-Attribute Expense (MAE) on the x-axis and Multi-Attribute Utility (MAU) on the y-axis.

Figure 19 provides an overview of the process to aggregate single attribute utility functions into a multi-attribute utility functions. This process is demonstrated in the two case studies in this thesis.

The process of determining the MAE and MAU for each portfolio is calculated in a bottoms-up fashion. The lowest level performance and cost attributes are multiplied by the preference weighting given by the program manager and the next higher level of hierarchy. Each layer of the hierarchy undergoes this process until they terminate at the portfolio level. Portfolio-level preference weightings are applied at that level yielding the portfolio's unique MAE and MAU.

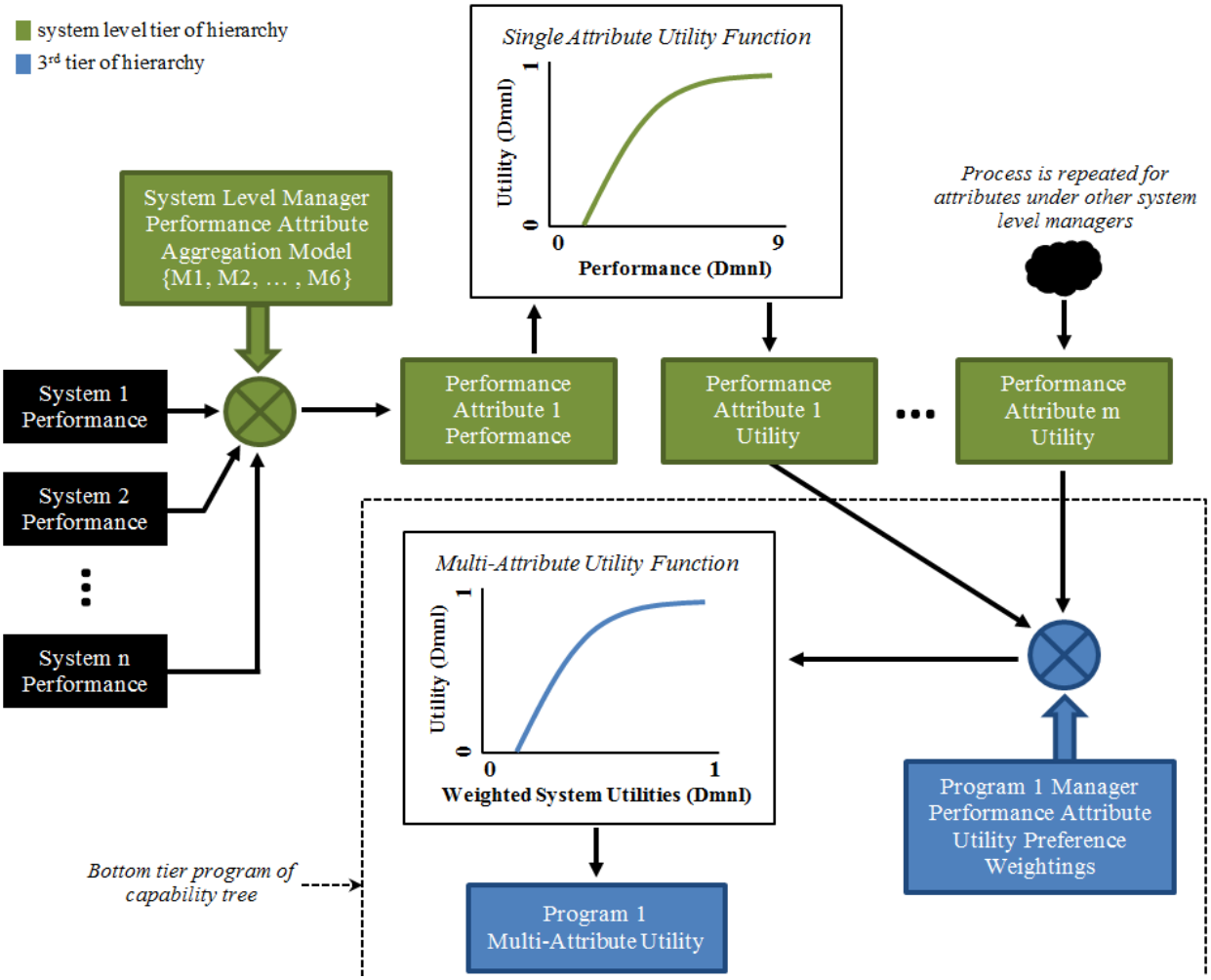

Figure 19. Multi-Attribute Utility Aggregation (Vascik, Ross, and Rhodes, 2015)

The universe of portfolios is the complete enumeration of the design variables, and portfolio class constraints may reduce that universe to a "suitable" subset. By further evaluating these available portfolios against stakeholder preferences, the portfolio designer may help to reduce the list yet again.

3.4.7. Process 7: Single Epoch Analysis

Process 7 involves plotting each valid portfolio in the tradespace, with Multi-Attribute Utility (MAU) on the y-axis and Multi-Attribute Expense (MAE) on the x-axis. This process focuses on the analysis of each epoch in isolation. The non-dominated or nearly non-dominated can be analyzed to determine which systems are most common, and which portfolios perform well in each epoch.

3.4.8. Process 8: Multi-Epoch Analysis

Process 8 involves comparing potential portfolios across multiple epochs. Many of the metrics discussed above in Section 2.2.10, including those introduced in the enhanced RSC and VASC methods by Schaffner (2012) and Fitzgerald (2014), respectively. These metrics permit an objective evaluation of portfolios across a sequence of epochs, allowing the decision maker to analyze the robustness of individual portfolios in the face of changing contexts, but also to compare portfolios to one another against the same contextual backdrop.

3.4.9. Process 9: Era Construction

As was discussed earlier in the overview of Epoch-Era analysis, an era is a set of epochs arranged in a particular order. This is intended to represent a period of time in which the system or portfolio of interest is operational.

There is no set duration of an epoch or an era, or number of epochs per era. One assumption is that an era should be long enough to evaluate a portfolio over multiple contexts such that changes to the portfolio, such as upgrades to legacy systems, deployment

of new systems and divestment of irrelevant systems can be modeled and analyzed. At the other end of the spectrum is a limit set by the ability to accurately predict the future. A range of 10 to 30 years is probably appropriate for many situations involving complex systems.

A detailed temporal model can be developed, if the potential benefits derived from the results offset the time and money to develop such a model. Some examples might include the timing of new capabilities entering the portfolio gradually to represent Low Rate Initial Production, and similarly the gradual sunsetting of legacy capabilities. Adversary activities that inform the context can also be modeled over the same period.

Eras may be modeled through a number of means consistent with other types of forecasting, including expert opinion, market research, futurists, quantitative forecasting, etc.

3.4.10. Process 10: Single-Era Analysis

Process 10 is similar but distinct from Process 8. In this process, the portfolio designer analyzes how well portfolios under investigation perform over the time-ordered sequence of epochs developed in Process 9. As with Process 8, a number of metrics discussed above in the overview of EEA can be brought to bear to identify the most promising portfolios. It may also be useful to explore some of the dominated portfolios to understand why they underperform. Understanding some of the emergent mechanics that drive portfolio utility and the sensitivities can equip the portfolio designer with useful heuristics that may prompt iterative analysis.

It is important to consider that “life goes on” beyond the end of the era of interest, so there will be edge effects at the end of the era. New or upgraded capabilities that arrived

late in the era will continue to serve beyond the era. Planning for new capabilities will begin in the era but may not be fielded until the next. The era is a construct of analytical convenience.

3.4.11. Process 11: Multi-Era Analysis

In the final process, multiple eras are analyzed to determine which portfolios show the greatest degree of utility at cost. It is clear that the time-ordering and durations of epochs contribute to the path dependence of portfolios, and thus, by comparing portfolios across multiple eras, the portfolio designer is better able to detect which portfolios are the most robust regardless of the path, versus those which may perform well in one era but poorly in another.

4. Case Study 1: U.S. Airborne Geospatial Intelligence Portfolio

In this section, the author applies the PLEEAA framework discussed in Chapter 0 to a case study as a means to illustrate broader applicability than the Carrier Strike Group analysis presented by Vascik and Ross (2015, 2016). This case study focuses on the U.S. Air Force's airborne geospatial intelligence portfolio. Air Force intelligence, surveillance and reconnaissance (ISR) platforms may carry multiple intelligence modalities simultaneously, such as a geospatial intelligence payload and a signals intelligence payload, but the author has elected to simplify the design problem to focus only on the geospatial intelligence portion of the problem. In a more comprehensive analysis, the decision maker could look at all of the capabilities that each of these platforms provide.

4.1. Introduction

The U.S. Air Force is at a technological crossroads across its portfolio of aircraft, and this is especially true of its Intelligence, Surveillance and Reconnaissance (ISR) platforms. At one of the spectrum is the manned U-2 Dragon Lady spy plane, a strategic tool used at very high altitudes and standoff ranges—out of reach of adversary missiles. At the opposite end of the spectrum are small unmanned aircraft like the MQ-9 Reaper, tactical tools that fly at comparably low altitudes in uncontested environments. Bracketed between these systems are a host of other manned and unmanned platforms, each with their own capabilities and mission profiles. There is no "one size fits all" in the realm of spy aircraft—each of the platforms were developed to address particular needs. Add to the equation the varying lifecycle costs for these platforms, and it is clear that the challenge of designing and sustaining the ISR portfolio in an uncertain future is nontrivial.

In its ISR strategic vision (Air Force ISR 2023: Delivering Decision Advantage), the U.S. Air Force states, “Key to maintaining the ability to operate in both permissive and contested environments is the appropriate mix of Airmen, manned platforms/sensors, and remotely piloted aircraft (RPA)…To achieve this optimal mix of Airmen and machines, we will rebalance the AF ISR portfolio by divesting some platforms/sensors and, where possible, reinvesting the savings in information architecture, all-source training, and next-generation penetrating ISR platforms/sensors.”

In the 2014 Quadrennial Defense Review, the Air Force said of its Intelligence, Surveillance, and Reconnaissance (ISR) portfolio: “We will rebalance investments toward systems that are operationally responsive and effective in highly contested environments, while sustaining capabilities appropriate for more permissive environments in order to support global situational awareness, counterterrorism, and other operations.”

4.2. Process 1: Value-Driving Context Definition

The early stages of the PLEEAA framework match the Responsive Systems Comparison (RSC) extension work by Schaffner (2014). The first step is to develop the problem statement, identify the stakeholders, elicit pertinent exogenous uncertainties, and create the initial value proposition.

In its strategy paper, Air Force ISR 2023: Delivering Decision Advantage, the Air Force summarizes its ISR portfolio optimization problem statement as: “Key to maintaining the ability to operate in both permissive and contested environments is the appropriate mix of Airmen, manned platforms/sensors, and remotely piloted aircraft (RPA). Our air, land,

maritime, space, human, and cyber sensors must be able to penetrate denied space, survive to operate, and provide required levels of persistence."

Joint Publication 2-0, Joint Intelligence, states the primary "user" stakeholder is the Joint Force Commander, the combatant commander. "The intelligence staff must provide the joint force commander with an understanding of the (operational environment), particularly with regard to the adversary's forces, capabilities, and intentions." This stakeholder, as the embodiment of the "user," is assumed to have a very high level of operational control over the portfolio assets but little influence over the budget or requirements.

Another stakeholder, the ISR asset owner, is the Deputy Chief of Staff for Intelligence, Surveillance and Reconnaissance, and is "responsible to the Secretary and Chief of Staff of the Air Force for policy formulation, planning, evaluation, oversight, and leadership of Air Force intelligence, surveillance and reconnaissance capabilities."[12] This stakeholder, compared to the combatant commander, is assumed to have almost total control of the budget that funds the assets, and has a responsibility to integrate new requirements into the constituent assets.

The massive breadth of the Air Force and the Intelligence Community (IC) means that there are scores of other stakeholders, who despite being subordinate to the aforementioned leaders, cast a large enough shadow to make for complex stakeholder interactions. While a thousand pages would barely scratch the surface of these various parties and their interactions, that is beyond the scope of this paper. Suffice it to say, other stakeholders

[12] http://www.af.mil/About-Us/Biographies/Display/Article/108431/lieutenant-general-veralinn-dash-jamieson/, accessed 1/4/2018

include Air Force program managers responsible for individual ISR platforms and sensor systems, pilots, maintainers, intelligence agencies, politicians, and even the prime contractors who furnish the assets.

While there are scores of stakeholders that touch the assets in question, the issue raised by Vascik, Ross and Rhodes (2015) about having multiple stakeholders is effectively resolved in this case by assuming that the combatant commander has authority for tasking the assets and only influences the budget and requirements for those assets. The Deputy Chief of Staff for Intelligence, Surveillance and Reconnaissance, on the other hand, serves as the executive of that function and thus has supreme authority over the budget and integrating requirements into the portfolio.

The Air Force ISR portfolio of record, necked down to focus on the assets capable of providing geospatial intelligence, as derived from open sources including as the "Air Force Unmanned Aerial System (UAS) Flight Plan 2009-2047" includes:

U-2S Dragon Lady

Conceived in the early days of the Cold War, the Lockheed Martin U-2 Dragon Lady has been upgraded many times of the years and remains operational to this day. It carries a pilot, unlike the other platforms discussed herein, and is considered a high-altitude asset with an operational ceiling over 70,000 feet. The altitude capability makes it a strategic asset, able to peer deep into the countryside while not penetrating the airspace of the target of interest.

Figure 20. U-2S Dragon Lady.[13]

In terms of geospatial intelligence capabilities the U-2 can fly with either a Synthetic Aperture Radar (SAR) payload—the Advanced Synthetic Aperture Radar System (ASARS)—or a multi-spectral Electro-Optical / Infrared (EO/IR) payload—the Senior Year Electro-optical Reconnaissance System (SYERS). Both sensors are installed in the nose of the aircraft, but a particular aircraft can only fly one configuration at a time, i.e. not both concurrently on the same tail number.

The U-2 is not known to carry about Full Motion Video (FMV) payloads.

For the purpose of this analysis, a simplifying assumption is made that all sensors of their respective types are of the same configuration—for example, all SYERS sensors are of the baseline SYERS-2C configuration.

[13] https://media.defense.gov/2003/Jan/27/2000030022/-1/-1/0/960601-F-6300R-041.JPG, accessed 1/5/2018

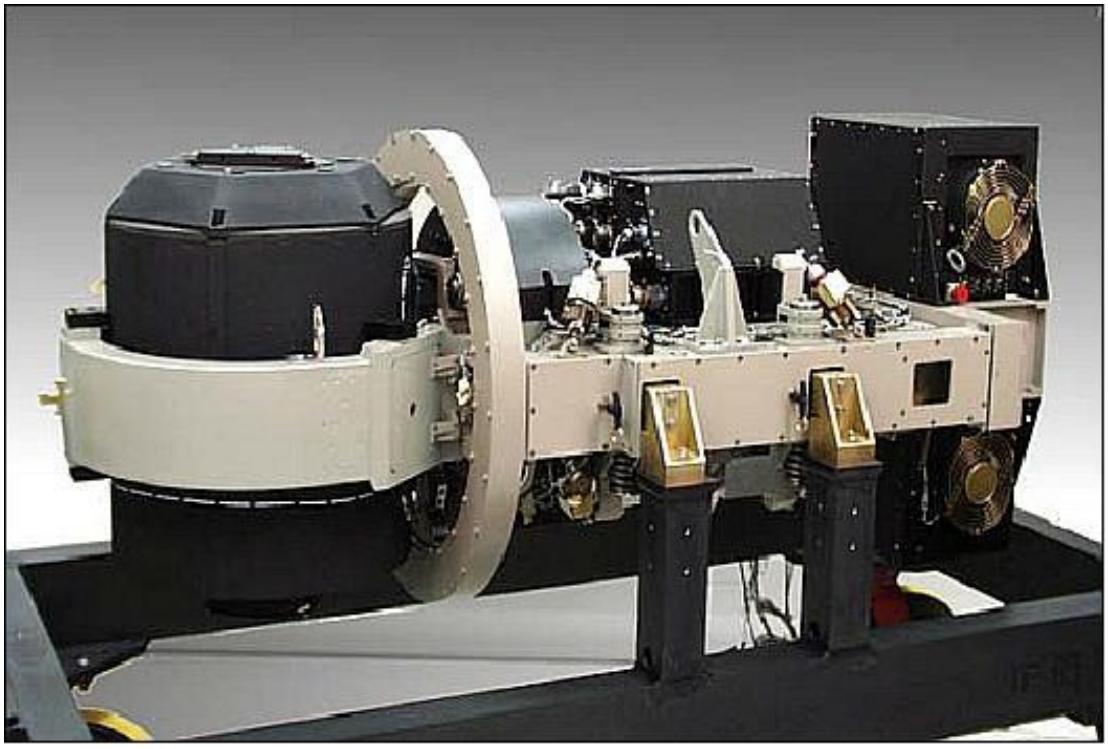

Figure 21. SYERS-2 EO/IR System[14]

The aircraft has a payload capacity of 5,000 pounds. Its cruise speed is 310 knots (410 mph), has a range of more than 6,090 nautical miles.[15] Because it is piloted by a human it is assumed to have a nominal endurance of 8 hours.

Nine operational sensor systems are assumed based on limited available open sources.[16] No analogous number of ASARS systems has been found in the literature, so the author has assumed that, being complementary capabilities, there are also nine ASARS sensors, for a total of 18 aircraft. The Air Force states that its active U-2 inventory is 26 aircraft, excluding

[14] https://directory.eoportal.org/web/eoportal/satellite-missions/o/ors-1, accessed 2/23/2018
[15] http://www.af.mil/About-Us/Fact-Sheets/Display/Article/104560/u-2stu-2s/, accessed 1/15/2018
[16] https://fas.org/irp/program/collect/syers.htm, accessed 1/15/2018

trainers and a NASA variant.[17] Considering that the U-2 can carry a variety of other sensor payloads, this estimate seems plausible for the sake of this analysis.

RQ-4 Global Hawk

The Northrop Grumman RQ-4 Global Hawk is an unmanned airborne system (UAS) used for ISR missions. There are two configurations, the Block 30, which carries the Enhanced Integrated Sensor Suite (EISS), and the Block 40, which carries the Multi-Platform Radar Technology Insertion Program (MP-RTIP) sensor system.

EISS provides independent electo-optical, infrared and synthetic aperture radar (SAR) modalities in the same sensor. Not all modalities can operate at the same time (Gilmore, 2011), presumably due to power limitations. The SAR sensor can operate concurrently with either the electro-optical or infrared sensors but seemingly not both.

As far as geospatial intelligence assets are concerned, Block 40 only carries the MP-RTIP radar, pictured in

Figure 22.

[17] http://www.af.mil/About-Us/Fact-Sheets/Display/article/104560/u-2stu-2s/, accessed 8 Jan 2018

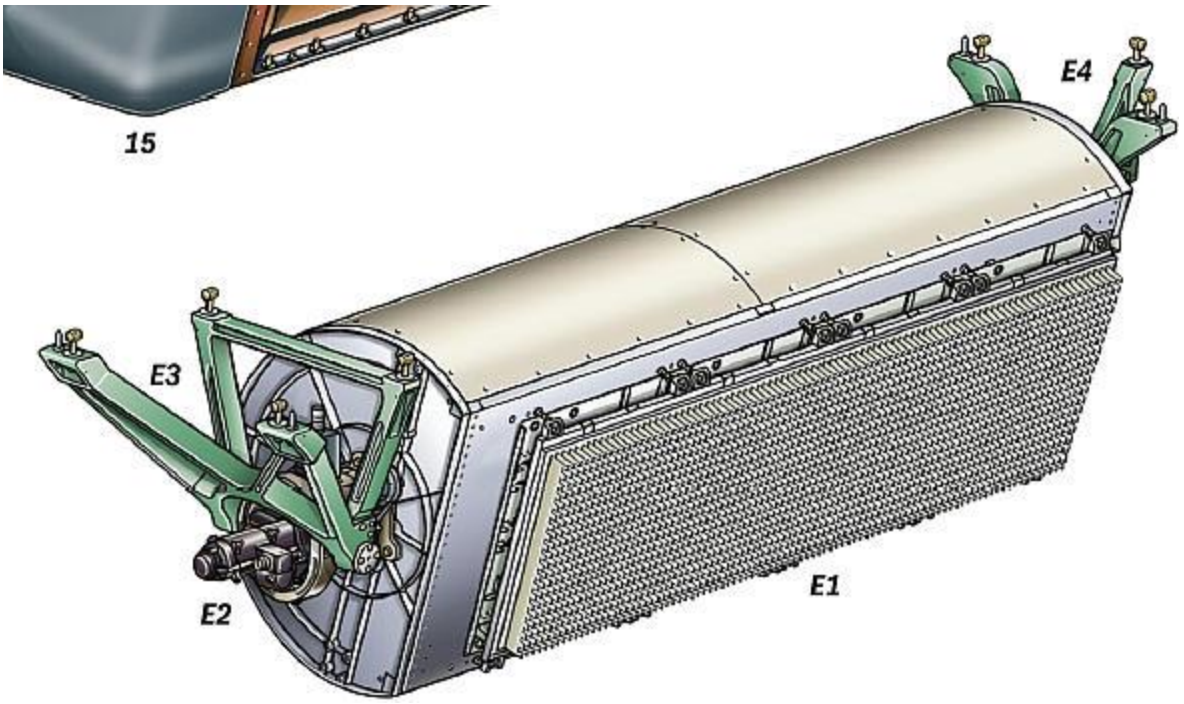

Figure 22. MP-RTIP Radar System[18]

The RQ-4 is not known to carry a full motion video capability.

Its operational ceiling is about 60,000 feet, and is also considered a high-altitude long-endurance (HALE) asset, though the approximately 15% lower acknowledged ceiling than the U-2 surely affects the slant range of the geospatial intelligence sensors. It has a payload capacity of 3,000 pounds. Its cruise speed is 310 knots (357 mph), has a range of 12,300 nautical miles and has an endurance of more than 34 hours.[19]

The Air Force says it operates 33 RQ-4s and 3 additional Block 30 aircraft were on order and scheduled to be delivered in 2017.[20] It is unclear from the sources whether any Block 40

[18] https://www.edn.com/design/analog/4421534/The-unmanned-aircraft-system--UAS--Part-two--The-electronics-inside, accessed 2/23/2018
[19] http://www.af.mil/About-Us/Fact-Sheets/Display/Article/104516/rq-4-global-hawk/, accessed 1/5/2018
[20] http://www.af.mil/About-Us/Fact-Sheets/Display/Article/104516/rq-4-global-hawk/, accessed 1/5/2018

systems are operational at the time of this writing. For the purpose of the analysis, the author assumes that 11 Block 40 systems[21] are either operational or on order and thus due to be operational in the near future and do not count in the total number of platforms stated above.

The aircraft unit cost is $222.7M in FY12 dollars. Sustainment costs were not listed. (GAO, 2013)

Figure 23. RQ-4 Global Hawk.[22]

RQ-170 Sentinel

The Lockheed Martin RQ-170 is a low-observable (i.e. stealthy), unmanned aerial system capable of penetrating denied airspace. Its existence is acknowledged by the USAF, though many of its specifications and costs are still largely classified.

[21] https://en.wikipedia.org/wiki/Northrop_Grumman_RQ-4_Global_Hawk, accessed 2/23/2018
[22] https://media.defense.gov/2010/Aug/06/2000336767/-1/-1/0/090304-F-3192B-401.JPG, accessed 1/5/2018

It is believed to have an operational ceiling of around 50,000 feet making it more of a Medium-Altitude Long-Endurance (MALE) vehicle.

It is known to have a gimbaled sensor turret capable of providing full motion video. It is also thought to have a SAR system on board.[23]

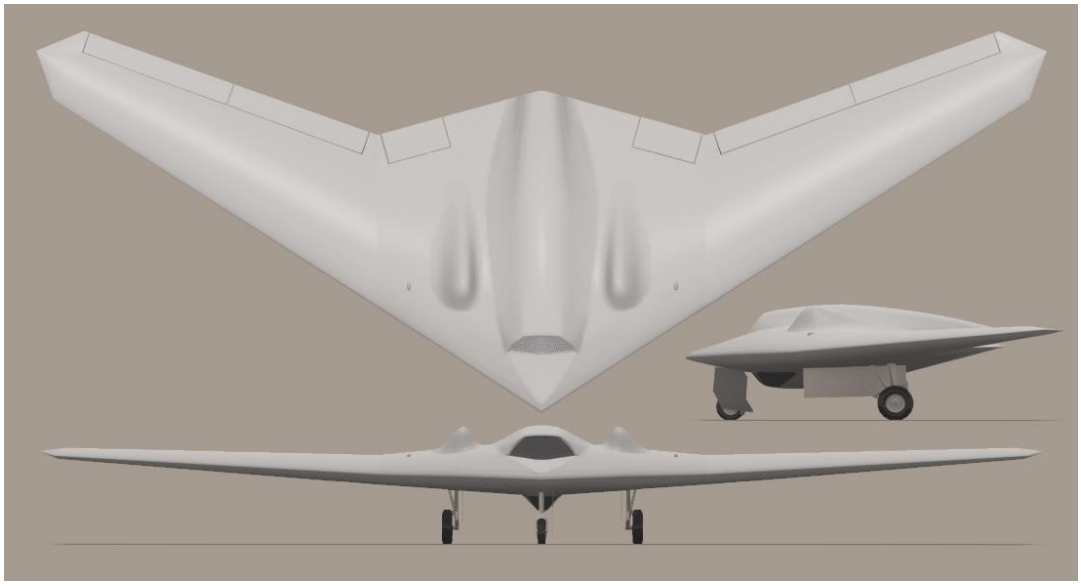

Figure 24. RQ-170 Sentinel.[24]

[23] https://www.popularmechanics.com/military/aviation/news/a25559/rq-170-sentinel-sighted/, accessed 2/23/2018

[24] https://en.wikipedia.org/wiki/Lockheed_Martin_RQ-170_Sentinel#/media/File:RQ-170_Sentinel_impression_3-view.png, accessed 1/5/2018

MQ-9 Reaper

The General Atomics MQ-9 Reaper is a medium-altitude ISR and attack asset in the USAF inventory. It epitomizes the shift from human-piloted ISR aircraft of the Cold War and Persian Gulf War, designed for high-end conflict with near-peer adversaries, to the age of overwhelming air superiority in the age of counterinsurgency conflicts. As will be discussed below, the Reaper is a comparably cheap and plentiful constituent of the USAF ISR portfolio.

The MQ-9 has a full motion video capability. Its other ISR payloads includes electro-optical / infrared (EO/IR) Multispectral Targeting Systems (MTS-B), Lynx Multi-mode Radar, and multi-mode maritime surveillance radar.[25]

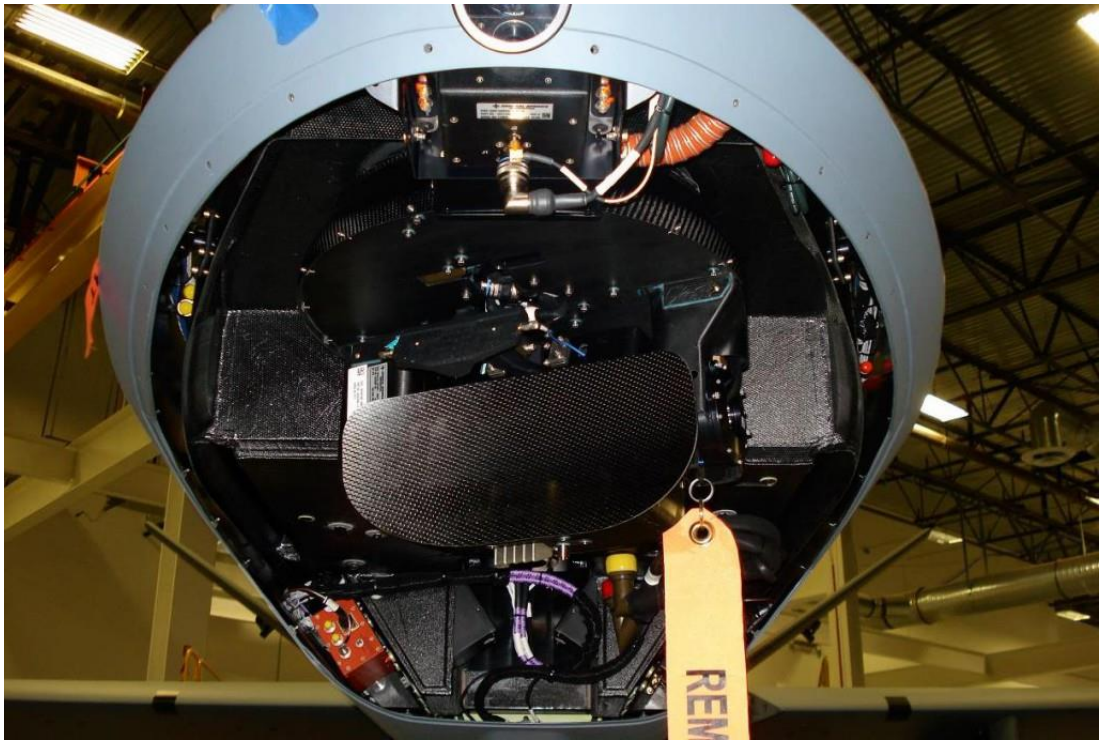

Figure 25. Lynx Radar[26]

[25] http://www.ga-asi.com/predator-b, accessed 2/23/2018

[26] https://navaltoday.com/2014/09/02/ga%E2%80%91asis-lynx-radar-detects-small-maritime-targets/, accessed 2/23/2018

Its operational ceiling is up to 50,000 feet, and is also considered a medium-altitude asset, used in permissive environments where allied air superiority has been established. It has a payload capacity of 3,750 pounds. Its cruise speed is 200 knots (230 mph), has a range of 1,000 nautical miles[27] and has an endurance of more than 27 hours.[28] According to General Atomics, a new variant of MQ-9 is underway that, by virtue of larger wings, will be able to carry more fuel and have an endurance of 42 hours.

Unlike the other aircraft addressed in this study, the MQ-9 can be armed. Hard points on the wings allow it to carry a number of different types of missiles as pictured below in Figure 26, or alternatively, fuel pods to extend the endurance.

The Air Force says it operated 93 MQ-9s as of September 2015.[29] The Air Force has a procurement goal of 364 MQ-9 platforms.[30] 267 planes are slated to be in service in FY18, according to the Center for the Study of the Drone (Gettinger, 2017).

The aircraft unit "flyaway" cost is $14.5M in FY15 dollars.[31] Sustainment costs were not listed.

[27] http://www.af.mil/About-Us/Fact-Sheets/Display/Article/104470/mq-9-reaper/, accessed 2/23/2018
[28] http://www.ga-asi.com/predator-b, accessed 2/23/2018
[29] http://www.af.mil/About-Us/Fact-Sheets/Display/Article/104470/mq-9-reaper/, accessed 2/23/2018
[30] http://dronecenter.bard.edu/drone-spending-the-mq-9-reaper/, accessed 2/23/2018
[31] http://dronecenter.bard.edu/files/2015/10/MQ-9-Procurement-Web-Sheet1-1.pdf, accessed 2/23/2018

Figure 26. MQ-9 Reaper.[32]

MQ-1B Predator and Other Assets

The MQ-1B Predator is not included in this analysis because the Air Force announced it would retire the asset in summer 2018, to be replaced by the MQ-9 Reaper. (Defense News, 2017)

The author has also neglected to include by name officially-unacknowledged classified aircraft, as well as one-off demonstrations with geospatial intelligence systems, such as the test of the MS-177 on the E-8C JSTARS in 2010[33] or SYERS-2 on the RQ-4 in 2016.[34] This choice was borne out of the need to keep this research in the public domain for one, to steer clear of certain biases and political forces that may have contributed to the some of the tests for

[32] https://media.defense.gov/2009/Mar/17/2000608254/-1/-1/0/090127-F-7383P-001.JPG, accessed 1/5/2018

[33] https://www.prnewswire.com/news-releases/eye-in-the-sky-utc-aerospace-systems-ms-177-sensor-enables-us-military-to-see-farther-than-ever-before-300438804.html, accessed 2/23/2018

[34] https://www.prnewswire.com/news-releases/eye-in-the-sky-utc-aerospace-systems-ms-177-sensor-enables-us-military-to-see-farther-than-ever-before-300438804.html, accessed 2/23/2018

two, and not least of which to represent the "programs of record" that are officially part of the USAF's ISR portfolio.

However, the author has elected to return to this section and add hypothetical assets that add significant novelty to the portfolios under consideration. These include a high-altitude low-observable platform capable of penetrating denied airspace ("High Altitude Stealth"); a hypersonic asset capable of supporting the Prompt Global Strike mission ("Very High Altitude Hypersonic"); and a very small, potentially sacrificial, low-altitude platform capable of providing situational awareness to advancing ground forces and close air support aircraft ("Low Altitude Swarm Asset").

The author acknowledges it would have been interesting to cast a still-wider net and examine novel portfolios including notional "gap-filler" assets or by departing from traditional roles, such as outfitting refueling tankers with ISR sensors, and comparing and contrasting the resulting tradespace.

The portfolio constituents under consideration in this analysis are summarized in Table 1.

Possible Constituent	Legacy Variants	New Variants	Upgrade Variants
U-2 EO/IR (SYERS)	1	0	1
U-2 SAR (ASARS)	1	0	0
RQ-4 EO-IR-SAR (EISS)	1	0	1
RQ-4 SAR (MP-RTIP)	1	0	0
RQ-170	1	0	0
MQ-9	1	0	1
High-Altitude Stealth	0	1	0
Very High-Altitude Hypersonic	0	1	0
Low-Altitude Swarm Aircraft	0	1	0

Table 1. Case Study 1 possible constituent systems

4.3. Process 2: Portfolio-Level Stakeholder Value-Driven Design Formulation

The second process in the PLEEAA framework is for the portfolio architect to gather the portfolio-level stakeholders' top preferences of the capability tree, as well as to identify any constraints that will affect the portfolio's composition and costs. Vascik, Ross and Rhodes (2015) call these "Performance Attributes," "Expense Attributes" and "Portfolio Level Investment Strategy Constraints." Their definitions for these terms are:

i. Performance Attributes: "A set of overarching capabilities that the portfolio must be able to fulfill to meet the strategic objectives. These capabilities, or performance attributes, are assigned weights to reflect the stakeholder preferences based on elicited information. Utility functions are developed to capture these preferences.

ii. Expense Attributes: "The set of limited resources available to portfolio stakeholders is elicited. Expense functions are created to characterize the attractiveness of levels of potential portfolio usage of these resources, and acceptable thresholds are identified."

iii. Portfolio Investment Strategy Constraints: "Constraints are set concerning viable portfolio composition. These constraints may define limitation on resources, types of constituent systems, and acceptable risk. They could also be more specific and govern internal investment strategy decisions such as the maximum number of component systems allowed or the minimum resource allocation allowable to any single system.

The Expense Attributes are adapted from Vascik and Ross. Differences in terminology were made to try to improve the descriptiveness of the attributes.

Performance Attributes	Notional Portfolio Strategic Objective
Persistent	Asset(s) maintain constant, enduring contact with target, thereby increasing understanding about the target and enabling fast decision cycle (Pendall 2005)
Operationally responsive	Rapidly evolve and deploy assets that meet stakeholder needs
Penetrability	Asset(s) overcome adversary defenses and countermeasures from permissive to contested to obtain actionable intelligence
Offensive capability	Asset(s) engage target via kinetic means
Survivable	Assets are not expendable. Assets shall be secure from adversary tampering.

Table 2. Case Study 1 Portfolio Performance Attributes

Expense Attributes	Notional Portfolio Strategic Objective
Operations & Maintenance (O&M) Cost	The annual cost to sustain a portfolio constituent element
Acquisition Cost	The cost to procure a new portfolio constituent element
Late-to-Need Cost	The cost of inserting a portfolio constituent element later than needed, caused by acceleration of effort

Table 3. Case Study 1 Portfolio Expense Attributes

Table 2 and Table 3 yield five performance attributes and three expense attributes to establish the multi-attribute utility and multi-attribute expense functions for the ISR portfolio. The functions are calculated by using a simple linear-weighted sum, with the weights summing to one. As Vascik and Ross (2016) noted, this assumes that performance and expense attributes act independently.

Few portfolio constraints are levied. These include:

1. The portfolio shall provide day / night capability.

2. The portfolio shall provide the ability to fly and gather intelligence in all-weather conditions.
3. The portfolio shall be able to support the full spectrum of conflict.
4. The portfolio shall have sufficient capacity to support two theaters of conflict simultaneously.
5. No new U-2 aircraft procurements, or new SYERS or ASARS procurements shall be made, but upgrades to SYERS to increase contextual relevance are permissible. ASARS was left as a legacy configuration in order to limit computational complexity and processing time.
6. The portfolio shall be able to support low-, medium-, and high-altitude operations.

4.4. Process 3: Capability Tree Stakeholder Value-Driven Design Formulation

In this case study's third process, developing the portfolio capability tree, it is helpful to think of the role of ISR in the "Kill Chain," defined by Joint Publication 3-60, "Joint Targeting." The Kill Chain processes are Find, Fix, Track, Target, Engage, and Assess (F2T2EA). While these processes are discussed in much greater detail in 3-60, they are briefly outlined now.

"Find" is the process of identifying potential targets for further study. This requires the identification of available ISR sensors in range with the appropriate capabilities, and tasking one or more sensors to collect intelligence data.

"Fix" involves locating the potential target in space with sufficient accuracy to engage, and positively identifying the target.

The "Track" step is the process of maintaining situational awareness of the target by continuously observing it. If the target is mobile, the updated position location is recorded.

"Target" is the process of validating the target, determining the asset and ordnance that will engage the target, and getting (legal) approval to strike the target.

In the "Engage" step, the engaging asset is notified; Combat Identification (CID), the process of attaining an accurate, high-confidence, picture of the actors in a combatant's area of responsibility, is conducted; and action against the target is taken. (Joint Warfighting Science and Technology Plan, 1998)

Finally, "Assess" is the process of evaluating the effectiveness of the actions taken against the target.

It is clear that in the push to minimize the Kill Chain time to capitalize on time-sensitive targeting opportunities, ISR can play a role throughout the aforementioned process. The F2T2EA processes are helpful in framing the roles of ISR and the capabilities that a portfolio of geospatial intelligence assets should possess to fulfill those roles.

The portfolio capability tree is presented in Table 4. The complete portfolio capability tree and brief descriptions of the first two levels are included in Appendix A.

Portfolio-Level Performance Attributes
2nd-Level Program Performance Attributes
# of System-Level Performance Attributes

Persistent	All Weather Capability	6
	Day / Night Capability	6
Operationally Responsive		6
Penetrability	Low-Observable Capability	4
	High-Speed (Hypersonic) Capability	3
Offensive Capability	Air-to-Surface Missile (ASM) Capability	5
	Precision-Guided Munition Capability	4
Survivable	Enemy Weapon Systems Detection / Tracking	6
	Anti-Tamper	2
	Surface-to-Air Missile (SAM) Defense Capability	5

Table 4. Case Study 1 Portfolio Capability Tree

4.5. Process 4: Epoch Characterization

Schaffner (2014) explains in his Responsive Systems Comparison for affordability framework that the epoch characterization process involves translating key contextual uncertainties into epoch variables, and identifying possible future contexts. Additionally, he notes, uncertainties in the supply and availability of resources are identified, and changes in stakeholder preferences about resource usage.

Vascik and Ross (2015), in their analysis of the Carrier Strike Group case study, identified seven epoch variables and provided three-point estimates (low, middle, and high) for each outcome. The majority of these variables have direct applicable to the airborne ISR case under evaluation here. When variables were carried forward to this case study, the units and ranges were updated to address the stakeholders' perceptions about the future.

For the airborne ISR portfolio analysis, seven epoch variables were identified, and some were given a two-point range, and others were given three- or four-point ranges. These are summarized in Table 5 below. These yield $2^3 \times 3^3 \times 4$ combinations, or 864 potential futures.

Epoch Variable Category	Epoch Variable	Range	Units
Technology	A2/AD – Stealth	[1, 2]	Platforms
Technology	A2/AD – Speed	[0, 1]	Platforms
Technology	UAS – Swarm	[0,1]	Platforms
Policy	Budget	[95,100,150]	%
SoS Management	Cooperation Costs	[80, 95, 100,105]	%
Threats	Enemy Threat	[Low, Medium, High]	Level
Threats	Asymmetric Threat	[Low, Medium, High]	Level

Table 5. Case Study 1 Epoch Variables

A2/AD – Stealth: Stealth, also known as "low-observable" technology was first demonstrated operationally in the 1991 Persian Gulf War. It enables aircraft equipped with stealth features to penetrate enemy airspace with lower probability of detection by radar. Thus, a low-observable ISR aircraft participating in an anti-access / area denial (A2/AD) operation would have utility for the combatant commander, particularly if space assets are jammed. Additionally, if the stealthy ISR aircraft were equipped with munitions, it could support time-sensitive targeting better than strategic aircraft like the B-2. In other words, there is no known stealth equivalent to the MQ-9. The RQ-170 is believed to be a low-observable platform; certainly its wing geometry with sharp, dihedral angles and parallel edges is consistent with known stealth design principles. Thus, the lower bound of the range is 1, to account for the existence of the RQ-170, and the upper bound of 2 represents the RQ-170 plus a "High-Altitude Stealth" asset.

The impacts to the performance and cost attributes in epochs where two low-observable assets are present is presented in Table 6. For reference, "+1 level" represents a change to the ordinal values in the performance attribute—for example, if the value was previously assessed to be a 3 when the epoch variable was 1, the value would become 9 when the epoch

variable changed to 2. Not all assets were increased as a result of the presence of the epoch variable. This required some expert judgment on the part of the author, which must be noted as a source of potential bias. For instance, the presence of a high altitude stealth asset would likely have little bearing on the MQ-9, but it would impact its low-observable sibling, the RQ-170, since it they serve complementary roles. Making such an asset available carries the cost to acquire and sustain it in the portfolio. This same type of logic process was applied to the other applicable technology-based epoch variables below.

Capability Tree Attribute (Any)	**Impact**
Persistent - Day / Night Capability – All	+1 level
Penetrability – Low-observable Capability – Payload Capability	+1 level
Offensive Capability – All	+2 levels
Acquisition Cost (Including amortized R&D)	+$250M each
O&M Cost	+$50M/year each

Table 6. A2/AD Stealth Epoch Variable Impacts

A2/AD – Speed: ISR aircraft tend to be relatively slow. They are unable to outrun missiles, so their use is restricted to operations safely outside the threat range, or they are used once an enemy's ground defenses have been dismantled and air supremacy has been established. There was a time, however, when the U.S. possessed an ISR aircraft that could outrun missiles and did overfly adversary airspace. That aircraft was the SR-71 Blackbird. In A2/AD operations, reestablishing a high-speed asset could provide crucial ISR to the combatant commander. High-speed in the modern era likely means a vehicle with hypersonic capabilities.

The impacts to the performance and cost attributes given the range of variables is presented in Table 7.

Capability Tree Attribute (Any)	Impact
Persistent – All Weather Capability	+1 level
Operationally Responsive – Upgradeability	+1 level
Operationally Responsive – Timeliness	+1 level
Penetrability – High-Speed (Hypersonic) Capability – All	+1 level
[redacted]	
Acquisition Cost (Including amortized R&D)	+$175M each
O&M Cost	+$25M/year each

Table 7. A2/AD Speed Epoch Variable Impacts

Unmanned Aerial Systems - Swarm: In its Small Unmanned Aerial Systems (SUAS) Flight Plan (2016), the USAF made the case for small, swarming assets that can team with other systems and systems of systems, perform "Dull, Dirty, and Dangerous" missions, and introduce novel, emergent function to the battlefield.

It describes swarming as "a group of autonomous networked SUAS operating collaboratively to achieve common objectives with an operator on or in the loop. Such concepts employ two or more sensor platforms to accomplish complex mission tasks, exploiting advantages such as the ability to triangulate targets when seen from three or more vantage points. The swarm network will enable the SUAS operator to monitor health and status of the individual assets or the system as a whole. A wireless Internet Protocol-based network or other type of communication architecture will connect the SUAS to one another. The network is the key component that enables the swarm to operate as a single cohesive unit while permitting individual platform assignments and simultaneous sharing of real-time data. The networked swarm remains universally aware of its surroundings by sharing both external payload data inputs as well as internal aircraft systems information. This awareness enables the swarm to rapidly process and assign payload requests from authorized users to

detect both internal (aircraft system failure) and external (enemy engagement) threats through the use of programmed mission algorithms and sensory information. The SUAS network also permits the swarm to de-conflict and assign the best equipped and operational SUAS for each prioritized task based on location, mission parameters, payload characteristics, and intended effects.

Swarm assets could also be used as decoys, acting in concert to mimic the Radar Cross Section (RCS) of other, potentially high-value assets. Additionally, given their inherently lower cost than larger platforms, the swarm assets could leverage artificial intelligence (AI) to develop novel tactics that would be less palatable with human-piloted aircraft or higher-value UAS assets, such as intentionally sacrificing some in order to draw enemy fire and attention while a larger force concentrates elsewhere.

A Small Unmanned Aerial System swarm has utility on both the permissive battlefield, in which the United States has air supremacy, as well the denied battlefield. A concept for the latter is reproduced from the SUAS Flight Plan in Figure 27.

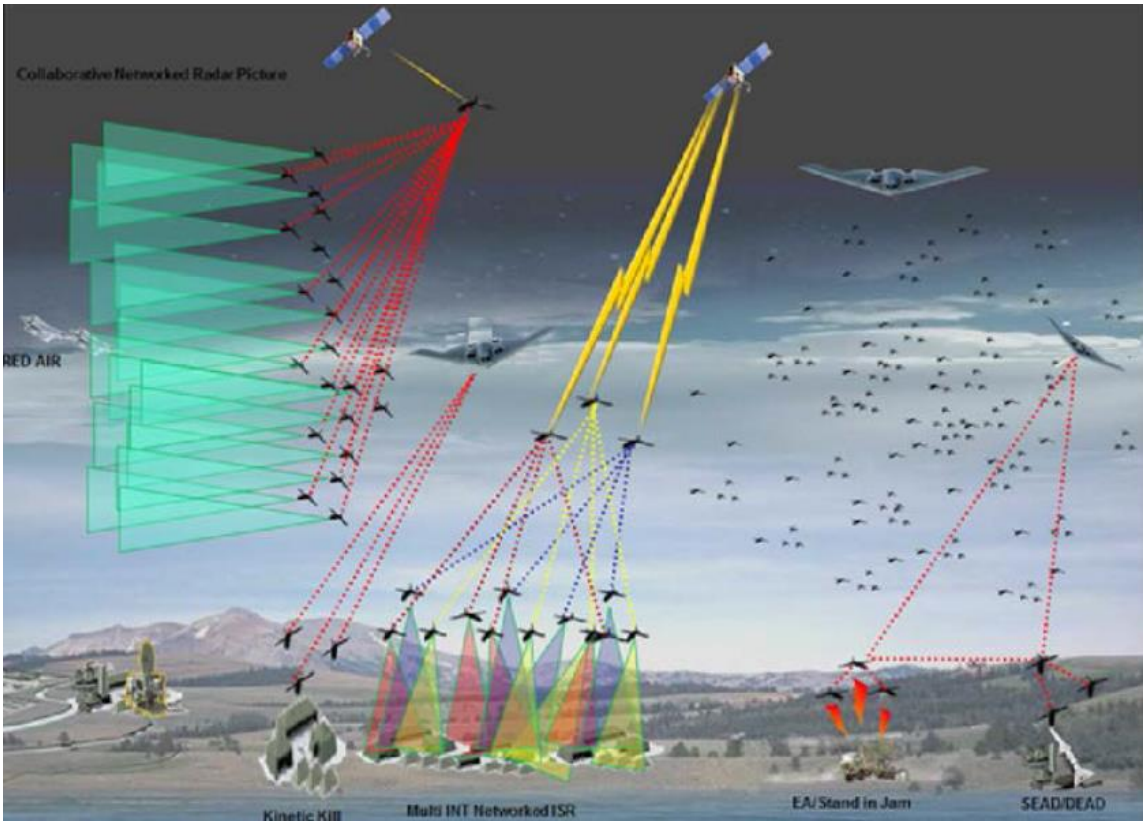

Figure 27. Swarming SUAS Concept in AD/AD Fight (SUAS Flight Plan, 2016)

The impacts to the performance and cost attributes given the range of variables is presented in Table 8.

Capability Tree Attribute (Any)	**Impact**
Persistent – Capacity and Cross-Cueing	+1 level
Operationally Responsive – Capacity and Cross-Cueing	+1 level
Penetrability – Low-Observable Capability – Minimum Depth Penetration and Radar Cross Section	+1 level
Offensive Capability – Precision-Guided Munition Capability	+1 level
Survivable – Enemy Weapon System Detection & Tracking – Detection and Tracking	+1 level
Acquisition Cost (Including amortized R&D)	+$50K each
O&M Cost	+$20K/year each

Table 8. UAS – Swarm Epoch Variable Impacts

Policy – Budget: Overarching budget cycles are influenced by variables such as changes in Presidential administrations and national security landscape. Budgets may grow slowly, at

approximately the annualized rate of inflation, or may grow or contract rapidly in response to those aforementioned forces.

The range of outcomes for this analysis is set at 95%, 100%, and 150%. The 95% situation would represent a situation where budget cuts were present, or, for instance, when a Nunn-McCurdy breach elsewhere in the Air Force prompted a "zero sum game" cut to the ISR portfolio to pay for the overrun elsewhere. 100% is the nominal base case. And 150% budget could arise in the case of, for instance, a surprise attack by a high-end enemy, which results in a huge infusion to the budget.

SoS Management – Cooperation Costs: Since all of the systems in this portfolio are united under one chain of command, the degree of cooperation is expected to be nominally high. There is, of course, likely to be less cooperation when budgets are tight and programs are fighting cuts or divestment, and conversely, more cooperation is expected when budgets are secure and/or enemy threats are higher.

The range of outcomes is again 80%, 95%, 100%, and 105%. The 100% is the nominal base case. Since costs and degree of cooperation are inversely proportion, the 105% case applies to the aforementioned tight budget, high competition situation. Conversely, the 95% case applies to times when the budget is high (owing to less competition among program offices), and the 80% case applies when enemy threats are high. The number is applied to the operational and late-to-need costs of the constituent systems.

Capability Tree Attribute (Any)	**Impact**
O&M Cost	80% / 95% / 100% / 105% of Baseline
Late-to-Need Cost	80% / 95% / 100% / 105% of Baseline

Table 9. SoS Management – Cooperation Cost Epoch Variable Impacts

Threats – Enemy Threat: Adapted from the Carrier Strike Group case study (Vascik et al, 2015, 2016), the enemy threat is a measure of the level of threat posed by a "high-end" enemy. It considers the capabilities, resources, aggressiveness and perceived threat of that adversary.

In this analysis the author assumes a range of low, medium and high. "Medium" is the baseline scenario, reflecting the current state of near-peer relations and their capabilities. "Low" reflects a significant warming in relations and decline in military posture, as was seen, for example, in the immediate aftermath of the collapse of the Soviet Union. "High" is the level that exists when conflict with a large state actor is either imminent or underway.

Changes in the threat level result in a change in stakeholder preference weightings throughout the capability tree. For instance, "Low" would result in a shift away from Penetrability and Operationally Responsive, while "High" would result in a shift toward Penetrability and Survivable.

Threats – Asymmetric Threat: Similar to the Enemy Threat variable, this threat considers other actors, such as counter-insurgency (COIN), smaller nations, and large actors working in asymmetric capacities.

In this analysis the author assumes a range of low, medium and high. As with Enemy Threat, "Medium" is the nominal base case. "High" is representative of the majority of armed conflicts the United States has participated in after the 1991 Persian Gulf War, and is likely to factor heavily into future regional conflicts given the United States' technological superiority over smaller adversaries.

Changes in the asymmetric threat level result in a change in stakeholder preference weightings throughout the capability tree. For instance, "Low" may imply little or no COIN operations, and would result in a shift away from preference for Persistent capabilities. "High," on the other hand, may drive a need for Persistence and Survivability, such as anti-tamper of the guidance systems.

Of the 864 potential epochs, the author selected a subset that presents a cross-section for further evaluation. These are depicted in Table 10. The combination of variables was selected to be relevant for each epoch. For example, a high-end major conflict would simultaneously invoke high Enemy Threat, a budget that reflects a war posture, a high degree of cooperation between programs and fellow branches of the Armed Services, and vigorous use of cutting edge technologies. Conversely, a period of cutbacks reminiscent of the 1990s is likely to contain small budgets, low cooperation, and favor for lower-cost assets, despite a low-to-moderate threat level.

Epoch Name	Epoch Variables						
	A2/AD – Stealth	A2/AD – Speed	UAS – Swarm	Budget	Cooperation Costs	Enemy Threat	Asymmetric Threat
Baseline	1	0	0	100	100	Med.	Med.
Regional Conflict	1	0	1	100	100	Med.	High
High-End Conflict	2	1	1	150	80	High	High
Sequestration	1	0	1	95	105	Med.	Med.
Peace	1	0	1	95	100	Low	Med.

Table 10. Down-selection of Case Study 1 noteworthy epochs

4.6. Process 5: System-Level Capability Assessment

Using the process outlined in Section 3.4.5, the author served as a proxy for the various stakeholders, and evaluated each of the 12 systems for its performance against each of the

47 system-level performance attributes, resulting in 564 unique ratings per epoch. This was done qualitatively using the publically-available information to assign values of 0, 1, 3, and 9. 0 indicated no performance, 1 low performance, 3 some performance and 9 high performance. The data set is not provided here because its expansive nature makes it impractical to view in this space.

4.7. Process 6: Design Epoch-Era Tradespace

Drawing heavily from Vascik et al (2015, 2016), models were developed to characterize how system-level program managers determine the single attribute performance from the set of constituents in a portfolio under investigation. Each performance attribute was given one of these models, with logic consistent with the program-level manager's values. Meanwhile, costs were aggregated through a bottoms-up summation of all constituent system costs—typically using the cost information outline in Process 1, and using estimates for any missing or incomplete elements of cost information. The models, based on the 0, 1, 3, and 9 ordinal scale ratings for system performance attributes, were carried forward from Vascik and are discussed immediately following and are summarized in Table 11.

It is helpful to note at this stage that the selection of model depended on the concept of operations (CONOPS) envisioned for the potential assets. This is obviously a source of bias, because it ties how assets would be employed to the functions that determine portfolios comprised of those assets. Future researchers may ponder CONOPS-agnostic utility aggregation schemes. The choice of model involved some judgment on the part of the author, another source of bias and potential error. While some models could seemingly be dismissed out of hand as not applicable to the situation, there were often two or more models

that could be argued as appropriate, and logic was applied to favor one model over the other. An agnostic model would eliminate the subjectivity and potential anchoring that results from conceiving an operational construct. Alternatively, with more than a single person participating in the performance analysis, a third party, such as an independent consultant, could be employed to assign models.

Model 1 (M1): This model "calculates the aggregate system level performance attribute as a summation of performance from groupings of systems with similar performance capabilities." This applies to situations where the constituent systems provide value in a given performance attribute via different means. It is the sum of the mean performance capability of each class; specifically, high altitude (U-2 and RQ-4), A2/AD (RQ-170, High Altitude Stealth, Very High Altitude Hypersonic), medium altitude (MQ-9), and low altitude (swarm assets).

Model 2 (M2): This model "calculates the aggregate system level performance attribute as the mean performance capability of all constituent systems with performance greater than zero." This model applies to situations where the portfolio performance depends upon the coordination of the performance-capable constituents to deliver value. This situation might arise, for instance, when a HALE asset like the U-2 with SYERS detects a spectral signature of interest, and cues an MQ-9 to move in with FMV to observe, validate, and track the potential target.

Model 3 (M3): This model "assigns the aggregate system level performance attribute as the best performance capability of any constituent system." This is intended for performance attributes that may be satisfied by a single system, such as a high-altitude stealth asset.

Model 4 (M4): This model "calculates the aggregate system level performance attribute as the summation of each constituent system's performance capability adjusted by the relative performance contribution of that system to the most-desired performance attribute of the bottom-level program manager." This applies to situations where the value of a constituent element depends upon its performance in an associated attribute.

Model 5 (M5): This model "calculates the aggregate system level performance attribute as the direct weighted average of all constituent systems' performance capability." Such a model is intended for attributes where the portfolio performance depends on each constituent system performing independently of the others.

Model 6 (M6): This model "calculates the aggregate system level performance attribute as the direct summation of the performance capability of all the constituent systems." It is used for attributes that scale linearly in the portfolio.

Model	Calculation Detail
M1	Summation of the average performance of each major system class: $\sum\left(\bar{v}_{Hi-Alt} \times \varphi, \bar{v}_{A2/AD} \times \varphi, \bar{v}_{Med-Alt} \times \varphi, \bar{v}_{Lo-Alt} \times \varphi\right)$ v is the performance capability of the system for an attribute under consideration $\bar{v}$ is the average performance capability of systems in that category φ is a multiple unit function which adjusts performance if more than one unit of a system type is present: $\varphi = \sum_{i=1}^{n} \frac{1}{i}$
M2	Mean of all constituent system performance capabilities > 0. $\frac{1}{n}\sum_{i=1}^{n}(v_i \times \varphi > 0)$ where *n* is the number of different potential systems, 12 in this case study.
M3	Maximum performance from any constituent system performance rating: $\bigvee_{i=1}^{n}(v_i \times \varphi)$
M4	Summation of constituent system performance capabilities, weighted by the relative contribution of the constituent system to the highest preferred program manager attribute:

	$\sum_{i=1}^{n}\left(v_i \times \varphi \times \frac{x_i}{x_P}\right)$ x_i is the system performance capability for the most desired program manager attribute x_P is the portfolio performance capability for the most desired program manager attribute
M5	Mean of all constituent system performance capabilities. $\frac{1}{n}\sum_{i=1}^{n}(v_i \times \varphi)$
M6	Summation of all constituent system performance capabilities. $\sum_{i=1}^{n}(v_i \times \varphi)$

Table 11. Bottom-level program manager performance and cost aggregation models

After performance and cost attributes were calculated for the lowest level of the portfolio, each value was then multiplied by the preference weighting given by the program manager at the next higher level of the capability tree. This process was iterated until the tree was aggregated up to the portfolio level. Portfolio-level preference weightings were then applied to derive the MAU and MAE for each portfolio. The techniques at each level of the tree are summarized in Table 12.

	Portfolio Manager	**2nd-Level Program Manager**	**System Performance Attributes**
Approach	Linear-weight sum applied to the 2nd-level program manager utilities	One of models from Table 11 which best matches 2nd-level program manager utility applied to systems	0, 1, 3, 9 scale used to evaluate each system for each performance attribute
Result	Portfolio utility on a 0 to 1 scale	2nd level program utility on a 0 to 1 scale	System performance attribute values

Table 12. Method to aggregate portfolio utility, adapted from Vascik et al (2015)

The process resulted in 326,592 portfolios. The types of configurations available were listed in Table 1 (for example, two different U-2 EO/IR configurations—a legacy version and an upgraded one). The portfolio constraints in Section 4.3 were used to establish what assets had to be present. For instance, the requirement that the portfolio could support low-, medium-, and high-altitude operations meant that a valid portfolio needed an MQ-9 or Swarm asset; an RQ-170; or a U-2, RQ-4, or High-Altitude Stealth asset, respectively. Similarly, the requirement for full-spectrum conflict meant that both permissive (e.g. MQ-9) and penetrating (e.g. RQ-170) needed to be represented in a valid portfolio. Finally, in order to provide some stratification in the valid portfolios, the quantities of each asset were arranged into blocks. For instance, 1 block of U-2 EO/IR legacy assets represented 4 systems. The MQ-9, on the other hand, was grouped into four blocks of 100 aircraft with a range of 100 to 400, and the Swarm asset was grouped into four blocks of 1000 aircraft with a range of 1000 to 4000. The universe of portfolios would be a simple combination calculation, but the presence of the portfolio constraints help to reduce the number. These portfolios were then screened for MAU and MAE in each epoch, resulting in a final yield for each epoch under consideration. These results are summarized in Table 13. The reader will quickly note some interesting behavior in the numbers below. Going back to the epoch variables, the author identified two budget characteristics—overall budget and cooperation costs—which tend to move in opposite directions when the context drifts "off-nominal." The result is a large surge in defense spending in times of national crisis, and significant contraction when threats are low and / or when budgets are cut. Another major reason was the application of portfolio constraints. Specifically, the requirement that the portfolio contain a mix of assets that

bracket the full range of military conflict drives the need for balance between inexpensive, permissive assets and penetrating, extravagantly expensive assets. The cost of a single stealth asset dwarfs the cost of any conventional asset. Finally, in order to bring the analysis into the realm of the computationally feasible, the quantities of systems were normalized into blocks—essentially equivalent to the concept of a Combat Air Patrol (CAP). For example, the Air Force intends to sustain nearly 400 MQ-9 Reapers, an order of magnitude more than most other assets in the portfolio. Adding another MQ-9 is unlikely to "move the needle" much in terms of marginal utility or marginal cost, so it is effectively wasted computer runtime to consider the analysis on these terms. Instead, the author created blocks of each asset in order to create some meaningful spread in the results. For low quantity assets like the U-2, the block increment was 1 aircraft, whereas for high quantity assets like the MQ-9 and swarm, the block increment represented 100 or more aircraft. Costs were made to scale appropriately by block increment.

Epoch	Valid Portfolios	Final Yield (%)
Baseline	132	0.04%
Regional Conflict	132	0.04%
High-End Conflict	75,951	23.26%
Sequestration	23	0.01%
Peace	24	0.01%

Table 13. Single-epoch portfolio feasibility as measured by final yield

4.8. Process 7: Single Epoch Analysis

In this process, the valid portfolios of each epoch are plotted and analyzed to identify the portfolio compositions that work particularly well in that context. In each of the epoch tradespace plots, a small number of non-dominated portfolios are identified by a number. At this stage the non-dominated portfolios are identified to highlight similarities or other

interesting architectures across epochs. Note that the figures use the same color for all portfolios regardless of constituent assets represented and their quantities. Given more time, an appropriate activity in this process of PLEEAA would be to use "color by" asset to identify drivers of MAU and MAE. Unfortunately, time constraints precluded their use in this study, so insights derived are somewhat limited due to this omission.

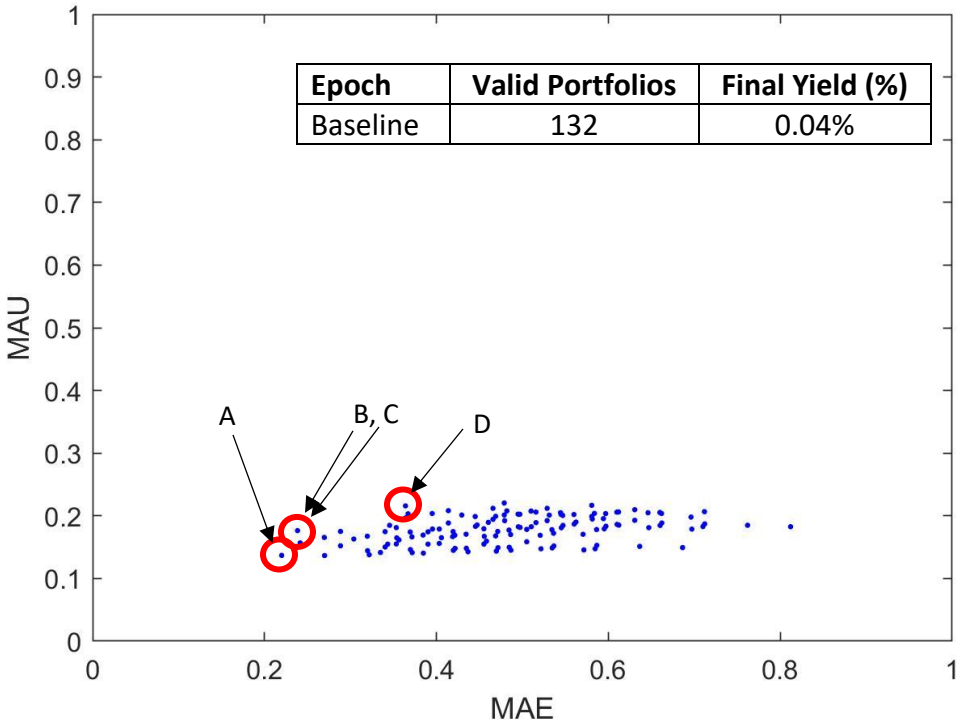

Figure 28. Case Study 1 Baseline Epoch Tradespace

In the Baseline epoch, the non-dominated portfolios span existing, operational systems—in large part because they lack acquisition costs. Table 14 below summarizes the composition of five interesting portfolios. Note that these five portfolios span all epochs considered, so in the Baseline epoch, only four of the five interesting portfolios are present. These were selected because they tended to endure as non-dominated or nearly non-dominated portfolios across most epochs, but it is worth noting that this selection was at the discretion

of the author and thus may not be generally representative of patterns in the full tradespace. The difference, incidentally, between portfolios B and C are the block quantities of high-altitude aircraft sensors, with one being an increase in the EO/IR payload and the other being an increase in the radar payload quantity—the points appear coincident in the figures, but there are subtle differences in the MAU (on the order of 0.003-0.007 variation) across epochs. MAE was the same because limited public information was available about the acquisition and sustainment costs of SYERS and ASARS, so they were assumed to be approximately equal. The difference in MAU is explained largely by ASARS' ability to operate in all-weather, compared to SYERS' inherent lack of cloud penetration—the Achilles heel of EO/IR systems. The constraint that all valid portfolios needed high-altitude systems, as well as day/night and all-weather operations meant that these capabilities were always present across epochs.

Portfolio	Different Systems	U-2 EO/IR (Baseline)	U-2 EO/IR (Mod 1)	U-2 SAR (Baseline)	RQ-4 EO-IR-SAR (Baseline)	RQ-4 EO-IR-SAR (Mod 1)	RQ-4 SAR	RQ-170	MQ-9 (Baseline)	MQ-9 (Mod 1)	High-Altitude Stealth	High-Altitude Hypersonic	Low-Altitude Swarm Aircraft
A	0	1		1	1			1	1				
B	1	2		1	1			1	1				
C	1	1		2	1			1	1				
D	3	2		2	1			1		2			
E	4		1	1		2		1		3			3

Table 14. Case Study 1 interesting portfolio compositions (# blocks for each)

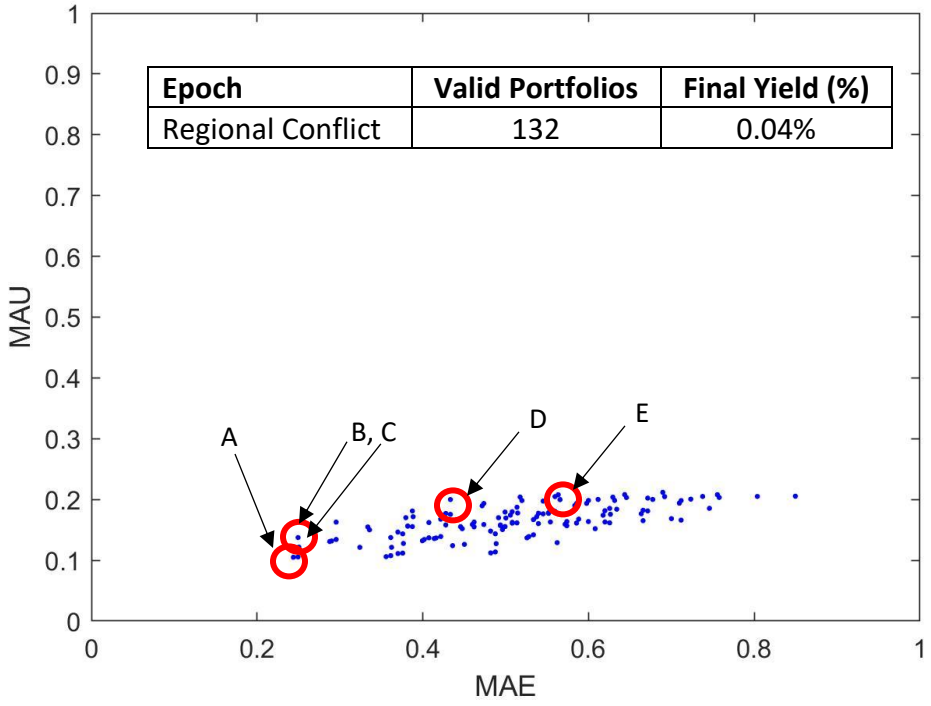

Figure 29. Case Study 1 Regional Conflict Epoch Tradespace

In the Regional Conflict epoch, the presence of the Swarm technology epoch variable gave rise to some new portfolio constructs, including three different variants of the Low Altitude Swarm Asset in varying quantities. The use case for such an asset is effectively "throw-away stealth," assets inexpensive and plentiful, and yet small enough to fly beneath an adversary's radar horizon with low risk of detection.

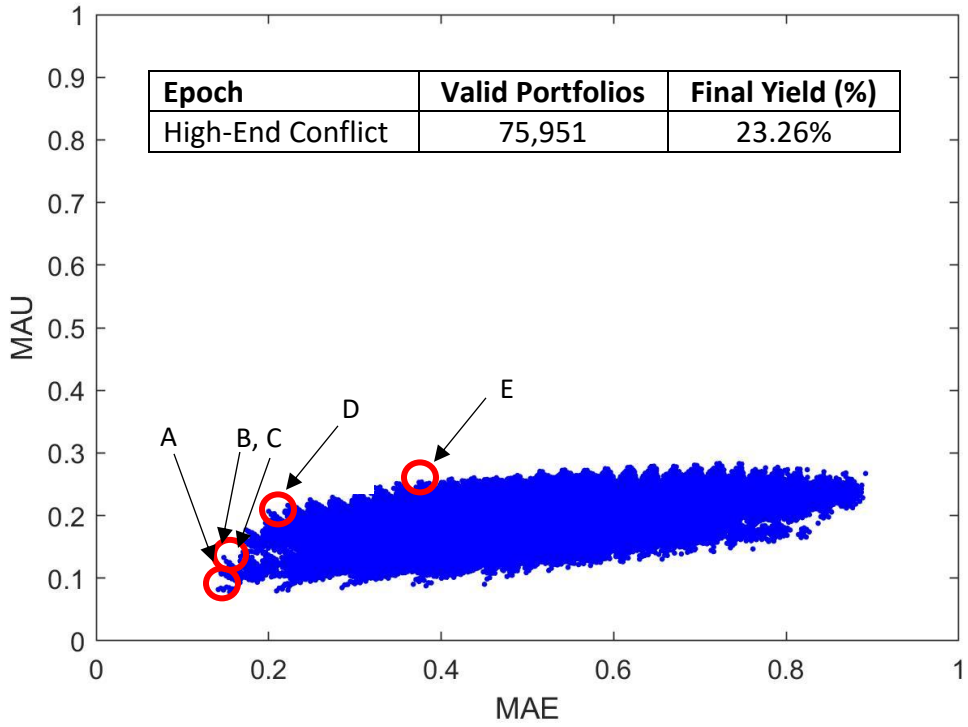

Figure 30. Case Study 1 High End Conflict Epoch Tradespace

The High-End Conflict epoch is characterized by maximum budget and cooperation factors and the presence of the technology epoch variables. There are more than 30 portfolio compositions on the Pareto front, and most non-dominated portfolios beyond the "knee" of the curve (around MAE = 0.2) simply feature more block quantity increments. For example, the non-dominated portfolios far to the right on the MAE axis contain an approximately equal number of High Altitude Stealth assets and upgraded U-2 EO/IR systems, a large number of upgraded MQ-9 Combat Air Patrols (CAP), and a large number of Swarm CAPs. The reader may note that the High-Altitude Hypersonic asset is not represented in the highlighted portfolios. This asset was considered and featured in some of the high-MAE portfolios, slightly below the efficient frontier. This could be a source of error and bias on the part of the author due to the limited information available about the costs for such an asset, and the

suitability and availability of ISR payloads. The X-51 Waverider demonstration unit was effectively the size of an air-to-air missile, and DARPA's FALCON Hypersonic Test Vehicle was also modestly sized. The author believed using unclassified information about the development cost for a one-off demonstration was not a good proxy for the acquisition and sustainment cost of an operational capability. By that same token, neither was the SR-71 Blackbird a good proxy. Its costs date to the 1950s, and the aircraft was a manned supersonic platform—factors that do not translate readily into a 21st century, likely unmanned, hypersonic vehicle. Point being, a hypersonic ISR asset may have more utility and / or less cost than the author estimated in this analysis, and it merely highlights the sensitivity of portfolio analysis outputs to the model inputs. Incidentally, this same comment applies to all the assets considered, and highlights the risk of bias that may anchor the analysis.

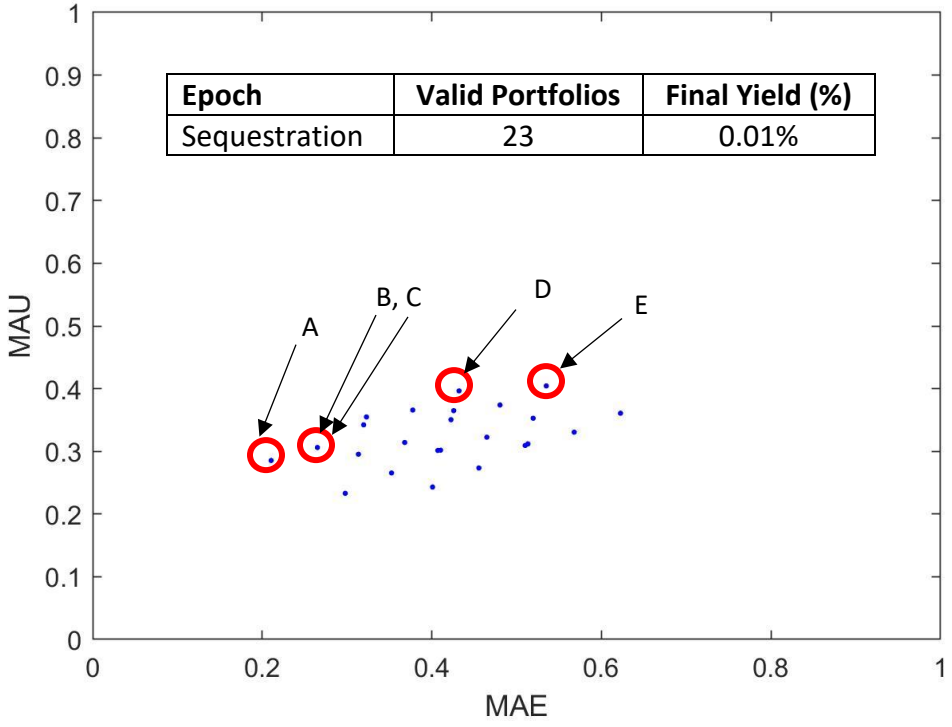

Figure 31. Case Study 1 Sequestration Epoch Tradespace

The Sequestration epoch is characterized by tighter budgets and less cooperation, but the presence of low-cost technologies, like the availability of the Swarm asset gives the portfolio designer a novel means to find emergent system of systems function. For instance, the very small size and low altitude of a swarm asset could allow it to serve as a "throwaway stealth" capability at a fraction of the cost. Whereas low-observable assets are large and gain advantage through special coatings and design geometry, swarming drones could be beneath the detection floor of adversary radar.

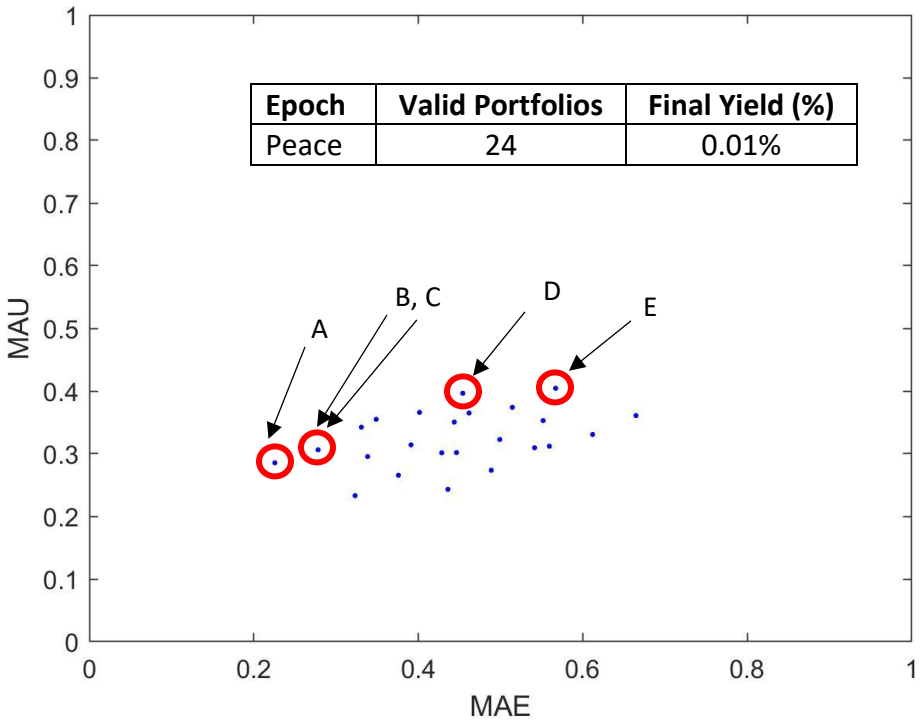

Figure 32. Case Study 1 Peace Epoch Tradespace

The Peace epoch looks very similar to the Sequestration epoch tradespace, and the Pareto front features the identical portfolio compositions. This is due to the similarities in epoch

variables—with only modest changes in cooperation and program manager preference weightings that affect the multi-attribute expense and utility calculations, respectively.

The last two epochs are slight modifications to the Baseline epoch and given the similarities, further commentary is not provided.

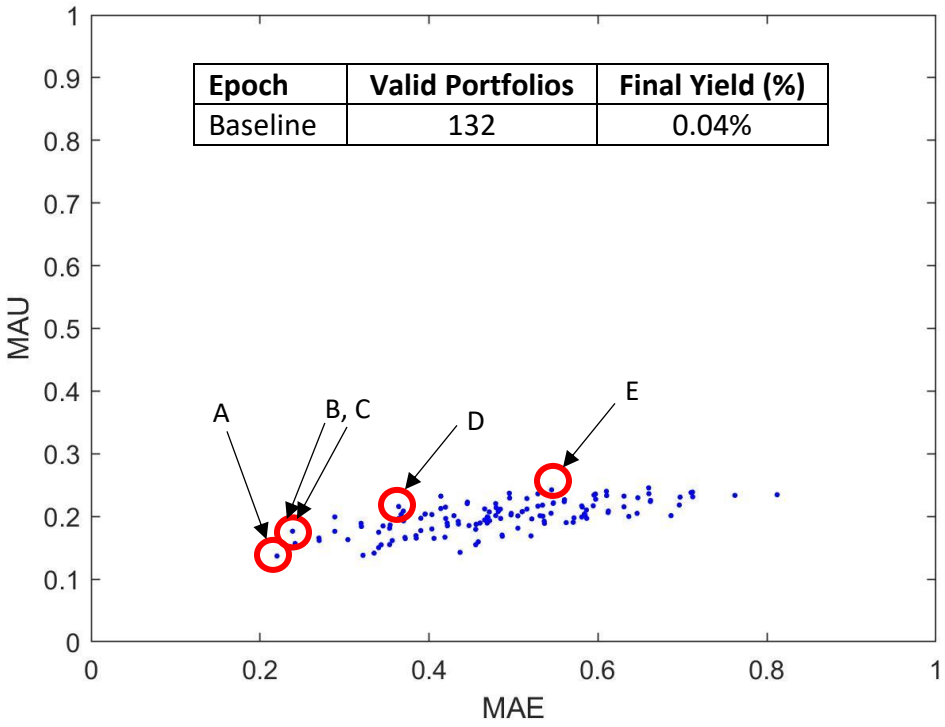

Figure 33. Case Study 1 Baseline 2 Epoch Tradespace

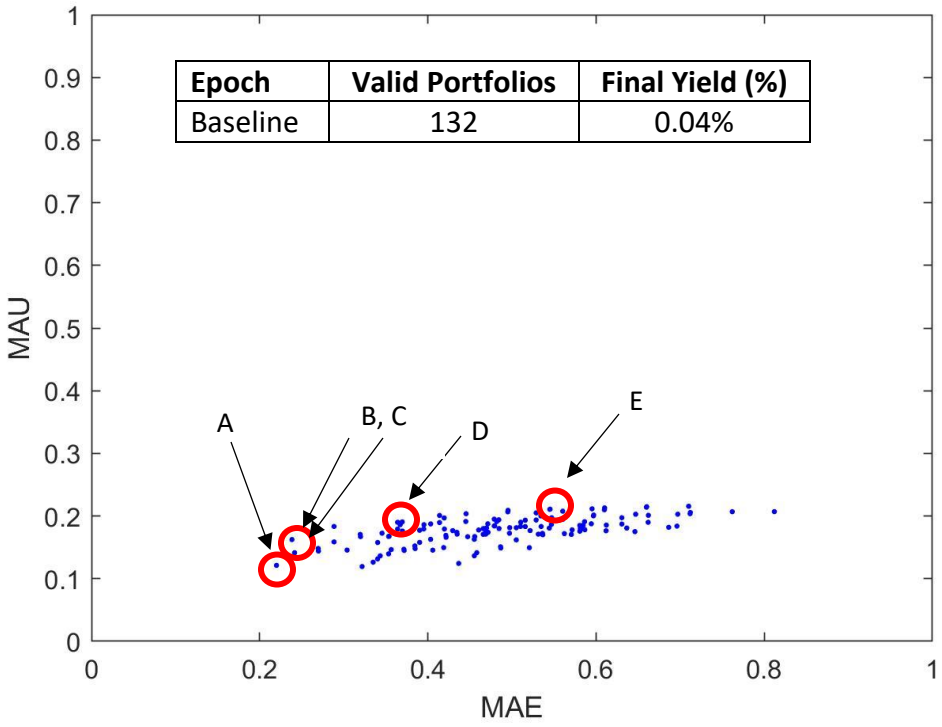

Figure 34. Case Study 1 Baseline 3 Epoch Tradespace

4.9. Process 8: Multi-Epoch Analysis

In the eighth process, the epochs are analyzed using metrics such as the Normalized Pareto Trace and its ilk. The NPT calculation assumes seven epochs in the denominator, of which the three Baselines are roughly equivalent, and counts the number of epochs in which the portfolio lies on the efficient frontier in the numerator. For example, Portfolio A, which is composed of one block each of U-2 SYERS baseline, U-2 ASARS baseline, RQ-4 EISS baseline, RQ-170, and MQ-9 baseline, appears on the efficient frontier in all seven epochs, so its NPT is 1.0. Similarly, Portfolios B and C, portfolios comprised of one additional block of U-2 SYERS baseline or U-2 ASARS baseline assets, respectively, appeared in five of seven epochs, or roughly 70%, so the NPT is 0.7.

Vascik et al (2015, 2016) appeared to take the literal portfolio architecture through the Pareto trace. Meaning, if the Carrier Strike Group allowed for a range of one to three vessels, the NPT analysis focused not on portfolios that had the identical asset classes with different quantities, but rather the exact composition across all epochs. This formality is perhaps more necessary in the context of a Carrier Strike Group, which is a team of systems in an integral Order of Battle. A portfolio designer may choose to relax that formality in cases such as top-level analysis conducted herein, because one could argue the recurrence of asset types across contexts is significantly more important than getting the quantity of those assets right. In other words, two portfolios that are identical in terms of assets present but differ slightly in terms of quantities of those assets (e.g. 2 versus 1 unit), might be considered the same portfolio in this analysis. The marginal cost of sustaining additional assets tends to be nonlinear in reality, and for all but the most exquisite systems, the incremental cost of adding an another unit to an existing constituent element is typically easier than adding an entirely new asset type. The effective fuzzy Normalized Pareto Trace (efNPT) metric could be used to identify the types of portfolio change, either changes to asset quantity or asset type, that result in near-Pareto-efficient portfolios across a large number of epochs. The author did not perform this analysis here due to time constraints, but future research may include this analysis.

In Table 15 below are the Normalized Pareto Trace and 5% Fuzzy Normalized Pareto Trace of five different portfolios across all seven epochs. Pursuant to the discussion in the previous paragraph, Portfolios B and C are architecturally similar to Portfolio A, but include an extra block of U-2 SYERS or U-2 ASARS assets. If they were considered part of a nearly identical

grouping of portfolios, A, B, and C would have an NPT of 1.0. Thus, a portfolio designer is encouraged to think carefully about the scope of his own analysis and decide whether unique portfolios or nearly identical portfolios are appropriate for this review in this process.

Portfolio	NPT	5% fNPT
A	1.0	1.0
B	0.7	1.0
C	0.7	1.0
D	0.7	1.0
E	0.6	1.0

Table 15. Case Study 1 NPT and fNPT metrics for 5 promising portfolios

4.10. Process 9: Era Construction

In order to more accurately model the "real world," PLEEAA leverages the EEA framework to create an ordered sequence of epochs that represent a hypothetical future in which the portfolio will operate. The power it brings to the portfolio design process is that it captures path dependencies, such as the timing of new capability delivery in response to a changing external context.

The U.S. Department of Defense and U.S. Air Force publish a number of strategic planning documents and refresh them approximately every five years, which establishes high-level investments and priorities relative to military technologies, as well as the approximate timing for the insertion of those technologies. In parallel, these can be overlaid on a range of potential futures that consider defense budget cycles, foreign affairs considerations such as regional conflicts, and even emerging science and technology forecasts outside of the defense industry.

For the purpose of this case study, the author simply has synthesized the available strategies and predictions and used them to evaluate the ISR portfolio largely as it exists

today, with the addition of some hypothetical gap-filler assets. If this analysis were to be performed by the actual portfolio stakeholders, the strategic plans are likely to be an output rather than an input, honed through multiple iterations.

In this case study the author identified two disparate futures for the purpose of illustration of the method. Because of the path dependencies, the analysis is not as trivial as reordering the epochs while holding utility and cost measures static. Additionally, new epochs may be introduced from one era to the next, warranting further analysis. So the author limited the analysis to demonstrate the applicability of the technique, but in practice the investigator may wish to capture more eras, depending on the available time and resources to commit to the analysis. One possible suggestion for selecting eras is to use a three-point technique, with a middle case (*m*) bracketed by a pessimistic case (*p*) and optimistic case (*o*). Depending on the type of probability distribution the stakeholders assume is representative of the future, a triangular or double-triangular distribution may be used to weight the portfolios that perform best over the range of outcomes.

The triangular distribution yields a simple arithmetic mean:

$$\frac{1}{3}(p + m + o) \tag{9}$$

And the double-triangular distribution yields a mean biased toward the middle value:

$$\frac{1}{6}(p + 4m + o) \tag{10}$$

Since in this simplified case study the author evaluated two eras, simpler calculation techniques could involve an arithmetic average or weighted-average, with the weights

determined through collaborative methods such as the Delphi technique. In this case study, both eras were given equal weight.

The first era to be considered in this case study largely represents a 20-year future that closely resembles the present. Specifically, the United States will continue to assert its hegemony around the globe, bumping up against near-peer large adversaries from time-to-time in regions like the South China Sea and the Middle East, and will likely participate in a small-scale regional conflict. Given the similarities to the present, this era is simply called "Status Quo," a Latin phrase meaning "the existing state of affairs." The specific epochs, their duration and sequence for the Status Quo era are given in Table 16. It is worth noting that the specific sequencing resulted in a new epoch, Baseline 2, being introduced. This is because the UAS – Swarm epoch variable was 0 in the Baseline epoch, but had advanced to 1 during the Sequestration epoch due to the rapid proliferation of commercial- and military-use drones, autonomy, AI, and other enabling technologies. It is improbable that the reduced budget would shelve this potentially game-changing technology, so when the Sequestration epoch ends and the Baseline epoch returns, the Swarm variable is set to 1. Table 17 details the epoch variables for the era.

The second era to be considered presents a more grim future, in which the United States is drawn into multiple proxy wars around the globe that are quietly fueled by large state actors. Increasing nationalism around the globe sparks jingoist fervor that helps lower the bar to armed conflict. Economic sanctions prove insufficient to extract the desired effect, and both sides engage in a shadow war that begins in the cyber domain. Cyberattacks on the financial system escalate to the energy grid, and serve as the *casus belli*—act of war—to

justify kinetic attack. Missile strikes on cyber command and control facilities make full-scale engagement inevitable. Kinetic warfare breaks out, and the near-peer nature of the conflict means that the war is protracted, drawing in allies on both sides, which expands the scale and scope. This era is the nightmare scenario that in many ways looks like World War I, updated for modern technologies. The author termed this era "Mars," a reference to the Roman god of war. The specific epochs, their duration and sequence for the Mars era are given in Table 18. As with Era 1, specific sequencing considerations necessitated the introduction of a new epoch, Baseline 3, to capture changes to the stakeholder preferences. Table 19 details the epoch variables for the era.

The specific construction of the two eras under consideration in this case study brings the total number of epochs evaluated to 7 of the universe of 864.

Epoch No.	1	2	3	4
Epoch Name	Baseline	Sequestration	Baseline 2	Regional Conflict
Epoch Duration	3	8	8	1
Era Duration	20 years			

Table 16. Case Study 1 Era 1 (Status Quo) epoch composition

Epoch Name	Epoch Variables						
	A2/AD – Stealth	A2/AD – Speed	UAS – Swarm	Budget	Cooperation Costs	Enemy Threat	Asymmetric Threat
Baseline	1	0	0	100	100	Med.	Med.
Sequestration	1	0	1	95	105	Med.	Med.
Baseline 2	1	0	1	100	100	Med.	High
Regional Conflict	1	0	1	100	100	Med.	High

Table 17. Details of Era 1 epoch variables

Epoch No.	1	2	3	4	5
Epoch Name	Baseline	Regional Conflict	High-End Conflict	Peace	Baseline 3
Epoch Duration	3	3	3	5	6

Era Duration	20 years

Table 18. Case Study 1 Era 2 (Mars) epoch composition

Epoch Name	Epoch Variables						
	A2/AD – Stealth	A2/AD – Speed	UAS – Swarm	Budget	Cooperation Costs	Enemy Threat	Asymmetric Threat
Baseline	1	0	0	100	100	Med.	Med.
Regional Conflict	1	0	1	100	100	Med.	High
High-End Conflict	2	1	1	150	80	High	High
Peace	1	0	1	95	100	Low	Med.
Baseline 3	1	0	1	100	100	Med.	Med.

Table 19. Details of Era 2 epoch variables

4.11. Process 10: Single-Era Analysis

In the tenth process, the portfolio designer analyzes the performance of potential portfolios over a time-ordered series of epochs, as identified in Process 9. This process brings to light the portfolios which are value-robust in the face of a modeled future, as well as those which may drift out of the affordability constraints.

In the first two figures, the Era 1 (Status Quo) Multi-Attribute Utility and Multi-Attribute Expense performance were plotted for the portfolios highlighted earlier. The process was repeated for Era 2 (Mars) in the subsequent two figures.

Portfolios B, C, and D appear to offer the best value-robust performance across both eras, with higher MAU—and MAE—on Portfolio D. Portfolio E offers higher utility, but also markedly higher MAE and higher complexity by way of a more diverse asset mix.

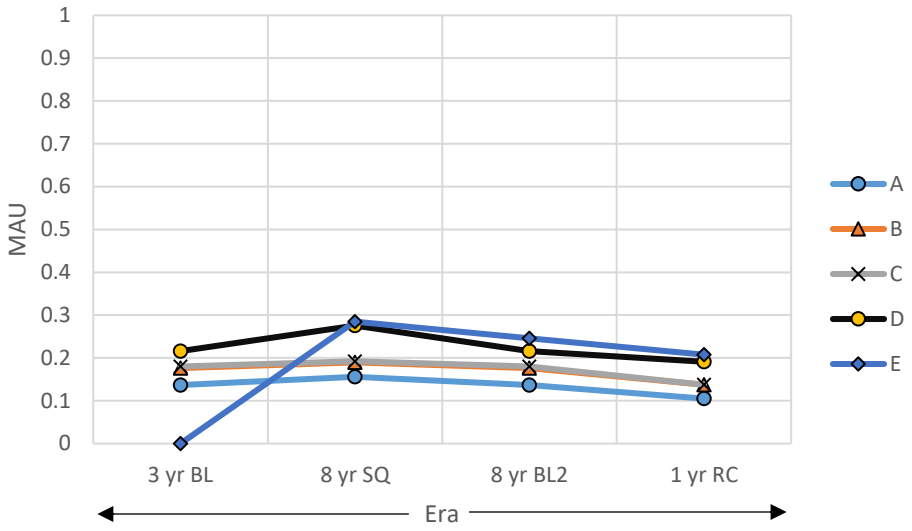

Figure 35. Case Study 1 Era 1 Utility (MAU) performance

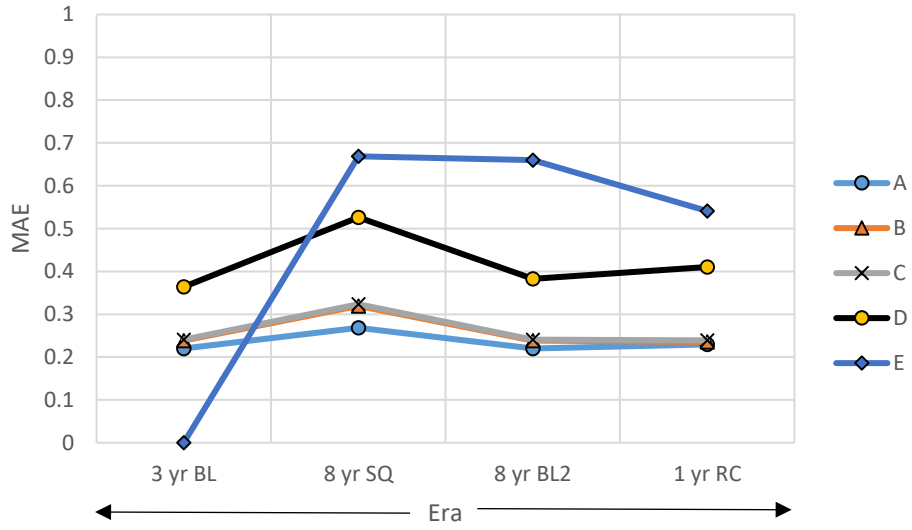

Figure 36. Case Study 1 Era 1 Expense (MAE) performance

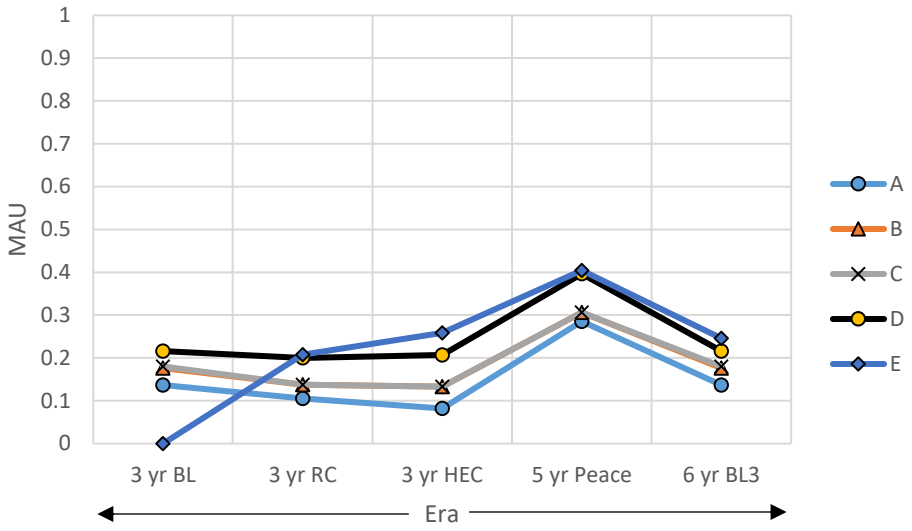

Figure 37. Case Study 1 Era 2 Utility (MAU) performance

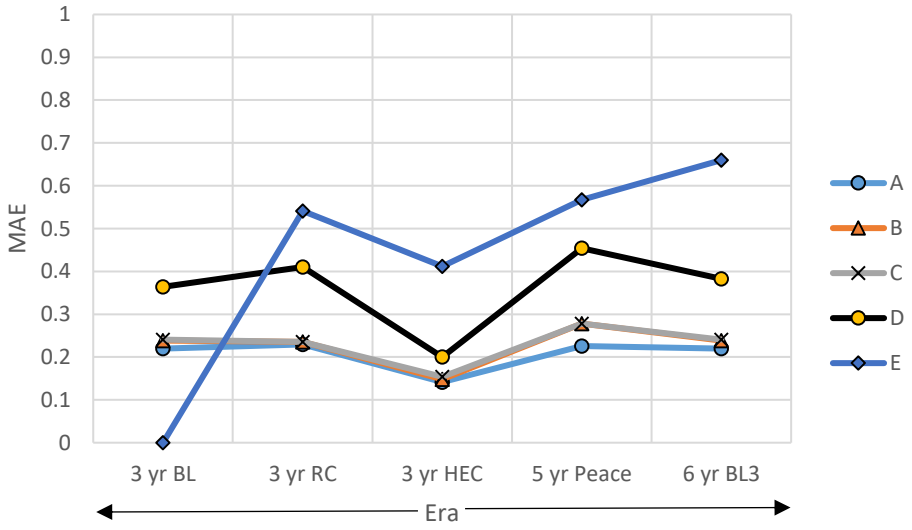

Figure 38. Case Study 1 Era 2 Expense (MAE) performance

4.12. Process 11: Multi-Era Analysis

Schaffner's thesis (2013) articulated a robust and rigorous approach to multi-era analysis. In the context of a single system such an analysis is demanding. It is made at least an order of magnitude more difficult when a portfolio of systems is involved, and some of those

systems likely have emergent behavior when paired with other constituents, making it all the more difficult and time-consuming to conduct multi-era analysis.

Earlier research in EEA and RSC tended to focus on systems, in which a large number of eras could be modeled and analyzed. Schaffner's work, for instance, explored 1000 simple eras. That approach applied to portfolios, while technically possible, is computationally intensive, time-consuming and costly when many stakeholders are involved. A tailored approach is a sensible compromise.

As was discussed in Process 9, a sensible compromise is selecting eras that bound what is deemed to be representative of the future contexts. The specifics of the analysis vary uniquely by the situation. For instance, in this research, the author focuses on two very different eras that arguably come close to bracketing the spectrum. In "real world" application the portfolio designer would be able to contemplate weighting schemes—for instance, equal-weighted or heavy-weighting one based on expert knowledge, exogenous strategy like foreign policy and national security strategies.

Specifically, portfolios that proved value-robust over the Era 1 and Era 2 were evaluated using NPT and fNPT. It would be fair to question what value this analytical approach offers, which is considerably more simple-minded than Schaffner articulated in his thesis on the Responsive Systems Comparison framework, and which brackets the earlier analysis in Process 8. The author believes that it is useful to analyze the value-robustness of portfolios in standalone eras to serve as a scenario planning tool. The multi-epoch analysis is agnostic to sequencing and duration of epochs, and eras may feature different epoch compositions. Thus, if the portfolio stakeholders can apply a weighting scheme to the era-based NPT / fNPT

measures, they can get a sense for potential portfolios' durable performance over a number of futures. In this case a 50-50 equal weighting yields roughly equal Multi-Era Net measures, but this is because the potential portfolios in both eras feature a diversity of assets meant to provide utility over a range of eventualities. This need not be the case. If the portfolio decision maker has high confidence in a particular operating context, the assets and portfolios thereof can be more tightly matched to the specific mission—and that could well come at the cost of performance in significantly different operating contexts. In that setting, one era would produce Pareto-optimal portfolios tuned to the task, but may offer suboptimal performance in other eras, with the result being a lower Multi-Era Net.

Portfolio	Era 1 – Status Quo			Era 2 – Mars			Multi-Era Net	
	NPT	fNPT 5%	Weight	NPT	fNPT 5%	Weight	NPT	fNPT 5%
A	1.00	1.00	50%	1.00	1.00	50%	1.00	1.00
B	0.75	1.00		0.80	1.00		0.78	1.00
C	0.75	1.00		0.80	1.00		0.78	1.00
D	0.75	1.00		0.80	1.00		0.78	1.00
E	0.25	0.50		0.25	0.50		0.25	0.50

Table 20. Case study 1 Multi-Era NPT and fNPT for enduring portfolios

5. Case Study 2: U.S. Space-Based Geospatial Intelligence Portfolio

In this section, the author applies the PLEEAA framework discussed in Chapter 0 to a second case. This case study focuses on the constellations of satellite systems that provide geospatial intelligence to the U.S. Intelligence Community (IC). Throughout the Cold War, the United States Government designed, built, launched and operated its own portfolio of satellites, and no other source of supply existed. There are reasons for that, including expense, legal and regulatory reasons, and market forces, but this is a case study focused on the future so no further explanation will be provided. With the collapse of the Soviet Union the Cold War came to a close, and the U.S. policies about space shifted to allow commercial opportunities. Increasingly, commercial assets in space have been seen as a force multiplier, a means to increase the capacity and capability of U.S. Government-owned systems.

This case study is unique from Case Study 1 in that the USAF airborne geospatial intelligence portfolio consists entirely of U.S. Government-owned assets, while the overhead geospatial intelligence portfolio is a mixture of Government- and commercially-owned assets. This presents some opportunity for novel tactics, techniques, and procedures (TTP); hybrid government-commercial architectures; and cost synergies.

Some context is useful at this stage to help understand the backdrop that enables complementary use of government and commercial sources. National Security Presidential Direct (NPSD) 27 establishes the policy that the U.S. Government shall utilize commercial remote sensing capabilities to augment its own assets (NPSD, 2003). Specifically, NPSD-27 states as its goal:

"The fundamental goal of this policy is to advance and protect U.S. national security and foreign policy interests by maintaining the nation's leadership in remote sensing space activities, and by sustaining and enhancing the U.S. remote sensing industry. Doing so will also foster economic growth, contribute to environmental stewardship, and enable scientific and technological excellence.

In support of this goal, the United States Government will:

- Rely to the maximum practical extent on U.S. commercial remote sensing space capabilities for filling imagery and geospatial needs for military, intelligence, foreign policy, homeland security, and civil users;
- Focus United States Government remote sensing space systems on meeting needs that cannot be effectively, affordably, and reliably satisfied by commercial providers because of economic factors, civil mission needs, national security concerns, or foreign policy concerns;
- Develop a long-term, sustainable relationship between the United States Government and the U.S. commercial remote sensing space industry;
- Provide a timely and responsive regulatory environment for licensing the operations and exports of commercial remote sensing space systems; and
- Enable U.S. industry to compete successfully as a provider of remote sensing space capabilities for foreign governments and foreign commercial users, while ensuring appropriate measures are implemented to protect national security and foreign policy."

Further, Presidential Policy Directive (PDD) 4 establishes the U.S. national space policy, and addresses among other things the use of commercial space technologies. Two of the guidelines include: (1) "Purchase and use commercial space capabilities and services to the maximum practical extent when such capabilities and services are available in the marketplace and meet United States Government requirements," and (2) "Develop governmental space systems only when it is in the national interest and there is no suitable, cost-effective U.S. commercial or, as appropriate, foreign commercial service or system that is or will be available." (PDD-4, 2010)

In *Democracy's Arsenal*, Gansler compared and contrasted commercial and defense markets along several dimensions (2011). These are reproduced in Table 21.

Aspects	Commercial Markets	Defense Markets
Products	Proven technology that is rapidly applied	Cutting-edge technology that is slowly applied
Market Structure	Many buyers and multiple producers	One buyer; large items bought in small quantities
Demand	Competitive; sensitive to price and quality	Monopolistic; rarely price-sensitive; driven by maximum performance
Supply	Competitive; adjusts to demand	Oligopolistic; large excess capacity
Entry and Exit	Movement in and out of the market	Extensive barriers to entry and exit (such as unique requirements, perception of higher cost of two suppliers, special accounting, Congress
Prices	Constrained by market competition	Cost-based and regulated
Outputs	Constrained by market competition	Determined by government
Risk	Borne by firm	Shared between firm and government
Profits	Constrained by market competition	Regulated by the government
Competition	In production	Usually for R&D

Table 21. Commercial markets and defense markets (Gansler, 2011)

5.1. Introduction

Any conversation about U.S. Government geospatial intelligence satellites should begin with a high-level introduction to the National Reconnaissance Office (NRO). According to Joint Publication 2-0 (2013), the NRO is "responsible for integrating unique and innovative space-based reconnaissance technologies, and the engineering, development, acquisition, and operation of space reconnaissance systems and related intelligence activities."

The NRO is a U.S. Department of Defense (DoD) agency and member of the Intelligence Community (IC). The Director of the NRO reports both to the Director of National Intelligence (DNI) and Secretary of Defense.

According to Joint Publication 2-01, the NRO's mission is to "collect intelligence and information to support national and department missions and other U.S. Government needs." NRO's activities support warning intelligence (e.g. missile launches), monitoring of arms control agreements (so-called "National Technical Means" or NTM), access to denied areas, and the planning and execution of military operations. It provides direct support and liaison to combatant commanders and their joint operations centers.

The IC, of which the NRO is a member, is an amalgamation of 16 executive branch agencies (e.g. Central Intelligence Agency (CIA) and National Geospatial Intelligence Agency (NGA)) that are funded in the National Intelligence Program (NIP). The IC is headed by the Director of National Intelligence. The Office of the Director of National Intelligence (ODNI) has "authority over the NIP budget, appointment of certain IC agency heads" and numerous other administrative functions (JP 2-01).

Lastly, the National Geospatial-Intelligence Agency (NGA) is a fellow member of the IC, and effectively owns geospatial intelligence tradecraft. NGA develops standards, strategic guidance and procedures, and develops information technology architecture and standards. (JP 2-01). NGA is responsible for acquiring commercial satellite imagery. Thus, NGA has some interaction with NRO and other members of the IC to help shape the strategic map as it pertains to geospatial intelligence.

This case study is focused on the geospatial intelligence portion of the space reconnaissance mission, so other stakeholders that focus on other domains of intelligence are excluded.

5.2. Process 1: Value-Driving Context Definition

According to JP 2-01, the NRO Director "manages and operates the NRO and its programs and activities and acquires NRO systems," and "receives and implements SecDef [Secretary of Defense] and DNI [Director of National Intelligence] guidance and direction by establishing strategic guidance policy and procedures for executing the NRO mission and accomplishing the Director, NRO, National Security Space responsibilities." As was alluded to in the introduction, the NRO has the responsibility for the constellation of satellite resources that, among other things, provide the DoD and Government with geospatial intelligence. They define the architecture of the systems in their purview, determine how much commercial sources will be leaned upon to satisfy demand for tasking, and control the budget in fulfillment of that mission.

Thus, the primary stakeholder for the overhead geospatial intelligence portfolio is the Director, NRO, who is effectively the chief executive of that organization. The other key stakeholder is the Director, NGA, who has oversight of commercial satellite imagery acquisition.

Given how important satellite-based geospatial intelligence is to the DoD and Government, it is unsurprising that there are a great many adjacent stakeholders. These include fellow IC members like NGA and the Central Intelligence Agency, politicians and diplomats from the State Department, Congress, and others, and military stakeholders like the combatant commanders around the globe. These myriad stakeholders are considered to be influencers for the purpose of this research, though the reality is undeniably more nuanced and complex.

The Director, NRO is assumed to have near-absolute decision-making control over the budget and requirements that influence the portfolio decisions simulated in this case study.

The constituent systems under evaluation in this analysis is more notional than in Case Study 1 due to the very limited amount of unclassified, open-source information available. In its "Strategic Vision" document, NRO includes the goal to "develop the cutting-edge systems and the innovative techniques necessary to overcome the toughest intelligence challenges and stay ahead of the threat," which includes the sub-goals of advancing "promising, revolutionary technologies and demonstrate their potential to deliver capabilities others think impossible," "insert innovative space collection technologies and develop new techniques for NRO acquisition programs to close known collection gaps or vulnerabilities," and "deliver the rapid reaction capabilities necessary to respond to critical user needs…" While it is important to consider ulterior motives for such strongly-worded goals, such as recruiting top talent, bolstering employee morale, justifying organizational budgets, and even deterring adversaries, it is also rooted in the ethos of the NRO, as will be demonstrated below in the publicly-acknowledged systems they have fielded.

The organization responsible for acquiring commercial satellite imagery is the National Geospatial-Intelligence Agency (NGA). Given that the individual budgets for the Intelligence Community are not made public, this case study makes a simplifying assumption that the combined budgets for satellite acquisition and commercial imagery acquisition are a single pool, and the portfolio decisions about how the mix of organic, Government-owned systems versus commercial imagery are made holistically.

KH-11 KENNEN Evolved Enhanced CRYSTAL Block IV

The KH-11 can be thought of as a terrestrially-aimed Hubble Space Telescope. According to public sources, the primary mirror is thought to be around 2.4 meters. Its tertiary mirror gives it a wider field of view, and other design features that give the ability to image from a variety of collection geometries.

These systems have an on-orbit life of around 10+ years, and there are believed to be four in orbit at the time of this writing, with launches spanning 2001 through 2013.

The Congressional Budget Office in 1990 published a report estimating the cost at between $1.25-1.75 billion, inclusive of launch costs. Adjusting for inflation, this represents $2.3-3.3 billion in 2017 dollars.[35] While precise details are unavailable, more recent data points suggest a unit cost in excess of $4.8 billion in 2017, which it may be reasonably inferred is the result of scope (i.e. technological capability) increases not in existence in 1990 when the earlier analysis was performed. For point of reference, the Nimitz-class aircraft carrier unit cost was on the order of $4.5 billion.[36] This is provided to illustrate the place of strategic significance these systems occupy in the portfolio of space-borne intelligence systems.

Finally, these systems are thought to be EO/IR multispectral, meaning they are detecting light through a number of discrete wavelength bands, spanning the visible and infrared regions.

[35] https://en.wikipedia.org/wiki/KH-11_Kennen, accessed 3/9/2018
[36] https://en.wikipedia.org/wiki/Nimitz-class_aircraft_carrier, accessed 3/9/2018

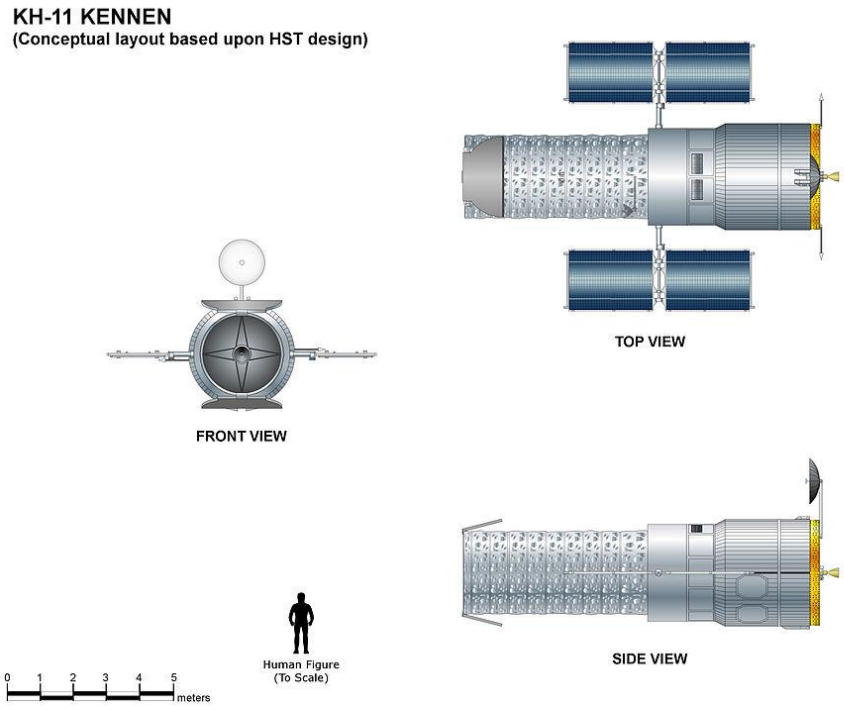

Figure 39. KH-11 KENNEN Concept[37]

Figure 40. KH-11 Cutaway View[38]

[37] https://en.wikipedia.org/wiki/KH-11_Kennen#/media/File:KH-11_KENNEN_01.jpg, accessed 1/22/2018

[38] http://www.americaspace.com/2012/06/06/top-secret-kh-11-spysat-design-revealed-by-nros-twin-telescope-gift-to-nasa/kh-11-pix-1-3/, accessed 3/4/2018

LACROSSE / ONYX

The LACROSSE or ONYX systems are believed to be the radar equivalent of the large-aperture EO/IR systems. Since EO/IR systems cannot penetrate clouds and some manmade obscurants, radar is a natural complementary capability.

Three systems are believed to be operational at this time.

Amateur astronomers described one of the ONYX systems as routinely performing a "disappearing trick,"[39] a phenomenon in which the satellite changes visible characteristics in a short period of time. While the nature of this behavior is not openly acknowledged, the author merely brings the point up to illustrate that there may be design differences between the systems that have been deployed under that name.

The Congressional Budget Office in 1990 published a report estimating the cost at between $0.5-1.0 billion, inclusive of launch costs. Adjusting for inflation, this represents $0.9-1.8 billion in 2017 dollars.[40] Of course, as will its KH-11 sisters, it is exceedingly likely that technological advances since that time have driven the unit cost well above that.

A partially integrated LACROSSE / ONYX system is depicted in Figure 41.

[39] https://en.wikipedia.org/wiki/Lacrosse_(satellite), accessed 3/23/2018
[40] https://en.wikipedia.org/wiki/Lacrosse_(satellite), accessed 3/9/2018

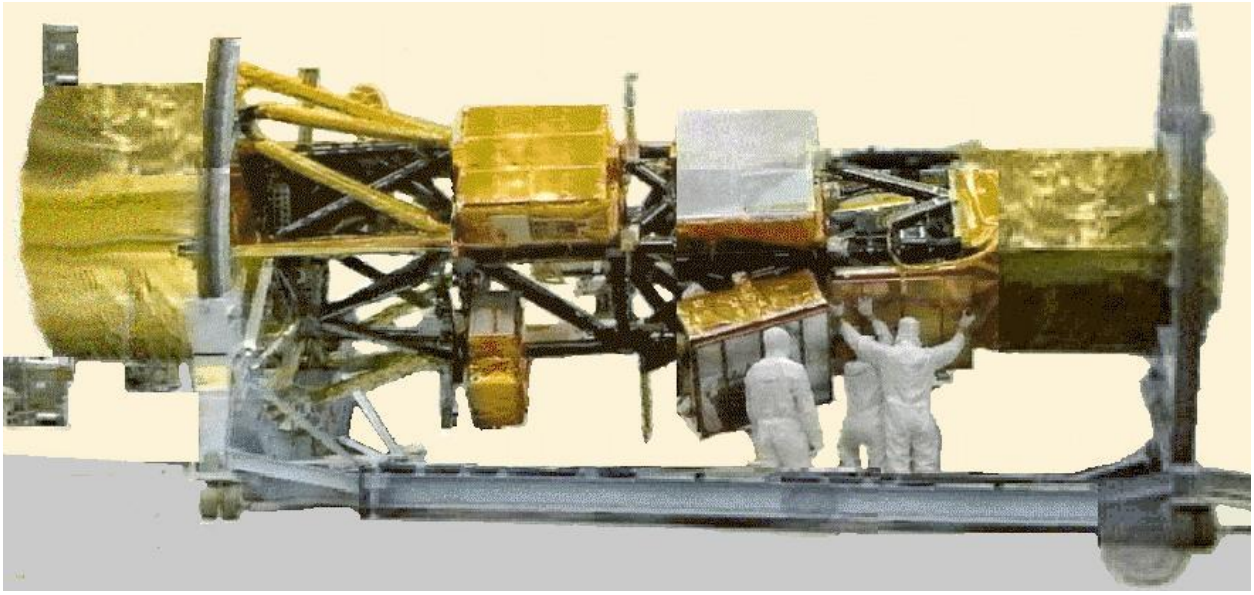

Figure 41. LACROSSE / ONYX Radar Satellite Under Construction[41]

DigitalGlobe WorldView

Case Study 1 dealt with an exclusively military portfolio of systems. Case Study 2 presents a novel complication: namely, that the U.S. has opened the space market to commercial purposes, and has codified in policy the use of commercial assets for military and other government purposes to the greatest extent possible. As discussed in the introduction to this case study, NPSD-27 and PDD 4 are two such Government policy directives that enable the procurement of commercial space-based capabilities.

At one end of the spectrum are large commercial providers, such as DigitalGlobe. This company has, at the present, five systems on orbit, with capabilities ranging from panchromatic to multispectral. Commercial applications of its imagery includes TerraServer and Apple Maps, and it serves various Government customers like NASA and NGA.[42]

[41] https://www.globalsecurity.org/space/systems/images/compos.jpg, accessed 1/22/2018
[42] https://en.wikipedia.org/wiki/DigitalGlobe, accessed 3/9/2018

Pictured below is its latest satellite, WorldView-4. Its figures of merit are comparatively easy to obtain relative to the Government-owned assets, and reveals that it is not a direct competitor to the exquisite KH-11 systems. Its aperture is much less at 1.1 m and have a mission life on the order of 7 years.[43] Its revisit rate is every 4.5 days or sooner, depending on the required collection geometry.[44] Its cost was estimated at $835 million.

DigitalGlobe furnishes its full-resolution imagery to the U.S. Government customers and downsamples the imagery to lower resolution for most commercial users.[45]

DigitalGlobe has few pure-play competitors in the large commercial satellite niche. French company Spot Eye is one. Being a non-U.S. company, the author has excluded them from consideration a source for intelligence.

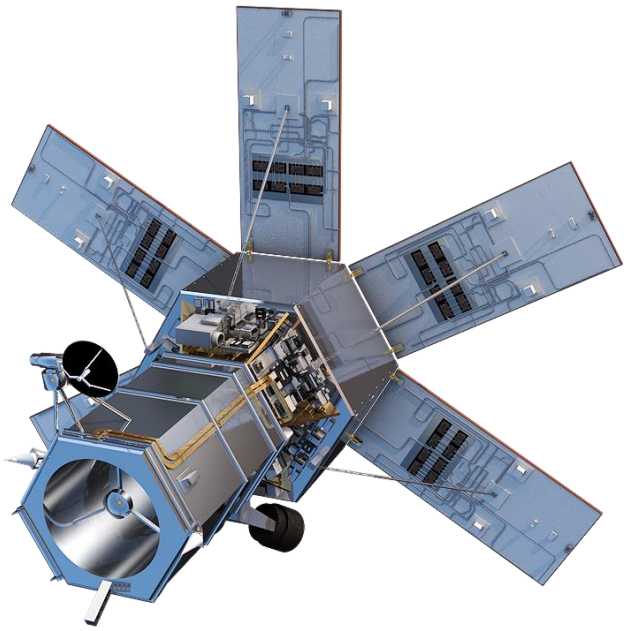

Figure 42. DigitalGlobe WorldView-4[46]

[43] https://en.wikipedia.org/wiki/WorldView-4, accessed 3/9/2018
[44] https://www.satimagingcorp.com/satellite-sensors/geoeye-2/, accessed 3/9/2018
[45] http://spaceflight101.com/worldview-4/worldview-4-imaging-satellite-declared-ready-for-operation/, accessed 3/9/2018
[46] http://www.satpalda.com/uploads/images/worldview%204.png, accessed 2/2/2018

Small Sat Companies

A market niche that has seen significant growth is in the recent years. James Vedda of The Aerospace Corporation's Center for Space Policy and Strategy suggests that one of the main reasons is export regulations codified in the International Traffic in Arms Regulations (ITAR) (Vedda 2017). While the intent of the ITAR was to maintain the United States' lead in space technologies, it had the unexpected consequence of driving foreign countries to invest in their own capabilities, which has in turn spawned an industry of international remote sensing providers. In parallel, the introduction of competition in launch providers in the form of companies like SpaceX has pushed the bar lower in terms of the cost to get satellites into orbit. Thus there are now a significant number of companies both inside and outside the United States with constellations of small satellites ("small sats") all vying to sell geospatial imagery.

For the purpose of this analysis, the author has taken note of just two small sat providers. Planet Labs, who acquired Google's satellite business, have a constellation of "Dove" satellites, pictured in Figure 43. As of 2017, Planet had 175 Doves and 5 larger RapidEye systems in orbit.[47] While the very small aperture systems provide imagery resolution in the range of 3-5 m, which is dramatically lower resolution than the exquisite military systems addressed earlier, the sheer number of systems means that the same spot can be canvassed as often as hourly. Conventional satellite tasking operations, where a discrete target deck is tasked to each asset, would suggest that the command and control problem would become

[47] https://en.wikipedia.org/wiki/Planet_Labs, accessed 3/9/2018

very complex the larger a constellation grows. However, novel tasking concepts likely exist, such as a publish-subscribe ("pub/sub") pattern, with a blockchain-style ledger to maintain the knowledge of which asset(s) responded to the call. Additionally, assets imaging the same target from different collection geometries at subtly different times may present novelty for stereo imaging, change detection algorithms, and automated three-dimensional feature extraction.

The other small sat provider of note for this analysis is BlackSky. Like Planet they are in the process of building a sizeable constellation of small sats, in this case approximately 60. Unlike Planet, BlackSky is aiming for 1-meter resolution. It also seeks to fuse other sources of information, such as social media and content from news outlets, to add value to the products they provide[48]—in a sense becoming a commercial provider of "all-source" intelligence analysis.

There are many other small sat providers at the time of this writing. Supply and demand forces may lead to a market shakeout, so the analysis here simply focuses on the inclusion of small sats as a constituent of the portfolio rather than identifying particular companies.

As with the earlier comment about novel means to task a constellation of small sats, the problem gets still more complex when more than one provider's constellation is considered. In this scenario, the NRO could build a pub/sub brokerage, where it pushes out a wish list of geospatial coordinates and collection time to a list of subscribers (the small sat providers), with some offered price depending on the number of unobscured images and the resolution

[48] https://www.blacksky.com/, accessed 3/9/2018

obtained, and the respondents can task their constellations and submit images for compensation.

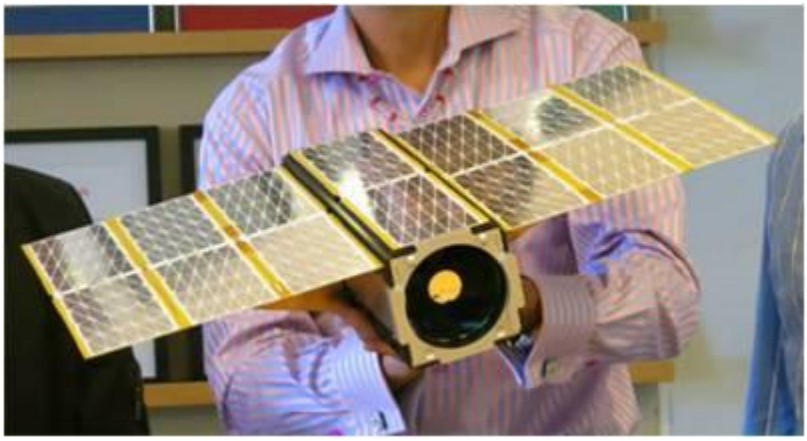

Figure 43. Planet Labs Dove Satellite[49]

Several commercial satellites are depicted in the image below to give the reader perspective on the relative sizes of these systems. Whereas a payload like DigitalGlobe's WorldView-4 satellite may be the only asset in a launch vehicle, small sats like Planet's Doves are invariably grouped with other satellites going up on the same launch.

[49] https://satelliteobservation.wordpress.com/2017/02/11/smallsat-constellations/, accessed 2/14/2018

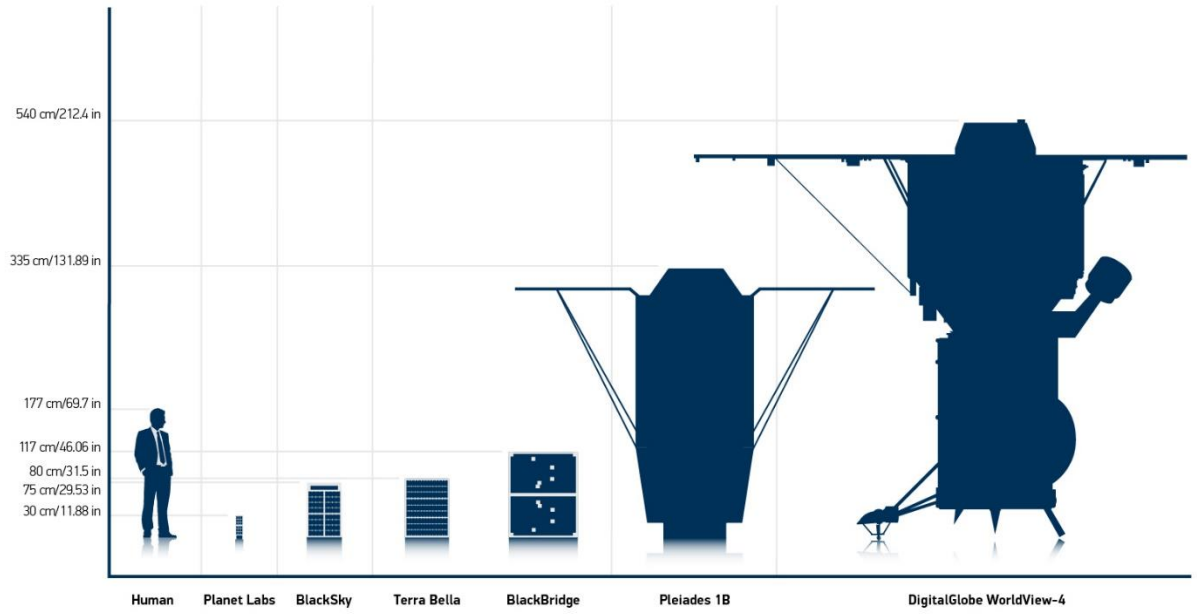

Figure 44. Relative Sizes of Several Common Commercial Imaging Satellites[50]

The portfolio constituents under consideration in this analysis are summarized in Table 22.

Possible Constituent	Legacy Variants	New Variants	Upgrade Variants
Exquisite EO/IR (KH-11)	1	1	1
Exquisite Radar (ONYX)	1	1	1
Large EO/IR (e.g. WorldView-4, ORS-1)	0	2	0
Small EO/IR (e.g. BlackSky Pathfinder)	0	3	0
Commercial Imagery High-End (<1m)	1*		
Commercial Imagery Low-End (1-3m)	1*		

Table 22. Case Study 2 possible constituent systems

*There are a significant number of commercial earth-observation companies in operation at the time of this writing. This analysis does not attempt to pick a source of supply among them, but rather assumes that the Government has the ability to buy a timely image of a

[50] http://blog.digitalglobe.com/news/frequently-asked-questions-about-worldview-4/, accessed 2/2/2018

target virtually anywhere on the globe at the resolution it needs to satisfy essential elements of information (EEI) designated for that target.

5.3. Process 2: Portfolio-Level Stakeholder Value-Driven Design Definition

Having already explained the second process in detail in Case Study 1 earlier, the results for Case Study 2 are presented here with minimal introduction. The decision maker's "Performance Attributes," "Expense Attributes" and "Portfolio Level Investment Strategy Constraints" are presented below.

The Expense Attributes are again adapted from Vascik and Ross.

Performance Attributes	Notional Portfolio Strategic Objective
Persistent	Asset(s) maintain constant, enduring contact with target, thereby increasing understanding about the target and enabling fast decision cycle (Pendall 2005)
Operationally Responsive	Rapidly evolve and deploy assets that meet stakeholder needs
Multi-"INT" Capability	When practical, systems shall provide multiple intelligence (INT) domains integrated in single payload.
Concealment and Deception Capability	Confuse adversaries by deploying fake or disguised assets. Leak false information, employ information warfare techniques to reduce signal-to-noise ratio of truth
Maintainable Capability	Asset(s) may be repaired or upgraded periodically via unmanned drones
Offensive Capability	Within the bounds of international treaties and law, intelligence assets shall provide kinetic capabilities to shorten the Kill Chain and serve as non-nuclear strategic deterrent
Defensive Capability	Assets are not expendable, and are hardened against cyber, directed-energy, and other threats.

Table 23. Case Study 2 Portfolio Performance Attributes

Expense Attributes	Notional Portfolio Strategic Objective
Acquisition Cost	The cost to procure a new portfolio constituent element
Late-to-Need Cost	The cost of inserting a portfolio constituent element later than needed, caused by acceleration of effort and procurement of commercial imagery to gap-fill

Table 24. Case Study 2 Portfolio Expense Attributes

Table 23 and Table 24 yield seven performance attributes and two expense attributes to establish the multi-attribute utility and multi-attribute expense functions for the satellite portfolio. The functions are calculated by using a simple linear-weighted sum, with the weights summing to one. Performance and expense attributes are assumed to act independently in this analysis.

In space applications, the biggest cost is acquisition—the cost to develop, build and launch a system. Once it is in orbit, most systems are generally not serviceable. While new technologies like the SpaceX Dragon, shown in Figure 45, and the Boeing X-37B space plane, shown in Figure 46, could conceivably be used to repair or upgrade satellites, neither are known to possess this capability at the time of this writing but several government groups and commercial entities are actively working the problem at the time of this writing. But the capability is an active area of development. For instance, Orbital ATK announced in 2018 that technology it was developing could be used to extend the life of satellites by up to five years, change its orbital characteristics, and enable upgrades and on-orbit assembly. (Knapp, 2018) As such, this case study includes the future ability to repair or upgrade a high-end military asset.

In terms of the expense attributes, Acquisition Cost is self-explanatory. Sustainment costs are ignored, though in reality there are likely some sustainment costs associated with maintaining the industrial base and operating the ground stations that have command and control of these systems. Finally, Late-to-Need cost involves some assumption that development schedules may slip and commercial imagery may need to fill the gap in the interim.

Figure 45. SpaceX Dragon Drone Capsule[51]

Figure 46. X-37B Space Plane[52]

Finally, the portfolio constraints are:

1. No more than 5 very large aperture EO/IR assets in orbit at a time.

[51] https://www.nasa.gov/mission_pages/station/multimedia/gallery/iss034e060060.html, accessed 3/9/2018

[52] https://www.extremetech.com/extreme/255114-spacex-prepares-launch-air-forces-secretive-x-37b-space-plane, accessed 3/9/2018.

2. Both EO/IR and radar sensor types shall be in orbit at all times.

5.4. Process 3: Capability Tree Stakeholder Value-Driven Design Formulation

In this case study, the capability tree is derived from U.S. publications about military operations in space. Some background information is helpful before presenting the tree.

Joint Publication 3-14, Space Operations, says:

"Single low and medium Earth-orbiting systems, or architectures that provide limited numbers of low or medium orbital systems, are well suited to the reconnaissance mission. Generally, their access to specific targets is limited in time based on their orbit such that data collected will be a "snapshot" of events in the portion of the electromagnetic spectrum where they can collect. Geosynchronous or geostationary satellites are capable of performing reconnaissance from space as well, focusing their collection efforts on a target or region for a relatively short amount of time before focusing on another area."

"While able to provide worldwide coverage, demands on individual space-based systems often exceed their capacity, and their associated orbit requirements may limit the ability to meet operational requirements. Space-based ISR is limited by advanced denial and deception techniques."

"ISR systems also enhance planning capabilities by providing updated information regarding terrain and adversary force dispositions. Space-based imagery, in particular, supports the full range of military intelligence activities including indications and warning, current intelligence, order of battle, scientific and technical intelligence assessments, targeting, and combat assessments. Imagery is also used to conduct mission planning and rehearsal."

Air Force Doctrine Document (AFDD) 2-2, Space Operations, includes more useful detail about when and how commercial satellite imagery is requested:

"Military resources will be stressed during large-scale contingencies and combat operations. In these situations, the military normally will use civil, commercial, and/or foreign space assets to support military objectives. The integration of non-military space assets may become vital to mission accomplishment. Military capabilities may be augmented with these assets or the assets may, by themselves, meet the military's needs. In most cases, the geographic combatant commander's staff will determine the appropriate avenue for meeting warfighter needs using these assets.

Civil, commercial, and foreign space assets can be leveraged through preestablished agreements, but often must be requested on an unplanned basis. For example, the military may request NASA to redirect focus from a scientific mission to support a military operation. DOD organizations like the National Geospatial-Intelligence Agency and Defense Information Systems Agency are designated to contract with commercial entities for services. In any case, because of unique C2 processes, pre-established agreements enhance effectiveness."

The portfolio capability tree is presented in Table 25. The complete portfolio capability tree and brief descriptions of the first two levels are included in Appendix B.

Persistent	All Weather Capability	8
	Day / Night Capability	8
Operationally Responsive		7
Multi-INT Capability	Signals Intelligence Capability	6
	Geospatial Intelligence Capability	7
Concealment and Deception Capability	Low-Observable Capability	3
	Concealment Capability	2
	Decoy Capability	2
Maintainable Capability		2
Offensive Capability	Hypersonic Missile Capability	5
	Directed Energy Weapon Capability	4
Defensive Capability	Imaging Capability	2
	Communications Capability	4
	Command and Control Capability	3

Table 25. Case Study 2 Portfolio Capability Tree

5.5. Process 4: Epoch Characterization

As a reminder, process 4 involves translating key contextual uncertainties into epoch variables, and identifying possible future contexts. Also codified are uncertainties in the supply and availability of resources are identified, and changes in stakeholder preferences about resource usage.

For the space-based geospatial intelligence portfolio analysis, seven epoch variables were identified, and some were given a two-point range, and others were given three-point ranges. These are summarized in Table 26 below. These yield $2^4 \times 3^3$ combinations, or 432 potential futures.

Epoch Variable Category	Epoch Variable	Range	Units
Technology	Serviceable Satellites	[Yes, No]	N/A
Technology	Next-Generation C2	[Yes, No]	N/A
Technology	Space Plane - Bespoke ISR	[Yes, No]	N/A
Policy	Budget	[80,100,150]	%
Policy	Commercial policy	[Yes, No]	N/A
Threats	Adversary Competition	[Low, Medium, High]	Level
Threats	A2/AD	[Low, Medium, High]	Level

Table 26. Case Study 2 Epoch Variables

Technology – Serviceable Satellites: As was mentioned earlier in Process 2, there is work underway in both the government and commercial sectors to enable repairs or upgrades to satellites. There are no known systems currently in existence that are permitted to do this kind of work, but the confluence of research into autonomous vehicles, robotics, machine vision, open standards, lower-cost rockets, and the like make it apparent that such capabilities are a matter of "when," not "if."

The range of variables is "Yes" and "No." The baseline state is the latter, but the former may be available in the future.

Technology – Next-Generation Command and Control (C2): Presently the task of Collection Management, the identification, apportioning, and tasking of space assets, is somewhat antiquated. Given technologies such as networking, encryption, publish-subscribe messaging and blockchain, the IC could architect a next-generation command and control system that allows a consumer of geospatial intelligence data to request imagery of a target described by latitude and longitude coordinates, a priority, and a Latest Time Information of Value measurement (a measure of time-to-staleness). All commercial partners and military assets would receive the request by a subscription service, assets within reach of the target

within the time-until-stale window are identified, ad hoc target lists are broadcast up to the respective constellations, semi- or fully-automated logic evaluates and resolves the ad hoc priority against other priorities in the collection deck in the window of opportunity, and tasking is given. The imagery is received back and deposited into a target folder, and the image "transactions" are logged in a blockchain that verifies the collection was satisfied. Such capability is not known to exist now. If it did, it could potentially make more efficient, coordinated use of space assets and provide better situational awareness to the consumers of the intelligence.

The range for this technology epoch variable is a binary "Yes" or "No." The baseline response is "No." A "Yes" response would result in an increase to Complexity of Combination coefficients for performance attributes that involve cross-cueing and communications.

Technology – Space Plane – Bespoke ISR: The mission of the X-37B, shown in Figure 46, is not publicly-acknowledged, but it presents a novel means to deliver multiple capabilities. These include the ability to repair or upgrade high-end satellites, as was discussed in the Serviceable Satellite epoch variable, roll over and provide space situational awareness, deliver and assemble larger payloads on-orbit, gather reconnaissance about adversary overheard assets such as providing information about their design or mission, use its own power to reposition its orbit characteristics, provide a communications relay if existing assets are jammed, serving as a decoy to draw adversary countermeasures while a nearby stealthy spacecraft simultaneously executes the task of gathering intelligence, serving as an orbital bombardment platform or space-based Anti-Satellite Missile defense system, and many other possible missions. While the initial Orbital Test Vehicle is relatively small, a larger space

plane, perhaps as large as the retired Space Shuttle, could provide a means to take on still more missions and carry larger payloads.

Policy – Budget: Very similar to Case Study 1 earlier, overarching budget cycles are influenced by variables such as changes in Presidential administrations and national security landscape. Budgets may grow slowly, at approximately the annualized rate of inflation, or may grow or contract rapidly in response to those aforementioned forces. A "technological surprise" akin to the 1957 Sputnik incident could spur an almost overnight surge in the budget for fear of falling behind in the quest for space supremacy.

The range of outcomes for this analysis is set at 80%, 100%, and 150%. The 80% situation would represent a situation where budgets were cut, perhaps spawned by a pivot to lower-cost commercial remote sensing. 100% is the nominal base case. And 150% budget could arise in the case of, for instance, an attack on U.S. space assets, forcing an urgent need to replenish the capabilities.

Policy – Commercial Policy: Currently, the laws governing commercial satellite imagery mandate some degradation below what the Government is able to acquire under the auspices of national security. As the United States sought to maintain its edge in space by restricting exports of satellite technologies, other countries responded by developing their own capabilities. The United States only recently relaxed the restrictions, but the damage is done in that many other nations have entered the market and have rapidly matured. Vedda (2017) lists twelve countries with resolution of 1.0-m or better. It is just a matter of time before international sources of imagery will exist that exceed what the U.S. allows, and so the United States, logically, will have no choice but to relax the resolution limit. The result is

likely to be a win for commercial satellite businesses, who will have a bigger market. Non-military / government customers who need high resolution imagery but hitherto could not access it can be served. The hunt for higher-revenue, high-resolution imagery will drive commercial providers up the proverbial food chain in the disruptive manner famously described by Clayton Christensen in *The Innovator's Dilemma*. In turn, this gives the U.S. options for higher quality imagery that in the past it alone could provide.

This epoch variable is binary, "Yes" and "No." The latter is the baseline, and the former would represent a relaxation of resolution requirements that allows U.S. commercial ventures to offer imagery with resolution at or near military-grade.

Threats – Adversary Competition: The Adversary Competition epoch variable represents the degree to which adversary nations ignite another "space race," similar to what was seen in the Cold War between the United States and the Soviet Union. If adversary nations increase their interest and capabilities in space, including the geospatial intelligence-gathering systems analyzed here, the U.S. risks losing its edge in this domain. Given that space-based capabilities are a force multiplier, the United States takes keen interest in the advances of other nations in space. It considers the capabilities, resources, aggressiveness and perceived threat of that adversary.

The author assumes a range of low, medium and high. "Medium" is the baseline scenario, reflecting the current state of near-peer relations and what is known publically about their activities in space. "Low" reflects a significant decrease in adversary space activities. "High" is the level that exists when adversary nations have made space capabilities a high priority.

Changes in the threat level result in a change in stakeholder preference weightings throughout the capability tree.

Threats – A2/AD: At the time of this writing multiple state actors are working on area-denial / anti-access technologies such as laser-based "dazzlers" to disrupt collection from satellites. Other technologies include camouflage and deception. Finally, changes to adversary tactics such as using underground facilities and conducting sensitive work inside buildings can be undertaken to limit what can be observed from overhead.

In this analysis the author assumes a range of low, medium and high. As with Enemy Threat, "Medium" is the nominal base case. Some open-source documentation draws into question the legality of dazzlers, so the author permits some downward range to the A2/AD threat. Of course, challenging the adversaries on the use of such technologies effectively confirms that the United States is observing them, and thus exposes intelligence "sources and methods". Such an outcome seems unlikely. Thus, the epoch variable also includes upward range as well, indicating a significant amount of A2/AD activity, and changes to adversary TTPs that minimize the effectiveness of U.S. overhead assets.

Changes in the asymmetric threat level result in a change in stakeholder preference weightings throughout the capability tree. For instance, "High" would favor the increased use of decoys and concealment, as well as defensive capabilities.

Of the 432 potential epochs, the author selected a subset that presents a cross-section for further evaluation. These are depicted in Table 27. Given that only a subset of the total were evaluated, the more compelling combinations were included here in the analysis. For example, a space race would simultaneously flip the epoch variables to the high end,

harkening back to the 1960s Apollo program. Conversely, a pivot to the commercial sector could rapidly introduce many new innovations, drive down the Government budget because it would field fewer of its own systems, and the persistent presence of satellites over adversary targets would prompt an uptick in concealment and deception.

Epoch Name	Epoch Variables						
	Serviceable Sats	Next-Gen C2	Space Plane	Budget	Commercial Policy	Adversary Competition	A2/AD
Baseline	No	No	No	100	No	Med.	Med.
Baseline Evolution	No	Yes	Yes	100	No	Med.	High
Commercial Pivot	Yes	Yes	Yes	80	Yes	Med.	High
Space Race	Yes	Yes	Yes	150	Yes	High	High

Table 27. Down-selection of Case Study 2 noteworthy epochs

5.6. Process 5: System-Level Capability Assessment

As with Case Study 1, the author used the process outlined in Section 3.4.5, again serving as a proxy for the various stakeholders. Each system was evaluated for its performance against each system-level performance attribute. This was done qualitatively using the publically-available information to assign values of 0, 1, 3, and 9. 0 indicated no performance, 1 low performance, 3 some performance and 9 high performance. Each of the 13 systems was evaluated against each of the 63 system-level performance attributes, resulting in 819 unique ratings per epoch. The data set is not provided here because its expansive nature makes it impractical to view in this space.

In this case study, there no high complexity of combination systems of systems assumed. This is in part because of narrow scope of the analysis, which ponders geospatial intelligence systems, rather than the broader portfolio of overhead systems, such as communications

satellites. By expanding the analysis to include interactions with the signals intelligence systems and the communications systems, higher level combinations would result—they just were not considered in this simplified analysis.

5.7. Process 6: Design Epoch-Era Tradespace

Using the same method as in Case Study 1, a number of performance and cost aggregation models were established. For the sake of brevity the descriptions are not repeated here, though the table is reproduced in Table 28.

The same critique of the models as a source of bias and even error discussed in Case Study 1 applies here.

Model	Calculation Detail
M1	Summation of the average performance of each major system class: $\sum\left(\bar{v}_{BigEO/IR} \times \varphi, \bar{v}_{BigSAR} \times \varphi, \bar{v}_{Med,Hi-Res} \times \varphi, \bar{v}_{Med,Lo-Res} \times \varphi\right)$ v is the performance capability of the system for an attribute under consideration $\bar{v}$ is the average performance capability of systems in that category φ is a multiple unit function which adjusts performance if more than one unit of a system type is present: $\varphi = \sum_{i=1}^{n} \frac{1}{i}$
M2	Mean of all constituent system performance capabilities > 0. $\frac{1}{n}\sum_{i=1}^{n}(v_i \times \varphi > 0)$ where *n* is the number of different potential systems, 13 in this case study.
M3	Maximum performance from any constituent system performance rating: $\bigvee_{i=1}^{n}(v_i \times \varphi)$
M4	Summation of constituent system performance capabilities, weighted by the relative contribution of the constituent system to the highest preferred program manager attribute: $\sum_{i=1}^{n}\left(v_i \times \varphi \times \frac{x_i}{x_P}\right)$ x_i is the system performance capability for the most desired program manager attribute

	x_P is the portfolio performance capability for the most desired program manager attribute
M5	Mean of all constituent system performance capabilities. $$\frac{1}{n}\sum_{i=1}^{n}(v_i \times \varphi)$$
M6	Summation of all constituent system performance capabilities. $$\sum_{i=1}^{n}(v_i \times \varphi)$$

Table 28. Bottom-level program manager performance and cost aggregation models

The same aggregation method was used as in Case Study 1, and is explained in Table 12 earlier. After performance and cost attributes were calculated for the lowest level of the portfolio, each value was then multiplied by the preference weighting given by the program manager at the next higher level of the capability tree. This process was iterated until the tree was aggregated up to the portfolio level. Portfolio-level preference weightings were then applied to derive the MAU and MAE for each portfolio.

The process resulted in 672,000 portfolios. The types of configurations available were listed in Table 22 (for example, three different Exquisite EO/IR configurations—a legacy version, a new version, and an on-orbit upgrade). The portfolio constraints in Section 5.3 were used to establish what assets had to be present. Compared with Case Study 1, there were few constraints that limited portfolio enumeration. For instance, the requirement that the portfolio needed both EO/IR and radar systems in operation simultaneously meant that a valid portfolio needed at least one each of an exquisite EO/IR and exquisite radar. Given the large cost of the exquisite and large systems, the number of systems in the model was meant to coincide one-for-one with the actual systems (i.e., not block quantities). For instance, the exquisite systems varied between 1 and 5 each (with the added constraint that

if multiple variants of the same system type were present, the total could not exceed 5). Conversely, the small sats, both of Government- and commercial-ownership, were grouped in blocks to provide some meaningful stratification. For instance, 1 block of small assets represented 100 systems. Commercial vendors were allowed to vary 1 to 10 blocks, and the Government blocks were allowed to vary 0 to 5 blocks. The universe of portfolios would be a simple combination calculation, but the presence of the portfolio constraints help to reduce the number. These portfolios were then screened for MAU and MAE in each epoch, resulting in a final yield for each epoch under consideration. These results are summarized in Table 29.

Epoch	Valid Portfolios	Final Yield (%)
Baseline	462,490	68.8%
Baseline Evolution	464,889	69.2%
Commercial Pivot	358,980	53.4%
Space Race	413,956	61.6%

Table 29. Single-epoch portfolio feasibility as measured by final yield

5.8. Process 7: Single Epoch Analysis

In the seventh process, a tradespace is generated for each epoch under consideration, typically plotting MAU versus MAE. This process is helpful for the portfolio designer or key stakeholder(s) to understand how different portfolios perform under different contextual settings in isolation.

The minimum utility portfolio involved one each of the exquisite EO/IR and SAR systems.

Tradespace plots for each of the four epochs identified for review are included in Figure 47 through Figure 50, (Baseline, Baseline Evolution, Commercial Pivot, and Space Race respectively). Note that the figures use the same color for all portfolios regardless of

constituent assets represented and their quantities. The author lacked intimacy with Matlab to be able add a color scale to the figures indicating the composition, which would have been a useful visual aid.

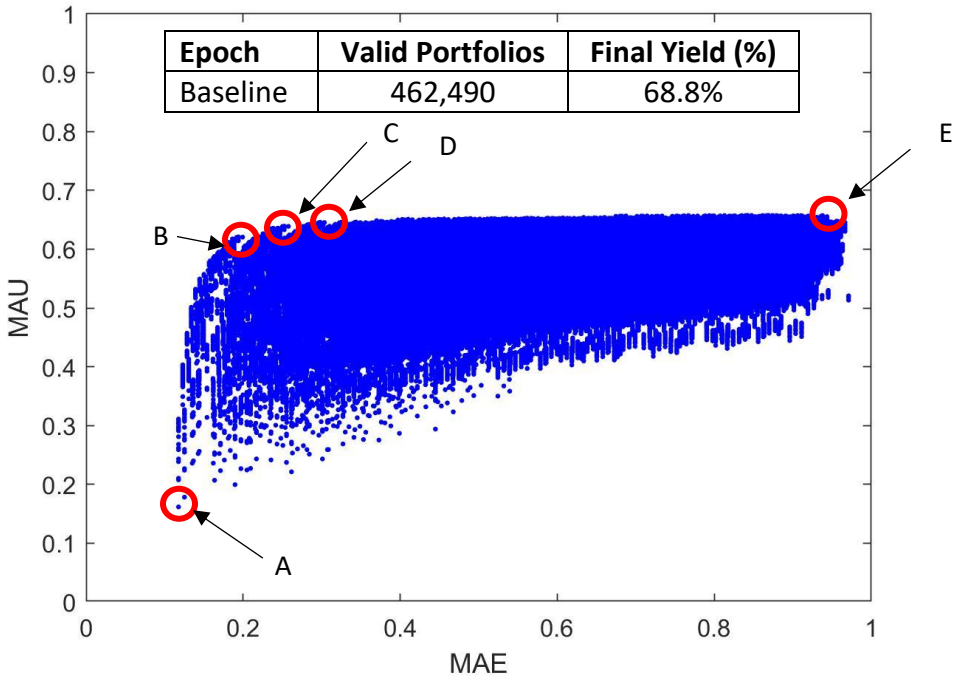

Figure 47. Case Study 2 Baseline Epoch Tradespace Plot

The Baseline epoch reflects a context reasonably close to the present day. The slope of the Pareto frontier is nearly undefined at the lowest MAE, meaning for a small uptick in MAE, a dramatic increase in MAU results. The Pareto front begins to asymptote in the vicinity of the fourth highlighted portfolio, meaning of course that marginal gains in MAU come at significant expense. In that region, the NRO has a variety of small, large and exquisite assets, and falls back on high-end commercial imagery to augment the portfolio.

Five interesting portfolios, identified as “A” through “E” are identified in each of the epoch plots and the constituent systems are identified in Table 30. These same portfolios recur on or near the Pareto front across all the epochs under consideration.

Portfolio	Different Systems	Exquisite EO/IR (Baseline)	Exquisite EO/IR (New)	Exquisite EO/IR (Upgrade)	Exquisite Radar (Baseline)	Exquisite Radar (New)	Exquisite Radar (Upgrade)	Large EO/IR (New 1)	Large EO/IR (New 2)	Small EO/IR (New 1)	Small EO/IR (New 2)	Small EO/IR (Small 3)	Commercial Imagery High-End	Commercial Imagery Low-End
A	0	3			3			4					1	
B	6	2	2		2	2		4		1	1		1	
C	8	2	2		2	2			4	1	1	1	1	
D	9	2	2		2	2			4	3	3	3	3	
E	11		2	2		2	2	2	4	5	5	5	5	10

Table 30. Case Study 2 Pareto portfolio composition (# blocks of each asset)

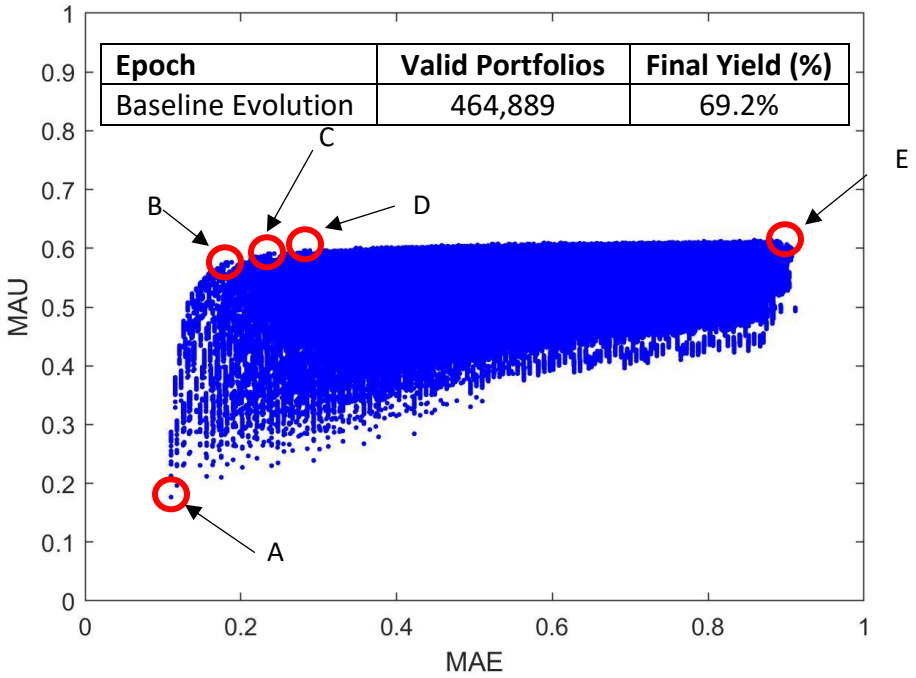

Figure 48. Case Study 2 Baseline Evolution Epoch Tradespace Plot

The Baseline Evolution epoch looks very similar to the Baseline epoch, with the same noteworthy portfolio composition. The slight downward shift in MAU on the Pareto front relative to the Baseline epoch is due to a change in stakeholder preferences across the Portfolio Capability Tree.

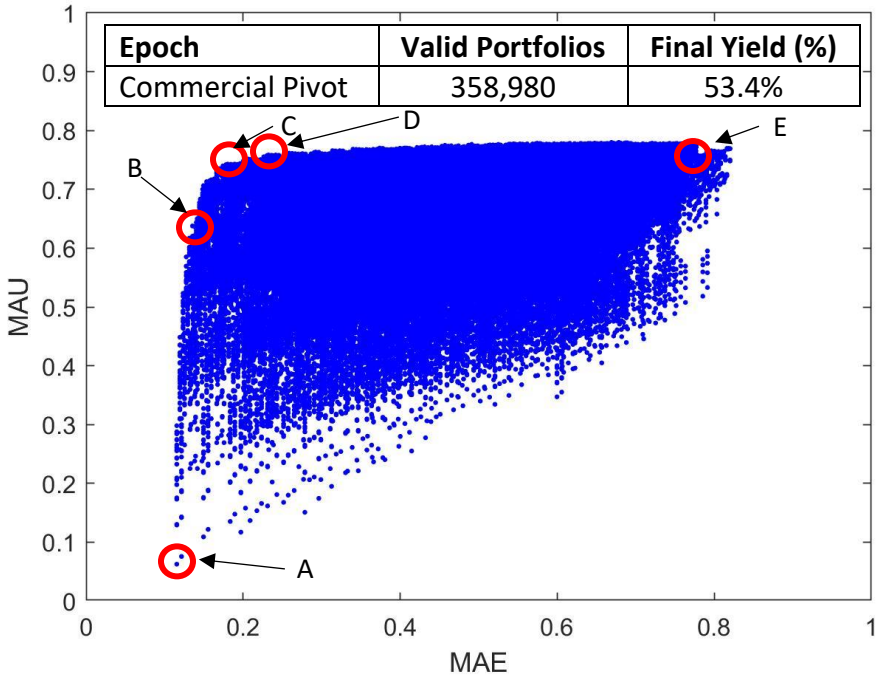

Figure 49. Case Study 2 Commercial Pivot Tradespace Plot

The Commercial Pivot epoch is characterized by a cut to the NRO's budget, either as the result of, or in response to, the presence of increased commercial capability and competition. The ability to repair and upgrade high-end satellites, the presence of more high-end sources of commercial imagery, and competition in launch services could help to drive down costs for even the exquisite products in the portfolio.

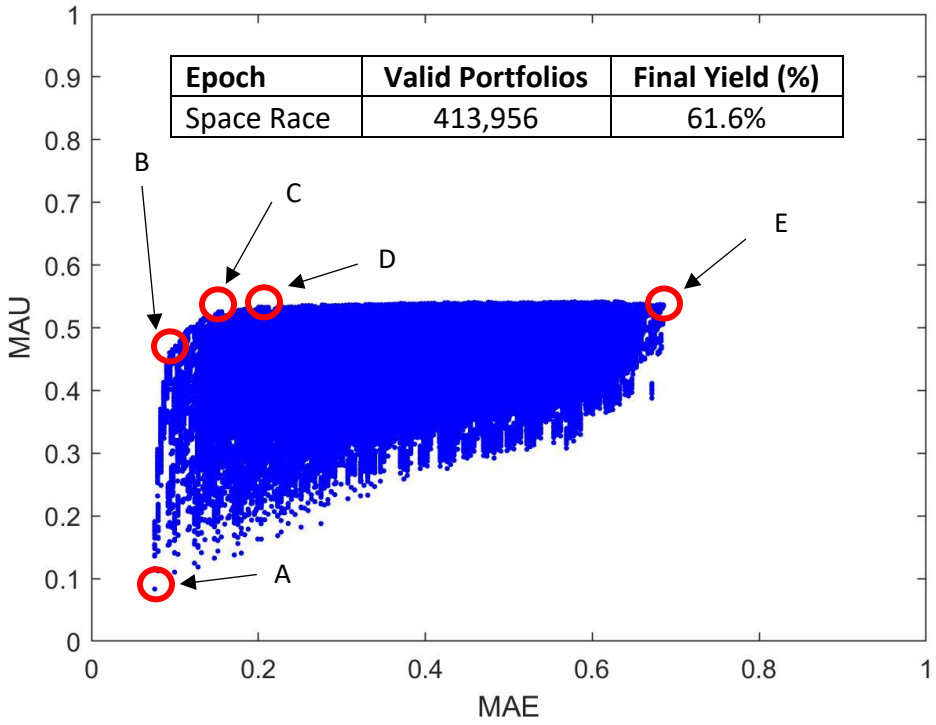

Figure 50. Case Study 2 Space Race Tradespace Plot

The Space Race Epoch is characterized by a focus on the space domain. The push for exquisite, cutting edge capabilities, and an uptick in preference for previously under-represented attributes (like offensive weapons) drives substantial cost. The cost limits what can be acquired, effectively driving down the MAU for the portfolio. A rough analogy might be akin to a consumer buying a home at their maximum affordability budget and lacking the funds to furnish it. One conclusion that might be drawn from this epoch is that too many exquisite, expensive assets can reduce the maximum achievable MAU.

The fundamental reason for the shift up in MAU in the Space Race epoch is that the heavy presence of commercial technologies, such as repairable and upgradable satellites, swarms of distributed small satellites, and the presence of multiple large WorldView-like assets helps

drive down costs through competition and economies of scale, increasing the utility-at-cost of space-based remote sensing (and presumably, other space-based capabilities).

The Space Race epoch rolls off with a lower Pareto front than the other epochs. It may seem counterintuitive upon first inspection that an epoch characterized by cutting edge technologies and an increased budget would shift Pareto front toward higher MAUs. The reality is that because the analysis is considering portfolios of assets, and those assets favor cutting edge technologies to stay ahead of adversaries who are similarly interested in space leadership, the portfolios have fewer assets. Consider the actual 1960s Apollo program for historical precedent. As was stated earlier, the program cost roughly 4% of the United States' Gross Domestic Product (GDP), but for all that expense, only six of the Apollo missions landed men on the moon, or seven if one includes the near-miss of Apollo 13. Contrast that statistic with the breadth and depth of the U.S. military, whose budget in 2014 amounted to 3.5% of GDP.[53]

5.9. Process 8: Multi-Epoch Analysis

In Process 8, the portfolio designer analyzes the behavior of portfolios over different contexts. The NPT calculation assumes four epochs in the denominator, of which the two Baselines are roughly equivalent, and counts the number of epochs in which the portfolio lies on the efficient frontier in the numerator. Compared to Case Study 1, this case study was much harder to parse, with at least 358,980 valid portfolios per epoch. What was intended to be an illustration of the computational explosion that results from permitting too much

[53] "The Biggest Military Budgets as a Percentage of GDP," https://www.forbes.com/sites/niallmccarthy/2015/06/25/the-biggest-military-budgets-as-a-percentage-of-gdp-infographic-2/#4421a0874c47, accessed 4/16/2018.

granularity in the asset combinations serves as proof of the intractable problem posed by tracing singular portfolios through epochs.

As in Case Study 1, the author notes that a simplifying assumption can be made in Process 8 that very similar portfolios are, for all intents and purposes, the same portfolio in an NPT analysis. This statement requires some common sense rather than general application. For instance, change from one exquisite KH-11-like system to two would result in several billion—repeat, billion—dollars difference in cost. This difference is, of course, nontrivial. On the other hand, the incremental cost of adding another block of small-sats is a comparably cheap affair. "Common sense" is an inherently subjective term and thus potentially introduces a source of bias into the analysis. Potential bias aside, the fact remains that in an analysis involving several hundred thousand valid portfolios and a yield in excess of 50% across all epochs, there are statistically likely to be a large number of non-dominated portfolios with high NPT / fNPT measures. The degree to which this is true depends upon the impact of epoch shifts, and underlying assumptions about diversity in both performance and utility expectations.

Table 31 below summarizes the Normalized Pareto Trace and 5% Fuzzy Normalized Pareto Trace of the five different interesting portfolios across all four epochs.

Portfolio	NPT	5% fNPT
A	1.00	1.00
B	0.75	1.00
C	0.75	1.00
D	0.50	0.75
E	0.50	0.75

Table 31. Case Study 2 NPT and fNPT metrics for 5 promising portfolios

5.10. Process 9: Era Construction

In the first era under consideration, the author considers a future in which the United States "doubles down" on space, recognizing that demand for intelligence in hot spots around the globe outstrip supply. Additionally, the rapid progress of high-end state actors in all domains of military technology, including space, necessitate the near-total reach that space-borne remote sensing can provide. The U.S. increases annual spending on space technologies, in part to maintain its lead in space, in part to overcome evolving and ever more sophisticated adversary countermeasures, and in part to deter less-affluent adversaries by invoking the 1980s policy of bankrupting them through an exotic arms race. Competition in launch services, coupled with the rise of autonomy and robotics ushers in an era of repairable, upgradeable satellites; and gives rise to satellite "swarms"—high-value remote sensing systems surrounded by smaller assets that maintain nearby situational awareness and provide early warning, defend the swarm via kinetic means, and cross-cue with other systems. The sequence of epochs is given in Table 32, and the epoch variables are listed in Table 33.

In the second era, the U.S., recognizing the burgeoning cost of maintaining the edge in space, cedes the opportunity to corporate ventures. The U.S. largely becomes a consumer of commercial satellite services, developing pub-sub relationships with the full spectrum of satellite-based geospatial intelligence providers, with the result being near-24/7 persistent surveillance at any and every spot on the globe. As the barriers to commercial remote sensing fall, imagery services disrupt the space market in the same way that digital cameras first, and smartphones later, disrupted film cameras. Resolution improves, and ISR-as-a-service is

born. This era is called the "Torch Pass." The sequence of epochs for this era is given in Table 34, and the composition of epoch variables is shown in Table 35.

Given the flow of the epochs in both eras, no further epochs were defined. The era durations of 15 years each were established to coincide with the rapid pace of change in the space sector.

Epoch No.	1	2	3
Epoch Name	Baseline	Baseline Evolution	Space Race
Epoch Duration	3	4	8
Era Duration	15 years		

Table 32. Case Study 2 Era 1 (Space Race Redux) epoch composition

Epoch Name	Epoch Variables						
	Serviceable Sats	Next-Gen C2	Space Plane	Budget	Commercial Policy	Adversary Competition	A2/AD
Baseline	No	No	No	100	No	Med.	Med.
Baseline Evolution	No	Yes	Yes	100	No	Med.	High
Space Race	Yes	Yes	Yes	150	Yes	High	High

Table 33. Details of Case Study 2 Era 1 epoch variables

Epoch No.	1	2	3
Epoch Name	Baseline	Baseline Evolution	Commercial Pivot
Epoch Duration	3	3	9
Era Duration	15 years		

Table 34. Case Study 2 Era 2 (Torch Pass) epoch composition

Epoch Name	Epoch Variables						
	Serviceable Sats	Next-Gen C2	Space Plane	Budget	Commercial Policy	Adversary Competition	A2/AD
Baseline	No	No	No	100	No	Med.	Med.
Baseline Evolution	No	Yes	Yes	100	No	Med.	High
Commercial Pivot	Yes	Yes	Yes	80	Yes	Med.	High

Table 35. Details of Case Study 2 Era 2 epoch variables

5.11. Process 10: Single-Era Analysis

In the tenth process, the portfolio designer analyzes the performance of potential portfolios over a time-ordered series of epochs, as identified in Process 9. This process brings to light the portfolios which are value-robust in the face of a modeled future, as well as those which may drift out of the affordability constraints. Note, "affordability" is determined by the budget, and budget is one of the epoch variables, which ranged from a low of 80% (Commercial Pivot epoch) to a high of 150% (Space Race epoch), per the earlier discussion. The 100% budget was assumed to be $11B. The details of the Intelligence Community's budget are classified, and the author chose a notional and somewhat arbitrary budget rather than risk backing into a number that is not publicly available.

In the first two figures, the Era 1 (Space Race Redux) Multi-Attribute Utility and Multi-Attribute Expense performance were plotted for the portfolios highlighted earlier. The process was repeated for Era 2 (Torch Pass) in the subsequent two figures.

Portfolios B, C, and D, and in particular, Portfolios C and D, offer the highest MAU across Era 1 with the least attenuation and low MAE. Similarly, in Era 2, Portfolios C and D feature the highest MAU with low MAE. As a reminder, these portfolios are comprised of baseline and new exquisite EO/IR and radar assets, new large NRO-owned systems, a mix of small

NRO-owned EO/IR assets, and acquisition of high-end commercial imagery. Intuitively this would seem to make sense, as it provides a diverse mix of systems spanning low-end to exquisite, balancing persistence and elegance.

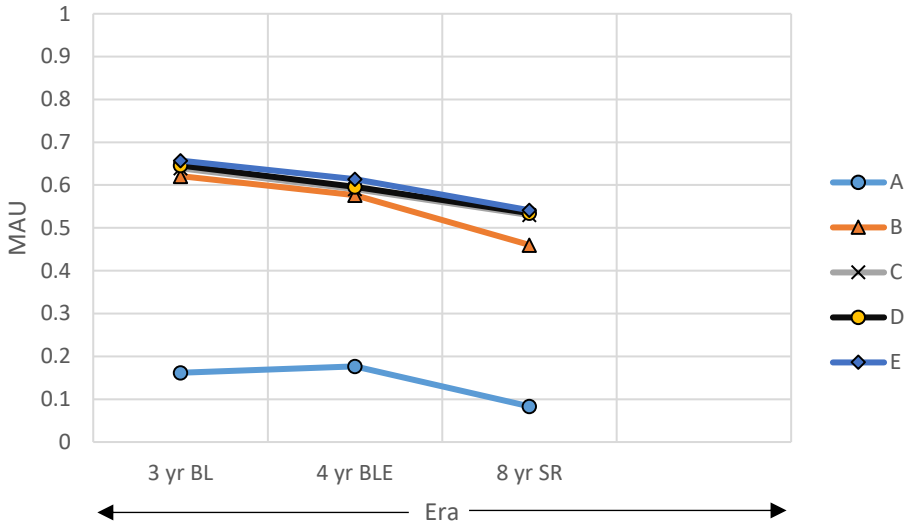

Figure 51. Case Study 2 Era 1 Utility (MAU) performance

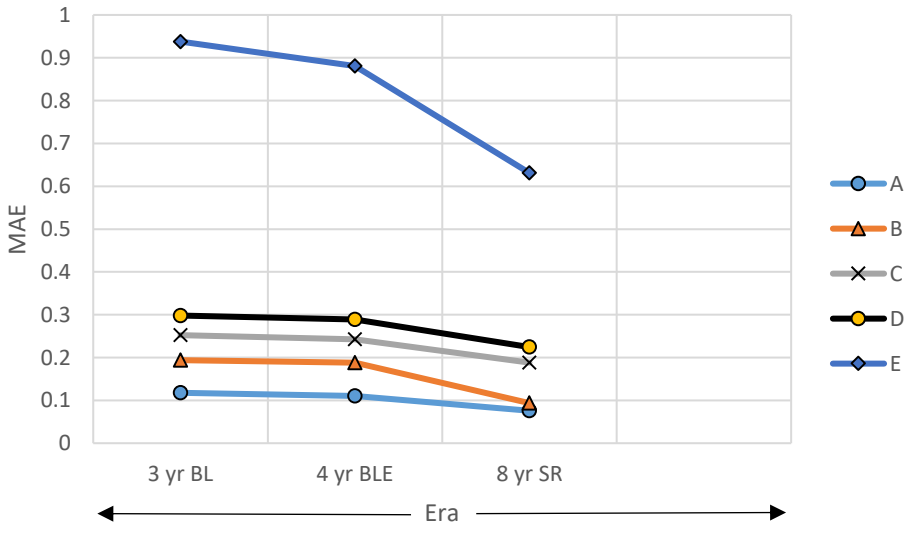

Figure 52. Case Study 2 Era 1 Expense (MAE) performance

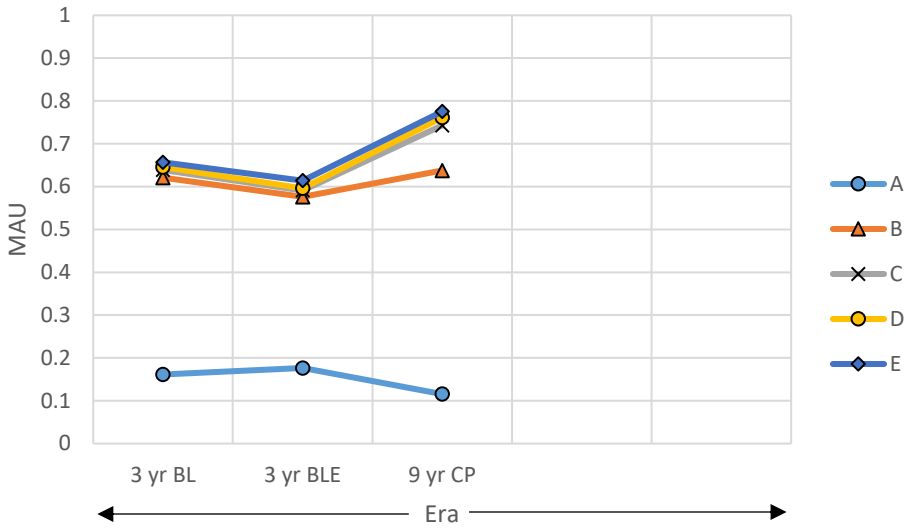

Figure 53. Case Study 2 Era 2 Utility (MAU) performance

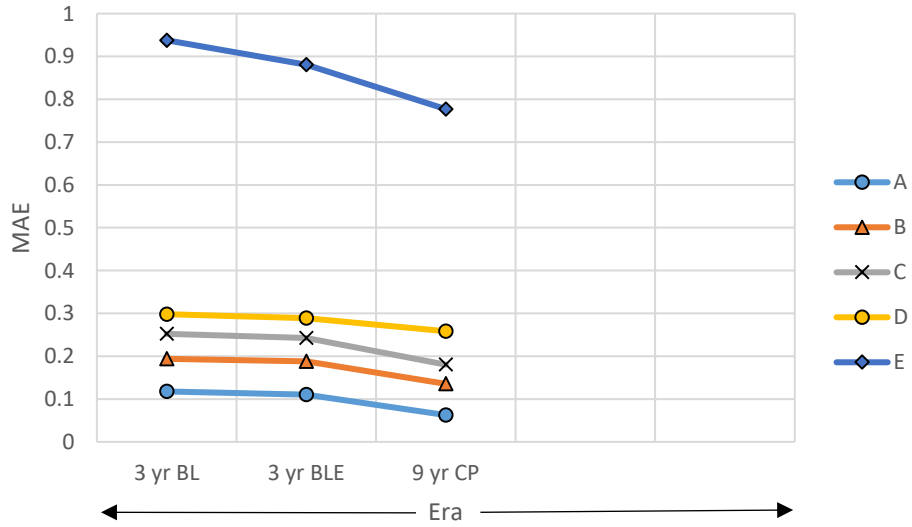

Figure 54. Case Study 2 Era 2 Expense (MAE) performance

5.12. Process 11: Multi-Era Analysis

The same approach used in Case Study 1 was used here. As was articulated in 4.12 earlier, the author chose two disparate bounding eras, evaluated them independently, and then compared the portfolio compositions to find commonality and value-added insights. Table

36 below summarizes NPT and 5% fNPT for the five interesting portfolios across the two different eras considered. Upon first inspection, Portfolio A has the highest NPT across both eras—but it also has the lowest utility in all epochs (so there is a tradeoff between cost/benefit efficiency and total benefit). Portfolios B and C, on the other hand, are closer to the Pareto front's knee, where incremental gains in MAU come at ever higher MAE, in both eras. A 40% weighting was applied to Era 1 and a 60% weighting applied to Era 2. This decision was made by the author, and was selected to illustrate the effect of unequal weights. This selection is a source of bias, since it is a prediction about the future. More sophisticated means could be used, such as using third party market research, and overarching strategy and doctrine such as foreign policy strategy. By aggregating the results, the portfolio manager is able to evaluate portfolios across multiple possible eras in a manner akin to Decision Tree Analysis.

Portfolio	Era 1 – Space Race Redux			Era 2 – Torch Pass			Multi-Era Net	
	NPT	fNPT 5%	Weight	NPT	fNPT 5%	Weight	NPT	fNPT 5%
A	1.00	1.00	40%	1.00	1.00	60%	1.00	1.00
B	0.67	1.00		1.00	1.00		0.87	1.00
C	0.67	1.00		1.00	1.00		0.87	1.00
D	0.50	1.00		0.50	0.67		0.50	0.80
E	0.50	0.67		0.50	1.00		0.50	0.87

Table 36. Case Study 2 Multi-Era NPT and fNPT for enduring portfolios

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6. Discussion and Recommendations

6.1. Discussion

The author will revisit the guiding questions in the Conclusion section that follows.

In this research the author used the Portfolio-Level Epoch-Era Analysis for Affordability (PLEEAA) framework, developed by Parker Vascik, Adam Ross, and Donna Rhodes, to investigate its broader applicability to two case studies: an airborne Intelligence, Surveillance and Reconnaissance portfolio and a space-based geospatial intelligence portfolio.

While neither case study was a particularly dramatic excursion from the Carrier Strike Group analysis performed by Vascik et al in the original research in that all were defense-based and employed the same techniques in each process, the outcomes do help to establish general applicability of the PLEEAA framework.

In the original CSG case, Vascik skipped the 11th process, multi-era analysis, citing the demonstrative nature of the work rather than an exhaustive effort.

In this research the author executed the 11th process in both case studies, albeit with considerably less breadth and depth than was articulated in Schaffner's Responsive Systems Comparison research (2013). The choice was not borne out of sloth or convenience, but rather, one of cognitive limitation, processing time, and usefulness of outcome. The power of Epoch-Era Analysis comes from being able to model complex events, path-dependencies, timing, and others. As was discussed earlier, Curry's PhD thesis (2017) illustrated the power of interactive EEA, and could be an interesting future direction for PLEEAA research. But such analysis is nontrivial; there is no "auto-mesher" analog from Finite Element Method that allows boundary conditions to flow automatically to neighbor nodes. Every variable and

interaction must be pondered and codified in the analysis. Even if it were trivial to condition software to batch the analysis across scores of eras, the computational intensity scales at least linearly with the number of eras considered. Finally, the usefulness to the portfolio designer of having a large set of myriad futures is questionable unless one is analyzing changeability, since many futures will be similar enough to near-neighbor futures, and the constituent systems will be value-robust enough to tolerate minor perturbations in context. Consider, for instance, the Space Shuttle, and NASA's calculation of the loss of crew and vehicle, codified in the Probability Risk Assessment Number (PRAN). This number has often been cited at around 1/100,[54] and indicates a roughly 1% chance of catastrophic loss event during a mission. The Shuttle was designed to safely return with its crew with a high probability of success, given the range of operating contexts it would face. Translating that analogy back to the multi-era analysis process in the PLEEAA framework, the marginal utility of analyses that yield similar contextual stresses on the portfolio and its constituents is arguably negligible. If a portfolio designer is not concerned with changeability, path dependence is less important, and the era-level analyses largely simplify to a multi-epoch analysis.

Like any modeling technique, the outputs are a function of the inputs, and the quality of those inputs has the potential to significantly swing the outcome. These quality issues may arise because of errors, imperfect information, inaccurate estimates, and significantly, stakeholder biases introduced unconsciously or with intent. Given the effort to put together

[54] https://www.popularmechanics.com/space/a738/3259521/, accessed 4/4/2018

a thoughtful PLEEAA study, the portfolio designer is strongly cautioned to review sources of error and bias that skew the results or be used to "game" the outcome.

These case studies were "top-down" in nature, contriving solutions to capability gap problems that appear to exist. But the various overarching strategy documents referenced to provide some context as to the perceived future threats, and how these portfolios will be used were taken as inputs. In real world use, there could and should be some recursion via feedback and feed-forward loops. The analysis helps inform how the systems could contribute to a future mission, feeding forward information to formulate strategic plans, and an understanding of the possible future contexts feeds back needs that can highlight gaps. If given enough time, a bottom-up / as-is analysis and a top-down / future state analysis may help identify some of those gaps, and codify objectively the effect of gap-filler systems on the overall portfolio utility-at-cost. The delta between the two is a function of the standalone utility-at-cost offered by the new constituents, and the utility-at-cost that arises from the synergistic, emergent behavior of the added capability with the other constituents.

Vascik et al used a 0, 1, 3, 9 ordinal scale to assess the potential constituent assets in each of the performance attributes, and while this was allowed for a rapid assessment, it must be noted that this is simultaneously imprecise and easy to "game" the outcome. For instance, evaluating an ISR asset for "all weather capability" distills to a platform assessment of features such as de-icing equipment, and the inclusion of a radar sensor payload that can penetrate clouds. The ordinal scale makes it easier to trivialize the nontrivial differences between radar payloads, or worse, to take advantage of the inherent subjectivity to manipulate the outcomes. The reader is urged to seek more objective means to evaluate the

potential constituent assets in performance attributes. The downside to such a recommendation is a potentially significant uptick in the time to conduct the analysis because it would necessitate polling subject matter experts in each of the systems.

These case studies were based on a conscious decision to focus on the geospatial intelligence systems in order to limit the scope and complexity to a tractable set. The risk of such simplifications, however, is that they ignore the emergent behavior that results from the synergy of multiple, disparate systems. In other words, many of the systems under analysis in both case studies either have additional, unconsidered functionality, or participate in systems of systems outside the scope of consideration. Since the goal of PLEEAA is to bring some objectivity to a complex analysis, it is difficult to objectively assess the utility of system performance beyond the considered scope. For example, many of the aircraft evaluated in Case Study 1 also carry signals intelligence payloads. While the geospatial intelligence and signals intelligence payloads can and do act independently, there are also use cases where they act in concert to increase the fidelity of information gathered about a potential target. Different systems have different capabilities, and thus, simply saying that both a U-2 and an MQ-9 have both types of systems on board grossly understates the value each brings to a portfolio; or said differently, trivializes the unique role performed by each aircraft and sensor. Similarly, in Case Study 2, to put it delicately, there are space-based capabilities spanning various domains, and that can act as systems of systems in certain contexts. Since the author started out with the explicit objective of steering clear of anything remotely sensitive, the analysis effectively dismissed higher-order interactions that would have increased the MAU and the overall value of the portfolio-level analysis to the decision maker. In summary,

accounting for the interactions between systems is challenging, particularly when the interaction is not anticipated within the scope of the analysis.

On a related note, both case studies looked at constituent assets that spanned legacy, new, and upgraded variants. This analysis blurred the line between the vehicle and the sensor, in no small part because it is difficult to abstract out the utility of the sensor without consideration for the vehicle it rides in. For example, the Global Hawk aircraft carries electro-optical, infrared and radar payloads, but at least the legacy configuration lacked deicing equipment that would allow it to operate in a broader range of weather. So while the payload could theoretically show good all-weather capability, the vehicle's limitations in weather limit its utility and thus force the analyst to consider more than merely the payload. One way to overcome this obstacle would be to analyze the platforms by themselves by their own set of performance attributes, and then to analyze the payloads, potentially agnostic to the platform. Such an analysis could be useful, for example, when considering the divestiture of a platform.

The case studies examined were somewhat different than the original Carrier Strike Group (CSG) study conducted by Vascik, Ross and Rhodes. The CSG study concerned itself with the construction of a fighting force that operate together, while the thesis-considered case studies looked at portfolios of assets that may not be present on the same battlefield together as part of a cohesive unit. The CSG study focused on the breadth of capabilities that the CSG would have to provide operationally, while the thesis-considered studies drew a tighter boundary around the geospatial intelligence capabilities those systems provide and ignored other intelligence capabilities. The two case studies herein, while somewhat similar

to each other, did produce plausible tradespaces and indications of value-robust portfolios, suggesting some level of general applicability to PLEEAA. The two case studies vividly illustrate how sensitive the analysis can be to inputs and boundary conditions, such as budget factors and constituent asset costs and utilities, as illustrated by the number of valid portfolios and the yield across epochs from one case study to the next.

The author set out in search of a tool that produced more objective portfolio decisions, and while PLEEAA has the potential to fulfill that mission, there is nontrivial challenge in managing the many opportunities in PLEEAA to introduce errors and bias, either consciously or unconsciously. As was discussed in several of the processes, without explicit management, sources of error and bias can enter the analysis (as is true in any analysis).

Another consideration is that overly restrictive boundary conditions may constrain the "art of the possible." The Carrier Strike Group example elegantly offered portfolio architectures that provided enduring value—that is, of course, if the CSG is still the vanguard of the naval forces in modernity. A competing (or complementary?) and potentially less quantitative tool is simple wargaming. Allow forces to simulate hypothetical battles against one another and observe the outcome. Human beings have a knack for ingenuity in the face of adversity. In a contest of life and death, scenarios that may not have been contemplated in a computationally derived manner could emerge—and could reveal portfolio compositions not contemplated by PLEEAA (potentially complementing a PLEEAA study in terms of both additional epochs and eras, and portfolios, for consideration).

Time pressures played a role in what was finished and what was passed over. The author's time spent troubleshooting MATLAB code, and lack of intimacy with MATLAB

somewhat diminished the time available for more analysis, such as being able to use "color-by asset" in the tradespace plots to look for insightful patterns, and to evaluate the families of portfolios which perform similarly over multiple contexts. The pitfalls and trials faced became evident only after delving into the act of performing the analysis, so it was difficult to know in advance that the analysis would bog down in certain phases. The author's technical challenges aside, there are some efficiencies to be realized through repetition. A third case study would in some ways be faster, owed to some lessons learned in software coding and familiarity with the 11 processes. For someone interested in becoming a PLEEAA practitioner, there is a case to be made that once the learning curve is overcome, this would free up time that could be applied to the actual analysis.

The two case studies were chosen in equal measures of familiarity and intellectual interest for the author—both of which helped provide some overarching faith in the analytical outputs. Said differently, if the author selected one or more case studies for which he had little domain knowledge or passion, the author's confidence in the results could easily have been diminished. For instance, as the author poured over Vascik et al's Carrier Strike Group study, he sought clarification several times from Vascik himself to be able to understand both the inputs and the outputs. With that said, as was highlighted throughout, "familiarity" and "intellectual interest" imply some underlying bias that may have anchored the analysis.

To its credit, PLEEAA is a well-architected process that helps isolate the effects of changing contexts so portfolios of systems can be logically and methodically analyzed. Specifically, once the studies are set up, each epoch is first analyzed in isolation to see how various

potential portfolios perform in those contexts. Then the epochs are considered together for a multi-epoch analysis which uses tools such as the Normalized Pareto Trace to identify portfolios that endure at or near the efficient frontier over a range of epochs. Then the epochs are arranged into a time-ordered sequence that represents a potential future, and portfolio MAU and MAE are evaluated for trends and crossover to unaffordable regimes. Finally, the shift focuses to changeability in multi-era analysis, in which portfolios are analyzed over a range of futures. This methodical process helps decompose complexity into manageable pieces that yield insights at each step. Throughout this analysis the author noted areas which can introduce errors and biases. The intent of such commentary is merely to draw the reader's attention to areas that could be improved through more objective means. Bias is not inherently "bad," either. Some bias can stem from experience—lessons learned—that can form the basis for better decision making. Subject matter expertise, for example, is generally regarded as a good thing in many design contexts.

Case Study 2 provided an unexpected insight. The Space Race epoch featured a major uptick in space-based capabilities and preference for high-end capabilities. Regardless of the presence of competition, high-end capabilities come at a price. Too many expensive capabilities crowded out more diverse portfolios, resulting in lower MAU overall. The lesson being, there is an upper bound to the amount of exquisite capability a portfolio can acquire. That lesson is transferrable to the entire military portfolio. In Case Study 1, the low-observable assets allow the portfolio to operate in a contested battlespace, but those capabilities come at a dramatic acquisition and operational cost relative to the permissive

assets. Putting such assets into storage still incurs some cost, but presents one option with having to flex to an operational need that is not readily served by other assets.

6.2. Recommendations for Future Research

Constrained by time, this thesis left a whole field of stones unturned for future researchers to claim as their own.

6.2.1. Extending Financial Portfolio Metrics to PLEEAA

PLEEAA, as defined, provides a tool for portfolio decision makers to conduct analyses that aid the portfolio architecture. Financial Modern Portfolio Theory and its offshoots are several decades old at the time of this writing, and an expansive body of research has contributed to its maturity. Portfolios of systems and systems of systems, however, are a comparably new concept, and opportunities may exist to leverage niche elements of financial portfolio management to further improve the tradecraft.

One such niche comes from the construction of bond—so-called "fixed income"—portfolios.

6.2.1.1. Fixed Income Portfolio Management

The prior art in the area of identifying overlap between the design and management of systems portfolios and financial portfolios focused largely on the Modern Portfolio Theory, as was discussed earlier. Systems portfolios bear some resemblance to the management of bonds. This will be explored in more detail after some initial introduction to bonds and bond portfolios.

Bonds are a financial asset class sometimes referred more generally to as "fixed income" assets, because they generate a fixed, predictable stream of cash flow to the bond holder in the form of interest or "coupon" payments.

A bond is a debt obligation, and represents a relationship between the investor and the bond issuer. While there are myriad types of bonds in modern finance, this research uses a "vanilla" instrument because it is the easiest to conceptualize.

Some basic fixed income terminology is necessary to lay the foundation for what follows. A bond has a face value, also called the par value. This is the principal amount of the debt. For the sake of illustration, an organization issuing a bond with a $1000 par value receives an up-front payment from the investor of $1000. The organization would use the cash inflow from this debt transaction, for example, to take on a capital-intensive program it deems worthwhile.

A vanilla bond has a series of interest payments paid at a predetermined interest rate, also called a "coupon rate;" frequency—e.g. annually; and maturity, which is the period over which the bond will be repaid. A 10% coupon in the example results in an annual interest payment of $100. A 5-year maturity means that interest payments will be made over the five

year bond life, and at the end of that period, the organization will return the $1000 par value to the investor. The investor therefore makes a steady, predictable stream of cash flow from the interest payments and receives his original investment back when the bond is retired.

Bonds are liquid assets, meaning they can be bought and sold during their lifetime. In the bond market, an investor will encounter a wide array of debt offerings from companies as well as federal, state and local governments. The interest rate affixed to those bonds will vary in response to factors such as the macroeconomic environment and the default risk on the debt. The bond investor is thus confronted with a choice of which asset to choose. An existing bond paying a lower rate of return than a bond of equivalent default risk paying a higher rate of return would reach equilibrium by the price of the former falling to achieve the same present value of cash flows to the latter. Thus, bond prices and yields move in opposite directions. When interest rates in the bond market rise, bond prices fall. Conversely, when interest rates go down, bond prices rise.

A simple hypothetical example adapted from U.S. News & World Report[55] (2014) is illustrative. Investors A and B contemplate a bond purchase. A bond is available today at a par value of $1000 with a 5-year 10% coupon paid annually, meaning that an investor would earn $500 in interest if held to maturity. Investor A is satisfied with this return and purchases the bond. Investor B, however, believes that interest rates will go up shortly and waits. Indeed, Investor B's intuition proves correct and interest rates rise. A bond issued by an

[55] Campbell, K., "A Guide to the Relationship Between Bonds and Interest Rates," U.S. News & World Report, May 29, 2014, https://money.usnews.com/money/blogs/the-smarter-mutual-fund-investor/2014/05/29/a-guide-to-the-relationship-between-bonds-and-interest-rates, accessed 1/25/2018

organization with a similar default risk as held by Investor A, again with a par value of $1000 and a 5-year maturity, now has a 12% coupon. This bond therefore pays an investor $600 in interest over the life of the bond. Investor B would not be willing to pay the same price that Investor A paid for 10% coupon bond because it offers less interest than the 12% bond, so Investor A's bond decreases in value.

Duration is a specific term that is separate and distinct from maturity. Duration is a measure of how long it takes for an investor to be paid back his investment by means of the bond's cash flows. It is a useful concept that helps quantify a bond's price changes relative to a change in interest rate. For a plain vanilla bond, as has been discussed herein, a bond's duration will necessarily be less than its time to maturity, due to the cash flows from coupon payments. Two main factors contribute to a bond's duration: time to maturity and the coupon rate. The longer a bond's maturity, the greater its duration, and the more sensitive it will be to interest rate changes. The higher the coupon rate, the faster it will repay the investment and thus the lower its duration. When the time value of money is accounted for in the calculation, this is called the Macaulay Duration[56], which is given by:

$$D = \frac{\sum_{t=1}^{N} \left(\frac{tC}{(1+y)^t} + \frac{NM}{(1+y)^N} \right)}{P} \tag{11}$$

Where:

[56] Macaulay Duration, https://www.investopedia.com/terms/m/macaulayduration.asp, accessed 2/3/2018

D = Macaulay Duration

P = Present value of bond cash flows

t = Time period

N = Maturity in years

y = Yield

C = Coupon payment

Duration is a linear concept, meaning an interest rate change will result in a linear change in bond price. In reality, the relationship between interest rate changes and price changes are nonlinear and convex in shape. The term "convexity" is used in fixed income asset management to describe this nonlinear behavior.[57] In Figure 55 below, the straight downward sloping red line is the bond's duration, while the convex black line is the bond's convexity. Clearly, the difference between duration and convexity will be small for small interest rate changes. Assessing the risk associated with large moves in interest rates, however, warrants the more precise convexity measure to minimize the price estimate error. Mathematically, convexity is given by:

$$C = \frac{1}{P(1+y)^2} \sum_{t=1}^{N} \left[\frac{CF_t}{(1+y)^t} (t^2 + t) \right] \tag{12}$$

Where:

C = Convexity

P = Present value of bond cash flows

[57] Convexity, https://www.investopedia.com/terms/c/convexity.asp, accessed 2/3/2018

y = Yield

t = Time period

N = Maturity in years

CF_t = Cash flow at time t

As with duration, interest rate risk and convexity move together. Conversely, when convexity is low, interest rate risk is lessened.

A fixed income portfolio manager who holds a basket of bonds can hedge interest rate risk through a concept called "immunization." This can be accomplished through a number of ways such as cash flow matching, duration matching, and convexity matching—all of which are similar in that they offset assets with liabilities. (Investopedia). Regardless of the specific technique used, all seek to make the fixed income portfolio more robust over time by mitigating risk.

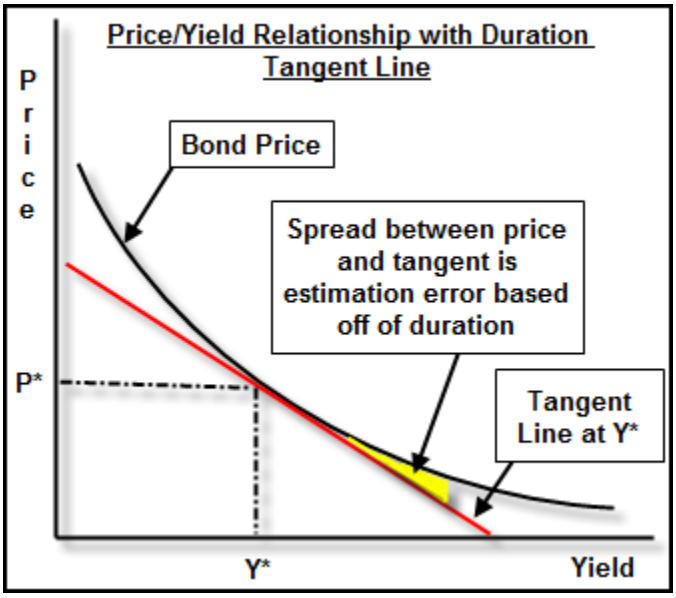

Figure 55. Price / Yield Relationship with Duration Tangent Line[58]

[58] http://www.mysmp.com/sites/default/files/images/convexity.png, accessed 1/26/2018

Implications for System Portfolios

The concepts of present value, duration, convexity and immunization translate qualitatively to the realm of systems and systems of systems portfolio management.

Present Value

The utility of unchanged systems and systems of systems may decrease over time as their operational contexts change, as was discussed previously. The financial concept of "present value" is the idea that money is worth more now than in the future, and it can be quantified by "discounting" the future value by an appropriate discount rate to the present period. What discount rate to choose for a particular analysis is a topic that could fill a whole textbook chapter, but suffice it to say for the purposes of brevity, that it could be the interest rate the funds would earn if invested over the period, an organization's cost of capital, an investment's risk-weighted rate of return or other measures. (Investopedia) The formula for present value is given by:

$$PV = \sum_{i=1}^{N} \frac{CF_i}{(1+r)^i} \tag{13}$$

The concept of the time value of money is somewhat analogous to the decay of prediction accuracy in the context of Epoch-Era Analysis (when a forecast is the intent of the study). Near-term predictive accuracy for epochs should generally be higher than far-term predictions. This concept of forecast drift is famously illustrated in Figure 56 below, which depicts the "North American Electric Reliability Council (NERC) Fan" (Nelson and Peck, 1985). Even subsequent revisions to the forecast based on updated actuals continued to overshoot the actual behavior—with smaller error in the near-term and larger-error in the long-term.

By preferentially weighting nearer-term epochs rather than equal-weighting all epochs, there is some consideration given to the idea that the forecast drifts, assuming, of course, that forecasting is a goal of the analysis.

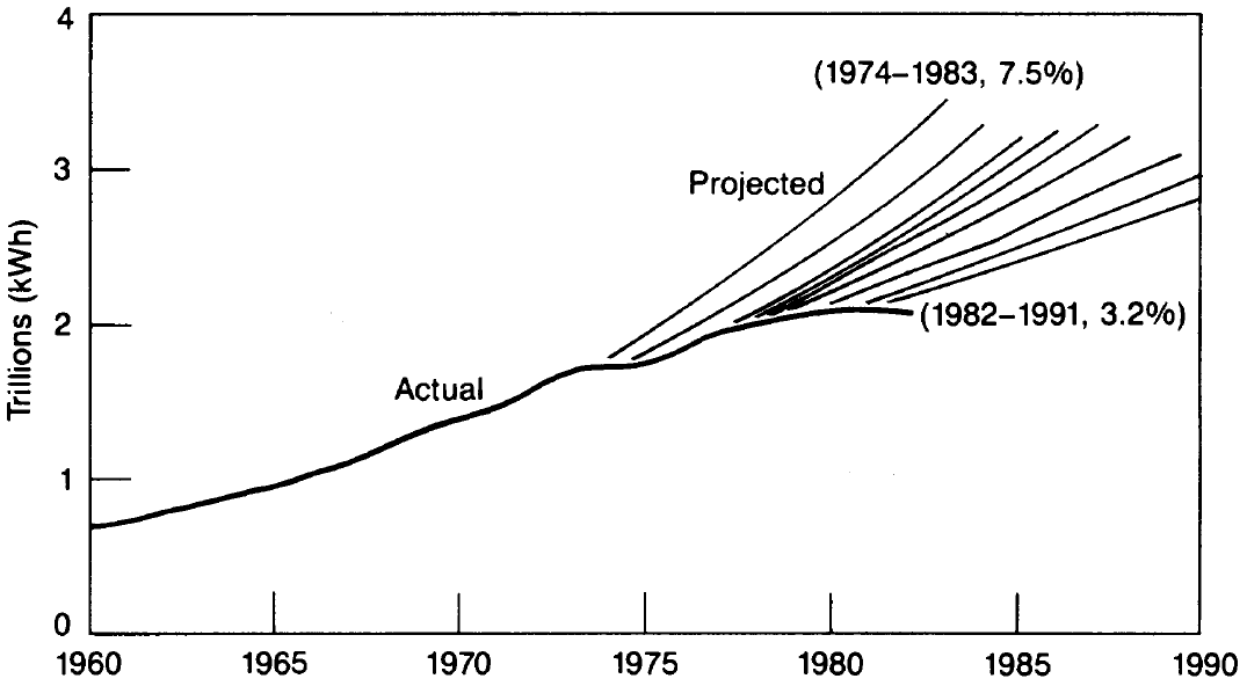

Figure 56. NERC Fan (Nelson and Peck, 1985)

Convexity

System portfolios are also analogous to fixed income portfolios in the concept of duration or its more sophisticated form, convexity. Figure 57 below shows the convexities for two hypothetical bonds (Patel, 2011). The bond depicted by the red line has greater convexity than the one given by the purple line. The lower convexity bond has less interest rate risk, meaning its price is more stable in the face of changing interest rates. Similarly, a portfolio of systems and systems of systems that maintains high multi-attribute utility across a sequence of epochs is superior to one that rapidly loses utility.

The real work for future research is translating the single variables of price and interest rate into their systems portfolio analogs. Furthermore, the concept of "price" has the implicit assumption of "all else being equal." For instance, a convexity analysis assumes no change to underlying credit risk. In a portfolio of systems setting, there are many dimensions that may be considered to evaluate value-robustness, and the mechanics of how to decompose and conduct that analysis are left to others to investigate.

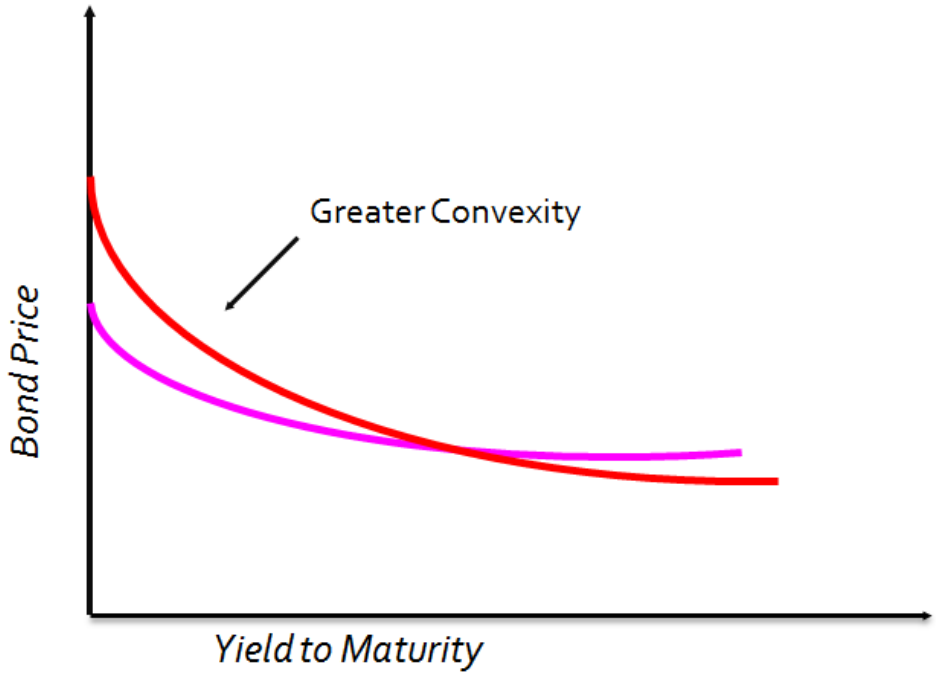

Figure 57. Convexity to two hypothetical bonds (Patel, 2011)

What other metrics from financial asset management could be brought into the realm of system portfolio management?

6.2.2. Other Recommendations

Recognizing that complex systems of systems often permit alternative configurations via modularity (e.g. an aircraft capable of carrying one type of asset or another), this analysis looked at each SoS configuration as a unique asset. A more sophisticated analysis may involve

looking at the platforms and their configurations recursively and to consider unauthorized combinations to make optimization decisions that may yield novel results. In a hypothetical example, rather than simply looking at the official combinations of record, what the author calls an "authorized" combination, consider the effect of cross-walking one capability to a different, "unauthorized" platform. In the real world this would carry a nonrecurring switching cost to port the capability to a new application, and potentially a different carrying cost. These effects could be quantified through system architecture and systems engineering analysis.

The insertion of real options, including concepts such as the values of perfect and imperfect information, could perhaps be used to objectively quantify how much "fuzziness" to employ on the Pareto front. Given the very high cost of SoS acquisitions and the risk associated with getting the portfolio mix "wrong," the value of information about the future is qualitatively high. Trying to quantify the value of information could pay dividends in selecting value-robust portfolios and in strategic planning.

Taking the time to develop a richly detailed portfolio capability tree with many layers of decomposition may yield insights into emergent behavior of constituent elements. Additionally, "big data" tools and visualization methods may illuminate patterns well beyond the cognitive capability of human portfolio designers. That said, such an approach would benefit from efforts to streamline the setup.

The author's approach to determining asset utility is somewhat subjective, and could be improved with more objective methods. For example, using an incontrovertible measure such as "on-station time" or "number of hard points per aircraft" to assess system

performance, instead of an ordinal scale of 0, 1, 3, and 9, would make it more difficult to game the outcome.

In 2017, Google used artificial intelligence (AI) to program a computer opponent in the game "Go." That the computer player beat the world's top Go player is unremarkable; computer opponents already bested human experts in games like Chess long before this. What was remarkable, however, was that the computer player came up with novel Go strategies.[59] In Vascik and Ross' Carrier Strike Group (CSG) case study (2015), it was assumed that a CSG was still a desired force architecture. However, it may be that technologies have evolved dramatically since World War II when aircraft carriers established their utility, and the CSG may no longer be as relevant. Could artificial intelligence provide novel solutions for multi-attribute tradespace exploration analyses by escaping the inherent biases and anchoring introduced by human stakeholders? A strong wargaming engine based on artificial intelligence and deep learning injected into the analytical workflow may provide new avenues for exploration.

PLEEAA uses a range of discrete inputs in its models. This is done in part to reduce the computational burden and to create some meaningful spread in the outcomes. Expanding the analysis to consider a near-continuous spectrum of inputs with a probability distribution, using techniques like Monte Carlo simulation, increases the realism, but also dramatically increases the model complexity and computational power required to analyze it. Expanding the work of Curry (2017) to the PLEEAA framework could yield some novel results.

[59] https://qz.com/639952/googles-ai-won-the-game-go-by-defying-millennia-of-basic-human-instinct/, accessed 2/24/2018

The interconnectedness of SoS performing complementary and, at times, overlapping functions led the author to ponder optimization, from the portfolio level all the way down to the system level, as a dynamic control problem. Spring-mass-damper systems are well understood and taught to every young engineer. Can requirements at all levels of decomposition be mapped to a control system model that in turn can be modeled and optimized? Do concepts like overdamping and underdamping, as well as transfer function poles and zeros apply to the interaction of requirements and how they manifest in the end product?

Captivated by the massively lopsided outcome of the First Gulf War in 1991, the author seeks to understand the ways that a technological gap could again be pried open and sustained. In the words of General Norman Schwarzkopf who prosecuted that conflict, "War is a profane thing."[60] The killing of one another, the commitment of a nation's blood and treasure, seems in the 21st century a relic of a more barbaric chapter of human history. While war is likely to remain a tragic element of the human experience well into the future, breaking a technological stalemate with near-peers by obtaining and maintaining an insurmountable gap is a potent deterrent to conflict. This topic is well beyond the narrow scope of the research herein, but its benefits are profound. Technology has the ability to render armed conflict obsolete, with the paradox being that the means to that end is by continuing to develop an exquisite arsenal.

[60] https://www.forbes.com/sites/kevinkruse/2012/12/27/norman-schwarzkopf-quotes/#6b9fe6af4eeb, accessed 1/9/2018

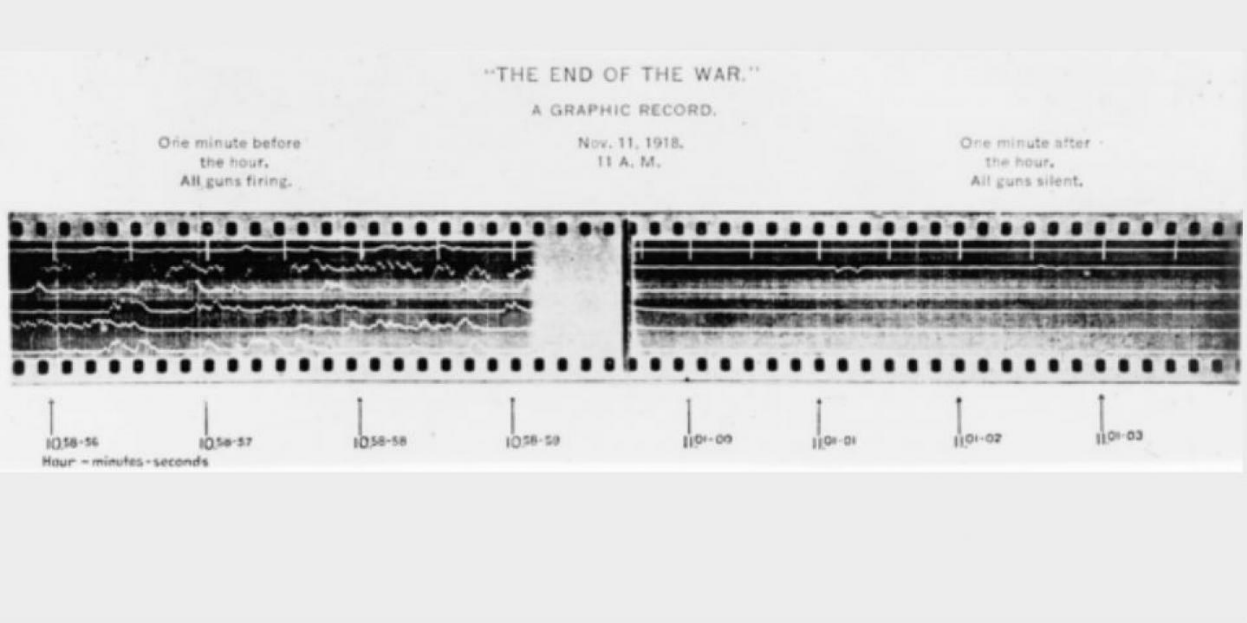

Figure 58. When the guns fell silent. A graphic record of the end of World War I.[61]

[61] http://www.newsweek.com/2014/11/14/amazing-photo-shows-moment-guns-fell-silent-282453.html, accessed 1/9/2018

7. Conclusion

This research sought to extend the Portfolio-Level Epoch-Era Analysis for Affordability framework through the analysis of two case studies, the U.S. Air Force Intelligence, Surveillance and Reconnaissance portfolio, and the U.S. space-based geospatial intelligence portfolio inclusive of both government-owned and commercial assets. Additionally, it sought to further generalize aspects of Modern Portfolio Theory from financial asset management to a portfolio of systems and systems of systems.

Section 1.3 laid out some questions to guide this research. They are revisited here at journey's end.

7.1. Guiding Question 1

The first question was:

Can principles of Modern Portfolio Theory from financial asset management be extended to portfolios of engineering systems?

The short answer is "yes." Caveats must be added to highlight that some of the underlying assumptions of Modern Portfolio Theory are particular to financial assets and do not translate to the oversight of portfolios of systems and systems of systems.

In no small sense, this question was already addressed by the likes of Walton (2002), Ricci and Ross (2012), Wu (2014), and Vascik (2015, 2016). In the Recommendations for Future Research section, the author briefly explored a previously unexplored topic—fixed income portfolio management, and specifically concepts such as duration and convexity—to attempt to expand the analogy. The concepts are used in financial risk management, and seek to find assets that have low price sensitivity relative to interest rate changes. The relationship is a

simple relationship involving interest rates and price. In the realm of systems portfolios the value robustness is assuredly more complex.

As Ricci and Ross (2012) noted, one significant area of divergence is with respect to the concept of covariance. In financial asset management, the diversifiable risk can be mitigated by acquiring assets that covary in opposite ways. Attempts to map the concept of covariance into the systems portfolio space are difficult, in part because the emergent properties of complex systems can provide non-normal probability distributions and nonlinearity. Additionally, the volume of trades that happen on a financial exchange daily assure a much richer, more easily obtained set of asset covariance. System portfolios, on the other hand, are context-dependent. Synergies between assets that may exist in one context may not exist in others.

Multi-attribute utility theory posits that value has various forms, and what is valuable to one stakeholder may not be valued to the same degree (or at all) by another. Thus, in these scenarios a normal distribution about an expected outcome may not be a realistic assumption for portfolios of systems.

In the case of defense acquisition, the saying goes that the military is "fighting the last war," meaning that the most recent conflict informs and biases the strategy and acquisition of new capabilities. The U.S. military, having spent the first two decades of the new millennium fighting wars of counterinsurgency has amassed an arsenal of weapons and techniques tuned to fighting that kind of conflict. If war broke out tomorrow with a high-end, near-peer adversary, the U.S. would initially have to adapt to now unfamiliar challenges of waging a full-spectrum conflict. All this is said to suggest that whereas in financial portfolio

management, where prior asset returns and volatility are used to extrapolate future performance, the high stakes of armed conflict are such that tomorrow's conflict will assuredly look different than yesterday's. Thus, the process of extrapolating the future portfolio performance based on the past performance is not relevant to systems portfolios. With that said, the use of epoch-era analysis helps build portfolio models that can take into account futures that look vastly different than the past.

7.2. Guiding Question 2

The second question was:

Is there a mix of higher cost, capably exquisite and lower cost, less capable systems that exhibits efficient frontier stability across a range of possible futures or epochs?

Both case studies considered portfolios that permitted mixed portfolios. A diverse mix is, for all intents and purposes, a necessity in matters of national security. For instance, in the space-based sensing case, the differences in resolution are obvious to the naked eye, as is clearly depicted in the following three figures—the last of which is a publicly-released, degraded image from a military asset. The point being, there are roles that each tier of capability serves, and for some mission needs, there is no substitute for the exquisite offering. While the extraordinary expense of the exquisite assets limits the number that can be procured in any given era, the utility they provide for certain missions is substantially better than that offered by less sophisticated assets.

Figure 59. MIT Dome, imaged by Planet's RapidEye 5m satellite, March 20, 2018.[62]

Figure 60. MIT Dome, imaged by Planet's Dove 3m satellite, imaged March 20, 2018[63]

[62] https://www.planet.com/, accessed 3/24/2018

[63] https://www.planet.com/, accessed 3/24/2018

Figure 61. Degraded KH-11 imagery released by DoD in December 1998[64]

Similar logic applied to the airborne example in the first case study. For instance, the low cost of an unmanned MQ-9 asset means they can be procured in significant quantity, but the utility they offer is limited to permissive operating environments. Standoff assets like the U-2 and RQ-4 provide deeper reach into denied airspace, but they, too, have their limits. An exquisite low-observable asset is the only suitable choice in an A2/AD situation.

[64] https://nsarchive2.gwu.edu/NSAEBB/NSAEBB13/9.jpg, accessed 3/24/2018

It is possible that case studies exist outside of national security in which exquisite offerings may have insufficient marginal utility to warrant the added expense. Thus the finding is offered as a heuristic only, not necessarily a general truth with universal applicability.

7.3. Guiding Question 3

The third question was:

How objective is the PLEEAA framework? In other words, what sources of bias and other errors can affect the inputs and outputs?

Throughout the case studies and discussion section, the author highlighted areas that are prone to estimating risk and injection of explicit and implicit bias. For instance, the development of the portfolio capability tree may not capture all portfolio objectives and system performance attributes. The assessment of systems in each performance attribute, at least on a subjective ordinal scale as was done in the cases studies is prone to gaming by people who could have a conflict of interest in the outcome. And the use of aggregation models is somewhat subjective—i.e., while some models may be easily dismissed as not applicable for some attributes, the choice among the remaining models is not always clear. Furthermore on the topic of models, the collection of models and which to apply involves some assessment of how the portfolio constituents will be employed in operational use. Therein lies another source of bias—the concept of operations helps drive the choice of models and in turn that drives the portfolio utility (and cost). Finally, even a choice as fundamental as the collection of assets to consider can anchor the outcome. For instance, in the Carrier Strike Group analysis, implicit at the outset of the analysis was the assertion that

an aircraft carrier is still a vital construct. This assertion fundamentally anchored the analysis. Perhaps alternatives to the CSG exist that would yield high utility at an affordable cost.

7.4. Guiding Question 4

The fourth question was:

Can the PLEEAA framework be used to make objective system asset investment and divestment decisions?

Yes, with caveats. The PLEEAA framework enables portfolio stakeholders to analyze the collection of constituent systems and their quantities to make more informed investment and divestment decisions. Of course, the adage "garbage in, garbage out" applies. The PLEEAA process is neither trivial nor quick, so care needs to be taken at each of the eleven processes to think critically about inherent biases that may be steering the analysis toward a preordained conclusion. The PLEEAA method as articulated requires the evaluation of asset performance and thus utility by people who have financial responsibility for those assets. While the upper tiers of the portfolio hierarchy may be focused on making unemotional, objective decisions, the lowest tiers have a selfish interest in ensuring the systems under their immediate control in the mix. The same non-altruistic biases may exist for the companies that furnish those assets, and the politicians who are lobbied by those companies and may seek to help companies and workers in their districts by favoring one asset over another. For the PLEEAA framework to give objective analysis, it requires the decision makers to examine biases that may drive the analysis—including the biases of the topmost decision maker(s).

Consider the first case study. Stakeholder bias or anchoring may be evident in the degree to which Unmanned Aerial Systems feature in the current and future portfolio architecture.

Scholarly research by Worden (1998) illustrated that the Air Force general officers were overwhelming pilots, and it was their mixture of professional experience on the one hand and pride on the other that informed the strategy and acquisitions on their watch. "This analysis focuses on the career specialty of Air Force general officers who served between 1953 and 1973. It indicates the clear dominance by rated or flying officers (mainly pilots and a few navigators) within Air Force leadership." "The issue here is not whether pilots should dominate the Air Force—the fact is they do. Rather, a more interesting phenomenon is that persons who sit on top of the world's most powerful air force are almost exclusively fighter pilots." (Worden, 1998) His hypothesis was that the experiences of these pilots-cum-generals helped establish their beliefs and thus biases as leaders for technological strategy and battlefield strategy.

Worden asserted in unusually strong words, "Technology functioned both as an instigator and a messiah to the air advocate. Married to machines, the World War II generation generals understood how numbers and technology altered the calculus of battle. If numbers were unaffordable, then, preferably bigger, higher-flying, faster and longer-range strategic bombers would make up the difference. In short, an institutional technological zeal would make doctrinal dreams seem real. This goal would remain the Air Force's primary solution to doctrinal shortfalls." (Worden, 1998)

The combat pilots who in their youth participated in the likes of Desert Storm will undoubtedly use their experiences and, consciously or unconsciously, their biases, to guide their leadership when it is their turn to set strategy as general officers. The importance of stealth aircraft as the means to penetrate heavily guarded airspace may well justify its

continued use. More recent memories like the high-profile loss of the then-secret RQ-170 in Iran[65] could prompt those same leaders to keep a manned spy plane in the portfolio, particularly where high-value assets are concerned.

Finally, given enough time and resources to devote to a PLEEAA-based analysis, the process should evaluate the "as-is" alternatives-based portfolio including both the assets already at hand and the ones in the development pipeline, and a "to-be" values-based portfolio that includes hypothetical assets that may not even be in development yet. The former is more of a bottom-up approach, and the latter is essentially a top-down approach. Conducting the analysis two ways would theoretically help to identify the incremental utility that stems from the investments that fill the gap between the two methods. The case studies in this research focused on the latter method, but the two methods in tandem could potentially yield better insights into the specifics of investment and divestment (e.g. timing, quantity).

7.5. Guiding Question 5

The fifth question was:

Can asset covariance analysis across epochs help inform key system interoperability decisions?

As was discussed on multiple occasions in this research, the mathematical concept of asset covariance is not necessarily applicable to complex systems. Covariance is given by:

$$cov(X,Y) = \sum_{i=1}^{N} \frac{(x_i - \bar{x})(y_i - \bar{y})}{N}$$

[65] http://www.militaryaerospace.com/articles/2016/05/unmanned-cyber-warfare.html, accessed 2/13/2018.

(14)

In the strictest sense of Modern Portfolio Theory, seeking an asset covariance matrix for systems portfolios would seem to be a dead end. With that said, there may be opportunities for future exploration already known to systems engineers. Specifically, the Design Structure Matrix, alternatively called an N^2 matrix, is a visual tool useful for showing interactions between elements. Level numbers, such as the same 0, 1, 3, 9 scale used in the case studies, can be used to model the strength of interactions. Negative numbers can also be used to indicate negative interactions. (Browning, 2001) For instance, the electromagnetic interference emitted by a radar system would have a negative relationship with the performance of a signals intelligence system operating nearby. Negative numbers introduce challenges of their own to the analysis of Design Structure Matrixes so their presence should be carefully considered.

Systems engineering artifacts such as SV-1 and OV-1 diagrams, which feature heavily in the DoD Architecture Framework, could prove useful in constructing DSMs that indicate at least first-order interactions between systems. A contrived example for 10 systems is shown in Figure 62. This type of analysis could be iterated across epochs to assess the evolution of emergent interaction in context.

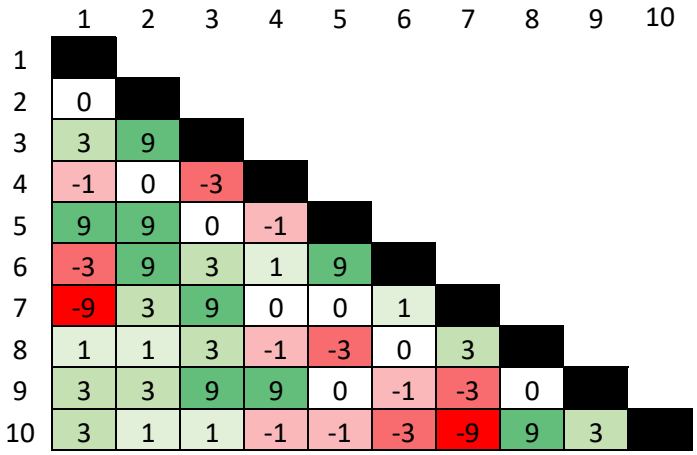

Figure 62. Example System Interaction DSM

Thus, while the mathematics need to be contemplated in detail before saying that covariance is "off the table," it appears there is an avenue to a quantitative approach worth exploring. The analysis is by no means trivial, because there are multiple dimensions of interaction, such as one that scales with quantity.

7.6. Guiding Question 6

The sixth question was:

Can the finance concept of investor risk tolerance in establishing the optimal location on the efficient frontier, be extended to systems of systems portfolios?

The earlier introduction to MPT, and Figure 5 in particular, introduce the idea of the efficient frontier and the optimal portfolio which is the point on the efficient frontier that is consistent with an investor's risk tolerance. The Capital Allocation Line (CAL) is the tangent line drawn on the efficient frontier at the optimal portfolio.

The systems portfolio analogous plot to expected return plotted as a function of portfolio standard deviation is portfolio utility as a function of portfolio cost. In both cases the utopia

point is the upper left—maximum expected return / utility at minimum standard deviation / cost.

Since all "investors," the system portfolio designers in the world could theoretically build their own portfolios of equivalent capability, the answer to this guiding question is "yes." In the case of national security, however, not every country in the world has a need or desire for the full breadth of capabilities. For instance, many smaller foreign militaries lack dedicated ISR aircraft and instead mount pod-based intelligence systems to its fighter jets. For the United States, relying on such systems as its sole airborne ISR platform would have comparably low utility, and its higher utility options—dedicated, purpose-built ISR aircraft—are simultaneously higher utility and higher cost. Additionally, some countries may desire more elegant, higher utility portfolios but are unable to given their economic capacity. For instance, the cost of keeping pace with the United States in the Cold War grew to be an exceptional burden for the Soviet Union, and it coped with the strains of simultaneously supporting a sophisticated arsenal and feeding its people—the so-called "guns or butter" decision. Thus, some countries may possess the means to operate on a larger section of the utility-cost pareto front than others, but how much depends at least on ability, stability and willingness to pay. This is discussed more in the final guiding question, and could easily be the basis for a whole new line of research.

A parting thought on this question is that unlike financial portfolios, the concept of expected return or utility is unique to the "investor." For a small nation like Switzerland, it may derive considerably more utility for a lower-end portfolio because the context in which the portfolio is to be used is undeniably different than for a large nation like the United States.

Thus utility is a relative concept. Cost is somewhat less relative, because cost is often anchored to an underlying economic foundation—for example, the cost of the raw materials and the cost of labor to shape those materials into something of utility. On the other hand, since most of the complex systems portfolios of the modern era are held by governments, the laws and regulations governing how those systems are acquired is likely to affect the cost such that the economic concept of Purchasing Power Parity does not hold. For instance, the United States has an enormous body of acquisition burden in the form of the Federal Acquisition Regulations (FAR), whereas in China or Russia, such regulations are either less restrictive or nonexistent. Thus, there is likely to be a range of costs across various economic regions that correspond to a given basket of capabilities that is not explained purely by Purchasing Power Parity.

7.7. Guiding Question 7

The seventh question was:

If so, what are the constituent elements that determine the system analog for "investor risk tolerance"?

In financial portfolio management, the concepts of risk and return are inextricably linked. Both are absolute measures that mean the same thing to all investors; the differentiation comes in deciding how much risk an investor can tolerate.

For systems portfolios, however, the analogous measures of MAU and MAE are not universally constant. As was discussed in Section 7.7, a portfolio owner—typically a national government—may have significantly different objectives than another. The example of Switzerland versus the United States is illustrative. Switzerland, despite its long history of

neutrality, has a military. It is overwhelmingly focused on defense and peacekeeping, and so its comparably miniscule military relative to the United States means that it assigns higher MAU to the roughly equivalent basket of capabilities than the U.S. would, because its objectives are different. Similarly, MAE would likely vary around the globe for the roughly equivalent basket of capabilities as was discussed above because the acquisition laws and regulations are different from one country to the next.

Thus, some portfolio investors have the financial means to acquire a broader range of assets including exquisite articles that may be outside the means of other investors. And today's high-utility exquisite capability is tomorrow's middle-of-the-pack, and a future laggard, as depicted in Figure 10. Utility is not static. Upgrades can be an effective strategy for maintaining a system's viability in the face of changing contexts. Portfolios that includes upgradeable systems thus able to offer more value robustness through real options.

Another way of considering investors' risk tolerance can be found in Everett Rogers' Diffusion of Innovations theory, which dates to the early 1960s. Rogers' concept of "relative advantage," the "degree to which an innovation is perceived as being better than the idea it supersedes," is pertinent to the discussion of investor risk tolerance. (Rogers, 2003) A game-changing innovation that has the potential to disrupt the status quo utility has a relative advantage over the incumbents, and can change the investor's values for all capabilities, by shifting down the utility of incumbent options. The effort associated with developing and maturing the innovative technology and including it in the portfolio has the effect of increasing the MAE.

Rogers' theory articulates the classes of adopters, as shown in Figure 63. The portfolio holders with the most formidable objectives will likely find themselves on the left half of this plot. How far left, and thus how much risk they are willing to accept in pursuit of capability and thus utility, depends on the breadth and depth of the objectives, as well as the ability, stability and willingness to pay to meet those objectives.

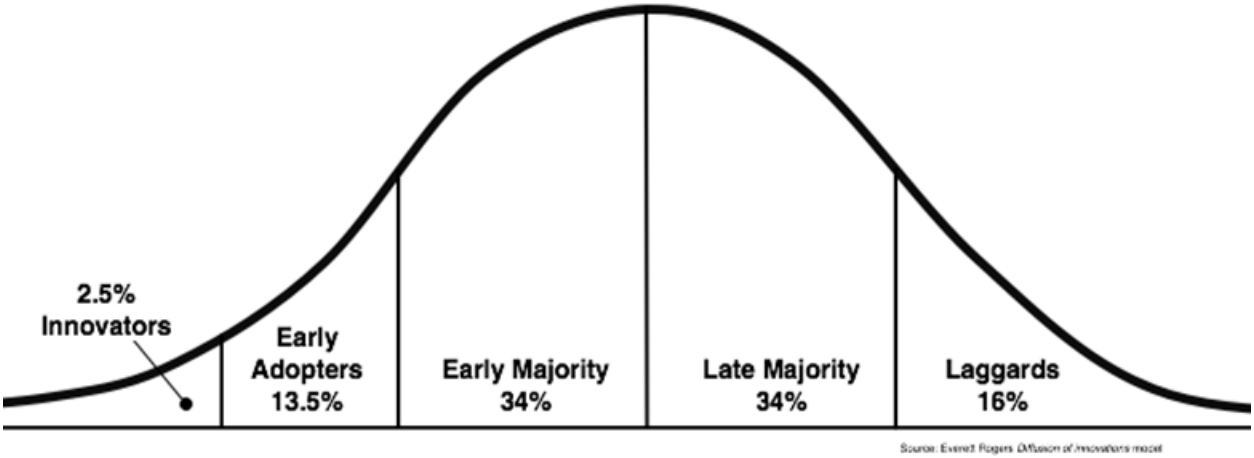

Figure 63. Diffusion of Innovation adoption curve[66]

One final comment about innovation is warranted. A new technology rarely exists in a vacuum. Rather, it is typically supporting by a number of adjacent enabling technologies. A smart phone, for example, requires disparate technologies spanning semiconductor manufacturing, wireless communications, rechargeable batteries, small format cameras, etc. The Space Race required several simultaneous innovations in weather forecasting, advanced materials, life support, communications, propulsion, guidance systems, and others. The term "moon shot," coined in that era, is used to convey highly ambitious, high risk, and almost assuredly, high cost, endeavors. According to the MIT Technology Review, the Apollo

[66] Diffusion of Innovation Theory, http://sphweb.bumc.bu.edu/otlt/MPH-Modules/SB/BehavioralChangeTheories/BehavioralChangeTheories4.html, accessed 3/27/2018

program employed as many as 400,000 people and consumed as much of 4% of the United States' Gross Domestic Product.[67] Clearly, not every country in the world can commit resources of that magnitude in pursuit of cutting edge innovation. Nor does every country wish to.

If the MAU vs. MAE tradespace is drawn to include the universe of possibilities as an absolute measure rather than the subset within reach of the portfolio in question, the universe of portfolio investors would fall roughly into the spectrum depicted in Figure 64.

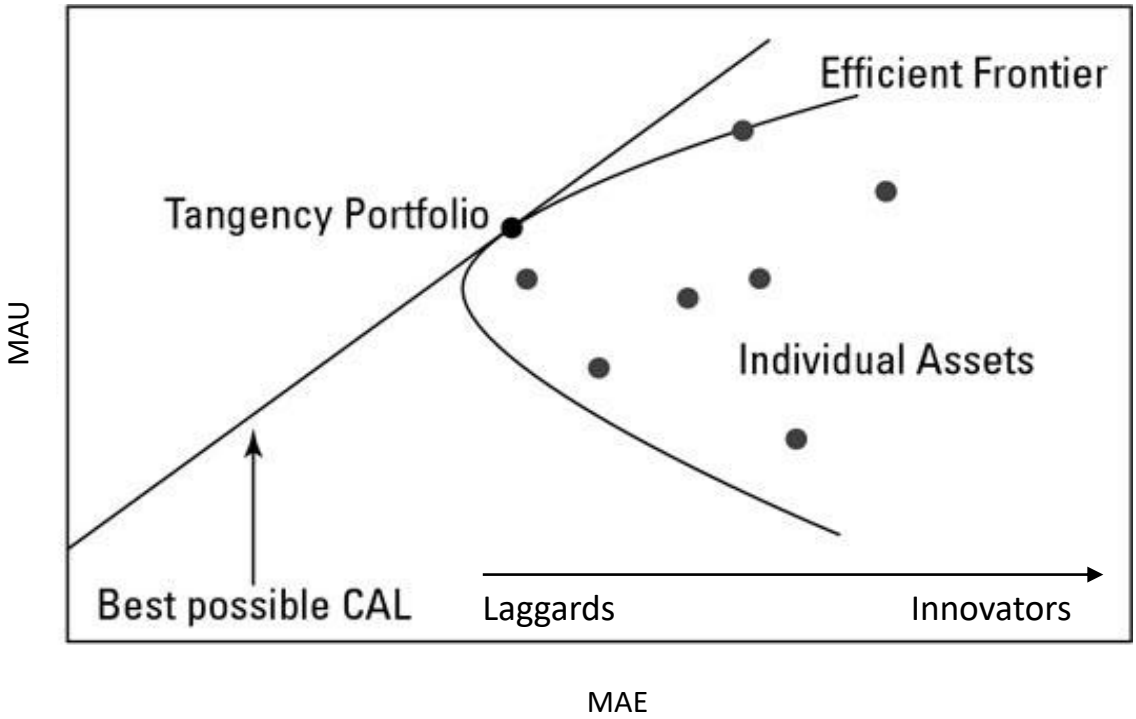

Figure 64. The spectrum of technology adopters applied to tradespace efficient frontier

In defense applications, such a plot could be useful in strategic planning activities, like conducting a strengths, weaknesses, opportunities, and threats (SWOT) analysis for

[67] Regalado, A., "What's a Moon Shot Worth These Days?" https://www.technologyreview.com/s/529591/whats-a-moon-shot-worth-these-days/, MIT Technology Review, July 29, 2014, accessed 3/27/2018.

adversaries. Understanding how much utility one portfolio of capabilities offers versus another can be a source of competitive advantage in devising strategies to win. The closer an adversary is to the portfolio owner on the tradespace, the more likely stalemate is. Wargaming to develop novel strategies and TTPs is more important in this situation than if the gap were larger—say, between an innovator and a laggard.

7.8. Concluding Remarks

In this thesis the author extended the applicability to the Portfolio-Level Epoch-Era Analysis for Affordability framework to two case studies involving complex systems and systems of systems.

The PLEEAA framework is by no means trivial, and requires a considerable investment in time and analytical rigor to ensure the outputs are meaningful and actionable.

It is vital to note that stakeholder biases at all level of the portfolio hierarchy can influence the composition and management actions. A portfolio owner would be wise to look very carefully at these sources of bias and seek to understand how much influence they have on the analysis. Richard Heuer, Jr.'s *Psychology of Intelligence Analysis* (1999), a book written for CIA analysts, rails against biases that can unconsciously constrain thinking to yield preordained conclusions. Heuer presents William E. Hill's famous 1915 cartoon that alternatively depicts via an optical illusion a young woman and an old woman, reproduced in Figure 65, as a reminder that cognitive bias can blind us to alternatives lying in plain sight. Despite the lighthearted example, the problem of biases is made stark by Operation Iraqi Freedom, a war derived from intelligence failures about weapons of mass destruction, at a

cost of more than 36,000 American casualties and nearly three trillion dollars of taxpayer money.[68,69]

Figure 65. "My Wife and My Mother-in-Law," Puck (1915)[70]

[68] Casualties of the Iraq war, https://en.wikipedia.org/wiki/Casualties_of_the_Iraq_War, accessed 3/27/2018

[69] Financial cost of the Iraq war, https://en.wikipedia.org/wiki/Financial_cost_of_the_Iraq_War, accessed 3/27/2018

[70] "My Wife and My Mother-in-Law," https://en.wikipedia.org/wiki/My_Wife_and_My_Mother-in-Law#/media/File:My_Wife_and_My_Mother-in-Law.jpg, accessed 3/27/2018

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Appendix A. Case Study 1: Capability Tree

Portfolio-Level Performance Attributes
2nd-Level Program Capability Attributes
System-Level Performance Attributes

Persistent	All Weather Capability	Capacity
		Endurance
		Detection Capability
		Tracking Capability
		Area Coverage
		Sensor Cross-Cueing
	Day / Night Capability	Capacity
		Endurance
		Detection Capability
		Tracking Capability
		Area Coverage
		Sensor Cross-Cueing
Operationally Responsive		Capacity
		Endurance
		Detection Capability
		Upgradeability
		Area Coverage
		Timeliness
Penetrability	Low-Observable Capability	Minimum Depth Penetration
		Radar Cross Section (RCS)
		Payload Capacity
		Speed
	High-Speed (Hypersonic) Capability	Minimum Depth Penetration
		Payload Capacity
		Speed
Offensive Capability	Air-to-Surface Missile (ASM) Capability	Hit Probability
		Range
		Deployment Time
		Supply
		Performance Survivability
	Precision-Guided Munition Capability	Weapon Effectiveness Index
		Deployment Time
		Supply
		Performance Survivability
Survivable	Enemy Weapon Systems Detection / Tracking	Detection Capability
		Tracking Capability

		Range
		Deployment Time
		Endurance
		Performance Survivability
	Anti-Tamper	Encryption
		Destruction Capability
	Surface-to-Air Missile (SAM) Defense Capability	Detection Capability
		Mitigation Capability
		Deployment Time
		Endurance
		Performance Survivability

Key:

1. Portfolio-level performance attributes

1.1 2nd-level capability attributes

1.1.1 System-level performance attributes

1. Persistent: the portfolio shall contain assets that provide the "unblinking eye" of persistent ISR, to track targets and maintain situational awareness.

1.1 All Weather Capability: the assets are able to operate and gather intelligence in all weather conditions. Electro-optical systems, for example, cannot penetrate most cloud cover, but radar-based systems can.

1.1.1 Capacity: utility versus the system imaging capacity in terms of utilization.

1.1.2 Endurance: utility versus how long the system could function nominally.

1.1.3 Detection Capability: utility versus the probability of actionable detection in all weather conditions including heavy cloud cover. Electro-optical systems have limited utility in these conditions, but radar has higher performance and utility in these conditions.

1.1.4 Tracking Capability: utility versus the probability of tracking targets.

1.1.5 Area Coverage: utility versus the area the system is capable of covering per unit time, such as square-miles per day.

1.1.6 Sensor Cross-Cueing: utility versus the degree of cross-cueing with other sensors in range to gather additional intelligence.

1.2 Day / Night Capability: the systems are able to operate and gather intelligence day and night.

1.2.1 Capacity: utility versus the system imaging capacity in terms of utilization.

1.2.2 Endurance: utility versus how long the system could function nominally.

1.2.3 Detection Capability: utility versus the probability of actionable detection in all light conditions including low-light. Radar systems are day / night agnostic, and electro-optical systems without infrared capability do not operate effectively at night.

1.2.4 Tracking Capability: utility versus the probability of tracking targets.

1.2.5 Area Coverage: utility versus the area the system is capable of covering per unit time, such as square-miles per day.

1.2.6 Sensor Cross-Cueing: utility versus the degree of cross-cueing with other sensors in range to gather additional intelligence.

2. Operationally Responsive: the portfolio shall contain assets that provide timely support to emerging combatant commander needs.

2.1 Capacity: utility versus the system imaging capacity in terms of utilization.

2.2 Endurance: utility versus how long the system could function nominally.

2.3 Detection Capability: utility versus the probability of actionable detection while minimizing probability of false positive detections.

2.4 Upgradeability: utility versus the number of systems and subsystems that can be upgraded.

2.5 Area Coverage: utility versus the area the system is capable of covering per unit time, such as square-miles per day.

2.6 Timeliness: utility versus the time to develop, build, and deploy a purpose-built asset.

3. Penetrability: the portfolio shall contain assets that can operate in Anti-Access / Area Denial (A2/AD) situations, skirting and/or penetrating enemy airspace undetected, and/or able to outrun enemy threats.

3.1 Low-Observable Capability: the airborne platform has stealth features that allow it to skirt or penetrate enemy airspace undetected by radar.

3.1.1 Minimum Depth Penetration: utility versus the minimum depth penetration into denied airspace the system can achieve.

3.1.2 Radar Cross Section: utility versus the Radar Cross Section of the system to reduce likelihood of detection and tracking by adversary tracking systems.

3.1.3 Payload Capacity: utility versus the system imaging capacity that can be concealed from the adversary.

3.1.4 Speed: utility versus the speed of the platform.

3.2 High-Speed (Hypersonic) Capability: the airborne platform has high-speed capabilities, e.g. hypersonic, to be able to outrun enemy threats.

3.2.1 Minimum Depth Penetration: utility versus the minimum depth penetration into denied airspace the system can achieve.

3.2.2 Payload Capacity: utility versus the payload capacity that can be carried on the platform.

3.2.3 Speed: utility versus the speed of the platform.

4. Offensive Capability: the portfolio shall contain assets capable of supporting the Kill Chain with offensive capabilities.

4.1 Air-to-Surface Missile (ASM) Capability: the platform has hard point mounts able to carry Air-to-Surface Missiles (ASM) to support target engagement.

4.1.1 Hit Probability: utility versus the ability of the weapon to hit its intended target when deployed.

4.1.2 Range: utility versus the distance at which the weapon can function nominally.

4.1.3 Deployment Time: utility versus the time required to transition from a neutral state to nominal, weapon-deployed functionality.

4.1.4 Supply: utility versus the number of weapons available to system.

4.1.5 Performance Survivability: utility versus the percentage of nominal performance the system can provide in a degraded state.

4.2 Precision-Guided Munition Capability: the platform has hard point mounts able to carry Precision-Guided Munitions to support target engagement.

4.2.1 Weapon Effectiveness Index: utility versus the ability to degrade, damage, or destroy enemy target.

4.2.2 Deployment Time: utility versus the time required to transition from a neutral state to nominal, weapon-deployed functionality.

4.2.3 Supply: utility versus the number of weapons available to system.

4.2.4 Performance Survivability: utility versus the percentage of nominal performance the system can provide in a degraded state.

5. Survivable: the portfolio shall contain assets that are able to remain mission capable in the presence of enemy threats and that protect sensitive technologies that, if allowed to fall into enemy hands, would gravely compromise technological superiority and national security.

5.1 Enemy Weapon System Detection / Tracking: assets shall possess signals intelligence systems capable of finding, fixing, tracking, and potentially targeting enemy threats.

5.1.1 Detection Capability: utility versus the probability of detecting enemy weapon systems while minimizing probability of false positive detection.

5.1.2 Tracking Capability: utility versus the probability of tracking enemy weapon systems.

5.1.3 Range: utility versus the distance at which the system can function nominally.

5.1.4 Deployment Time: utility versus the time required to transition from a neutral state to nominal functionality.

5.1.5 Endurance: utility versus how long the system could function nominally.

5.1.6 Performance Survivability: utility versus the percentage of nominal performance the system can provide in a degraded state.

5.2 Anti-Tamper: the platform and sensors have anti-tamper features that secure data in transit and data at rest with encryption, and if the asset falls into enemy hands, the platform and/or sensors are rigged with thermite or similar means to render the asset unusable.

5.2.1 Encryption: utility versus the ability to secure data at rest and in transit via encryption.

5.2.2 Destruction Capability: utility versus the ability to destroy data and sensitive technologies in the event the system falls into the adversary's hands.

5.3 Surface-to-Air (SAM) Missile Defense Capability: the platform has features to detect and mitigate Surface-to-Air Missile (SAM) attacks.

5.3.1 Detection Capability: utility versus the probability of detecting missile threat.

5.3.2 Mitigation Capability: utility versus the probability of mitigating the missile threat.

5.3.3 Deployment Time: utility versus the time required to transition from a neutral state to nominal, defensive functionality.

5.3.4 Endurance: utility versus how long the system could function nominally.

5.3.5 Performance Survivability: utility versus the percentage of nominal performance the system can provide in a degraded state.

Some of the system-level performance attributes were derived from a March 13, 2018 email exchange with Parker Vascik. The rest were defined by the author as unique to this case study.

Appendix B: Case Study 2: Capability Tree

Portfolio-Level Performance Attributes
2nd-Level Program Capability Attributes
System-Level Performance Attributes

Persistent	All Weather Capability	Capacity
		Endurance
		Detection Capability
		Tracking Capability
		Field of Regard
		Image Quality (NIIRS)
		Pointing Accuracy
		Revisit Rate
	Day / Night Capability	Capacity
		Endurance
		Detection Capability
		Tracking Capability
		Field of Regard
		Image Quality (NIIRS)
		Pointing Accuracy
		Revisit Rate
Operationally Responsive		Capacity
		Endurance
		Detection Capability
		Area Coverage
		Deployment Time
		Revisit Rate
		Timeliness
Multi-INT Capability	Signals Intelligence Capability	Detection Capability
		Tracking Capability
		Sensor Cross-Cueing
		Deployment Time
		Pointing Accuracy
		Performance Survivability
	Geospatial Intelligence Capability	Detection Capability
		Tracking Capability
		Sensor Cross-Cueing
		Deployment Time
		Field of Regard

		Pointing Accuracy
		Performance Survivability
Concealment and Deception Capability	Low-Observable Capability	Spectral Signature
		Radar Cross Section
		Payload Capacity
	Concealment Capability	Physical Size
		Orbit Matching
	Decoy Capability	Convincibility
		Constellation Size
Maintainable Capability		Serviceable Interfaces
		Retention Lug
Offensive Capability	Hypersonic Missile Capability	Hit Probability
		Range
		Deployment Time
		Supply
		Performance Survivability
	Directed Energy Weapon Capability	Weapon Effectiveness Index
		Deployment Time
		Range
		Performance Survivability
Defensive Capability	Imaging Capability	Laser Rejection Capability
		Performance Survivability
	Communications Capability	Encryption Capability
		Performance Survivability
		Endurance
		Jamming Mitigation
	Command and Control Capability	Encryption Capability
		Performance Survivability
		Endurance

Key:

1. Portfolio-level performance attributes

1.1 2nd-level capability attributes

1.1.1 System-level performance attributes

1. Persistence: the portfolio shall contain assets that provide the “unblinking eye” of persistent ISR, to track targets and maintain situational awareness.

1.1. All Weather Capability: the assets are able to operate and gather intelligence in all weather conditions. Electro-optical systems, for example, cannot penetrate most cloud cover, but radar-based systems can.

1.1.1. Capacity: utility versus the system imaging capacity in terms of utilization.

1.1.2. Endurance: utility versus how long the system could function nominally.

1.1.3. Detection Capability: utility versus the probability of actionable detection in all weather conditions including heavy cloud cover. Electro-optical systems have limited utility in these conditions, but radar has higher performance and utility in these conditions.

1.1.4. Tracking Capability: utility versus the probability of tracking targets through any number of means such as Moving Target Indicator, visual clues, or derived from unique system capabilities.

1.1.5. Field of Regard: utility versus the total area captured by the system per image, as measured by Field of Regard.

1.1.6. Image Quality (NIIRS): utility versus image quality derived from the system, as measured by National Imagery Interpretability Rating Scale (NIIRS).

1.1.7. Pointing Accuracy: utility versus the system’s ability to point reliably at a point of interest on the earth when the collection geometry is within the capabilities of the system.

1.1.8. Revisit Rate: utility versus the frequency of revisiting the same target. This is a function of the number of systems in a constellation and the orbit characteristics.

1.2. Day / Night Capability: the systems are able to operate and gather intelligence day and night.

1.2.1. Capacity: utility versus the system imaging capacity in terms of utilization.

1.2.2. Endurance: utility versus how long the system could function nominally.

1.2.3. Detection Capability: utility versus the probability of actionable detection in all light conditions including low-light. Radar systems are day / night agnostic, and electro-optical systems without infrared capability do not operate effectively at night.

1.2.4. Tracking Capability: utility versus the probability of tracking targets through any number of means such as Moving Target Indicator, visual clues, or derived from unique system capabilities.

1.2.5. Field of Regard utility versus the total area captured by the system per image, as measured by Field of Regard.

1.2.6. Image Quality (NIIRS): utility versus image quality derived from the system, as measured by National Imagery Interpretability Rating Scale (NIIRS).

1.2.7. Pointing Accuracy: utility versus the system's ability to point reliably at a point of interest on the earth when the collection geometry is within the capabilities of the system.

1.2.8. Revisit Rate: utility versus the frequency of revisiting the same target. This is a function of the number of systems in a constellation and the orbit characteristics.

2. Operationally Responsive: the portfolio shall contain assets that provide timely support to emerging Intelligence Community and combatant commander needs.

2.1. Capacity: utility versus the system imaging capacity in terms of utilization.

2.2. Endurance: utility versus how long the system could function nominally.

2.3. Detection Capability: utility versus the probability of actionable detection while minimizing probability of false positive detections.

2.4. Area Coverage: utility versus the area the system or constellation of systems is capable of covering per unit time, such as square-miles per day.

2.5. Deployment Time: utility versus the time required to slew from a neutral state to nominal, imaging functionality.

2.6. Revisit Rate: utility versus the frequency of revisiting the same target. This is a function of the number of systems in a constellation and the orbit characteristics.

2.7. Timeliness: utility versus the time to develop, build, and deploy a purpose-built asset.

3. Multi-INT Capability: as new systems are developed, when practical for the mission and the technologies used, payloads shall feature multiple intelligence types (e.g. geospatial intelligence, signals intelligence) integrated together to achieve cost synergies and synchronize multi-INT collections.

3.1. Signals Intelligence Capability: the systems shall employ signals intelligence capabilities including electronic intelligence and communications intelligence.

3.1.1. Detection Capability: utility versus the probability of actionable electromagnetic frequency detection.

3.1.2. Tracking Capability: utility versus the probability of tracking targets through any number of means such as signal strength triangulation or Doppler shift.

3.1.3. Sensor Cross-Cueing Capability: utility versus the degree of cross-cueing with other sensors in range to gather additional intelligence.

3.1.4. Deployment Time: utility versus the time required to slew from a neutral state to nominal, imaging functionality.

3.1.5. Pointing Accuracy: utility versus the system's ability to point reliably at a point of interest on the earth when the collection geometry is within the capabilities of the system.

3.1.6. Performance Survivability: utility versus the percentage of nominal performance the system can provide in a degraded state.

3.2. Geospatial Intelligence Capability: the systems shall employ geospatial intelligence capabilities including EO/IR multispectral and/or hyperspectral, as well as radar.

3.2.1. Detection Capability: the system shall provide spectral bandpasses that enable intelligence analysts to detect elements of essential information, such as finding materials of interest and detecting human activity.

3.2.2. Tracking Capability: utility versus the probability of tracking targets through any number of means such as Moving Target Indicator, visual clues, or derived from unique system capabilities.

3.2.3. Sensor Cross-Cueing Capability: utility versus the degree of cross-cueing with other sensors in range to gather additional intelligence.

3.2.4. Deployment Time: utility versus the time required to slew from a neutral state to nominal, imaging functionality.

3.2.5. Field of Regard: utility versus the total area captured by the system per image, as measured by Field of Regard.

3.2.6. Pointing Accuracy: utility versus the system's ability to point reliably at a point of interest on the earth when the collection geometry is within the capabilities of the system.

3.2.7. Performance Survivability: utility versus the percentage of nominal performance the system can provide in a degraded state.

4. Concealment and Deception Capability: the portfolio shall include decoy assets to confuse adversaries. Use of “fake news” and information warfare tactics, techniques, and procedures (TTPs) to augment launches of decoys.

4.1. Low-Observable Capability: the systems have stealth features that allow it to operate undetected spectrally and by radar.

4.1.1. Spectral Signature: utility versus the adversary’s ability to detect and track the system by electro-optical / infrared means.

4.1.2. Radar Cross Section: utility versus the Radar Cross Section of the system to reduce likelihood of detection and tracking by adversary tracking systems.

4.1.3. Payload Capacity: utility versus the system imaging capacity that can be concealed from the adversary.

4.2. Concealment Capability: the systems can hide in the line of sight and footprint of other overhead systems, at least temporarily matching the orbit characteristics of the host, allowing the systems to operate without being observed.

4.2.1. Physical Size: utility versus the physical size of the payload that can be concealed from the adversary.

4.2.2. Orbit Matching: utility versus the ability of a system to match the orbit and sit in the line of sight of other space-based systems, either U.S.-owned or other.

4.3. Decoy Capability: fake systems can be fielded to spread misinformation about the true capabilities of the real systems, and draw fire from adversary directed energy systems while real systems shoot oblique imagery of adversary targets.

4.3.1. Convincibility: utility versus the system's ability to convince the adversary via objective means that the decoys are operational assets.

4.3.2. Constellation Size: utility versus the constellation size (number of deployed systems) of decoys.

5. Maintainable Capability: as new portfolio assets are developed, they shall include features for capture by unmanned drone capsule, repairability and upgradeability through modularization.

5.1. Serviceable Interfaces: utility versus the serviceability of the system via modular assemblies capable of being serviced on-orbit.

5.2. Retention Lug: utility versus the ability to capture the system via a retention feature to accommodate positive union between the system and the repair capsule.

6. Offensive Capability: within the bounds of international treaties and law, portfolio assets shall provide kinetic capabilities to shorten the Kill Chain and serve as non-nuclear strategic deterrent.

6.1. Hypersonic Missile Capability: the spacecraft has a complement of hypersonic weapons that can be used as part of a space-based Kill Chain.

6.1.1. Hit Probability: utility versus the ability of the weapon to hit its intended target when deployed.

6.1.2. Range: utility versus the distance at which the weapon can function nominally.

6.1.3. Deployment Time: utility versus the time required to transition from a neutral state to nominal, weapon-deployed functionality.

6.1.4. Supply: utility versus the number of weapons available to system.

6.1.5. Performance Survivability: utility versus the percentage of nominal performance the system can provide in a degraded state.

Figure 66. Artist rendering of space-based missile barrage platform[71]

6.2. Directed Energy Weapon Capability: the spacecraft uses directed energy weapons to dazzle, damage or destroy adversary satellites.

6.2.1. Weapon Effectiveness Index: utility versus the ability to degrade, damage or destroy adversary space-based systems.

[71] https://newsonia.com/report/us-scrambles-to-assemble-space-based-missile-defense-system/, accessed 3/18/2018

6.2.2. Deployment Time: utility versus the time required to transition from a neutral state to nominal, weapon-deployed functionality.

6.2.3. Range: utility versus the distance at which the system can function nominally.

6.2.4. Performance Survivability: utility versus the percentage of nominal performance the system can provide in a degraded state.

7. Defensive Capability: the portfolio shall contain assets that are able to remain mission capable in the presence of enemy threats such as cyber and directed-energy systems.

7.1. Imaging Capability: the imaging systems shall be hardened against laser dazzlers and other directed-energy weapons.

7.1.1. Laser Rejection Capability: utility versus the ability to reject laser sources while passing other wavelengths of the light spectrum, such as via optical filters.

7.1.2. Performance Survivability: utility versus the percentage of nominal performance the system can provide in a degraded state.

7.2. Communications Capability: the communications systems shall be hardened against adversary jamming and hacking.

7.2.1. Encryption Capability: utility versus the ability to secure communications via encryption.

7.2.2. Performance Survivability: utility versus the percentage of nominal performance the system can provide in a degraded state.

7.2.3. Endurance: utility versus how long the system could function nominally.

7.2.4. Jamming Mitigation: utility versus the ability to mitigating adversary jamming, such as by frequency-hopping.

7.3. Command and Control Capability: the command and control systems shall be hardened against adversary attacks.

7.3.1. Encryption Capability: utility versus the ability to prevent adversary from intercepting signal and / or gaining control via encryption.

7.3.2. Performance Survivability: utility versus the percentage of nominal performance the system can provide in a degraded state.

7.3.3. Endurance: utility versus how long the system could function nominally.

Some of the system-level performance attributes were derived from a March 13, 2018 email exchange with Parker Vascik. The rest were defined by the author as unique to this case study.

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Appendix C: Dieffenbacher's Last Theorem

The author hinted in his Biographical Note that he has been fascinated by hard mathematical problems. Reading Wiles' proof of Fermat's Last Theorem and Mochizuki's seemingly brilliant Inter-universal Teichmüller Theory (for any readers who think "Hodge Theaters" are a place to watch movies, stop reading here) have served as a beguiling intellectual hobby for long plane flights to the far ends of the earth. Inspired by a 1990s Scientific American article about prime number "jumping champions," the author began arranging numbers into various geometric patterns in search of some new insight.

Arranging positive integers in the manner shown below, the areas inside the shaded boxes contain only composite (non-prime) numbers. The first three rows in which this phenomenon occurs all contain with single-digit primes (2, 3, 5, and 7). The frequency at which these rows occur starts at 0 and increments by 1. In other words, there are zero rows between the rows beginning with integers 1 and 2, then 1 row gap between rows beginning with integers 2 and 7, then 3 rows, and so on.

1	3	6	10	15	21	28	36	45	55	66	78
2	5	9	14	20	27	35	44	54	65	77	
4	8	13	19	26	34	43	53	64	76		
7	12	18	25	33	42	52	63	75			
11	17	24	32	41	51	62	74				
16	23	31	40	50	61	73					
22	30	39	49	60	72						
29	38	48	59	71							
37	47	58	70								
46	57	69									
56	68										
67											

Figure 67. Spacing of 100% composite number regions

In seeking answers for this phenomenon, the author spoke with MIT Professor Bjorn Poonen, who suggested it resembled an Ulam Spiral. This construct involves a different scheme to arrange the numbers, and is shown below in Figure 68. The Ulam Spiral yields similar, albeit different, "exclusion lines" as depicted in Figure 69. The pattern of lines appears similar to what was shown earlier, suggesting alternative arrangements of numbers seem to yield similar exclusion patterns.

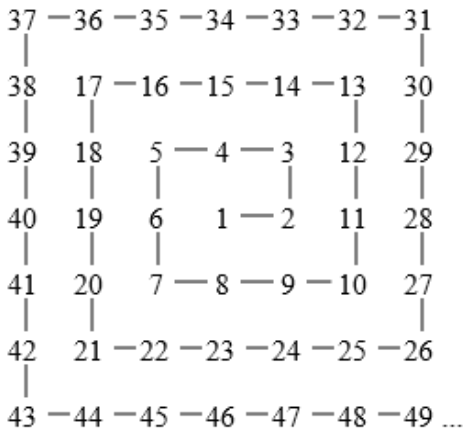

Figure 68. Ulam spiral construction[72]

72

https://upload.wikimedia.org/wikipedia/commons/1/1d/Ulam_spiral_howto_all_numbers.svg, accessed 4/4/2018

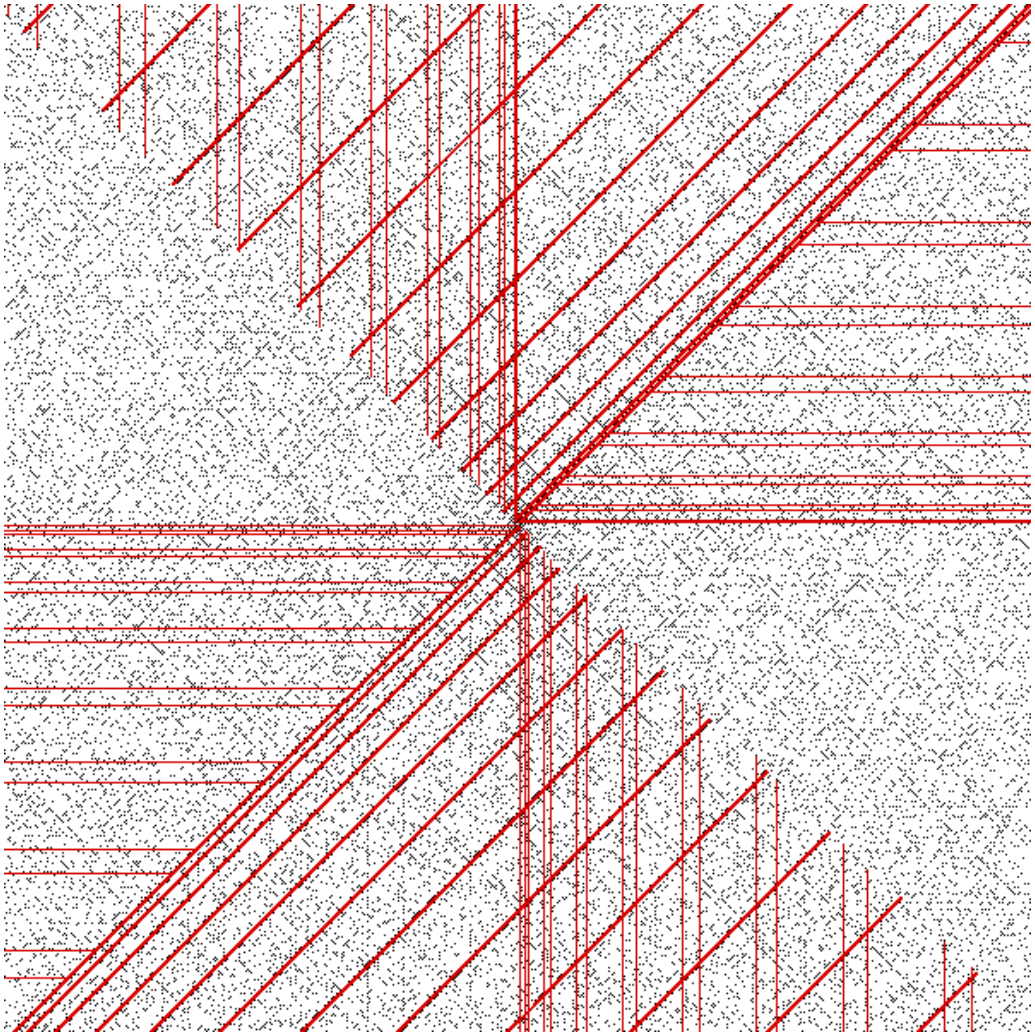

Figure 69. Ulam spiral with "exclusion lines" highlighted[73]

Finally, the author found another interesting pattern. For every prime number, p, draw a box with edge length p. The box of p^2 integers contains $1/p$ numbers that are either the prime or multiples of the prime, for seemingly all primes. That fact by itself is intuitively obvious, but, what appears remarkable is how the pattern is predictable and becomes more intricate with increasing p. The author has shown an example drawn for $p = 3$ in Figure 70, and sketched by hand the pattern's evolution through $p = 13$ in Figure 71. The increasing intricacy is apparent to the naked eye.

[73] http://ulamspiral.com/generatePage.asp?ID=2, accessed 4/4/2018

1	3	6
2	5	9
4	8	13

Figure 70. Example pattern for $p = 3$

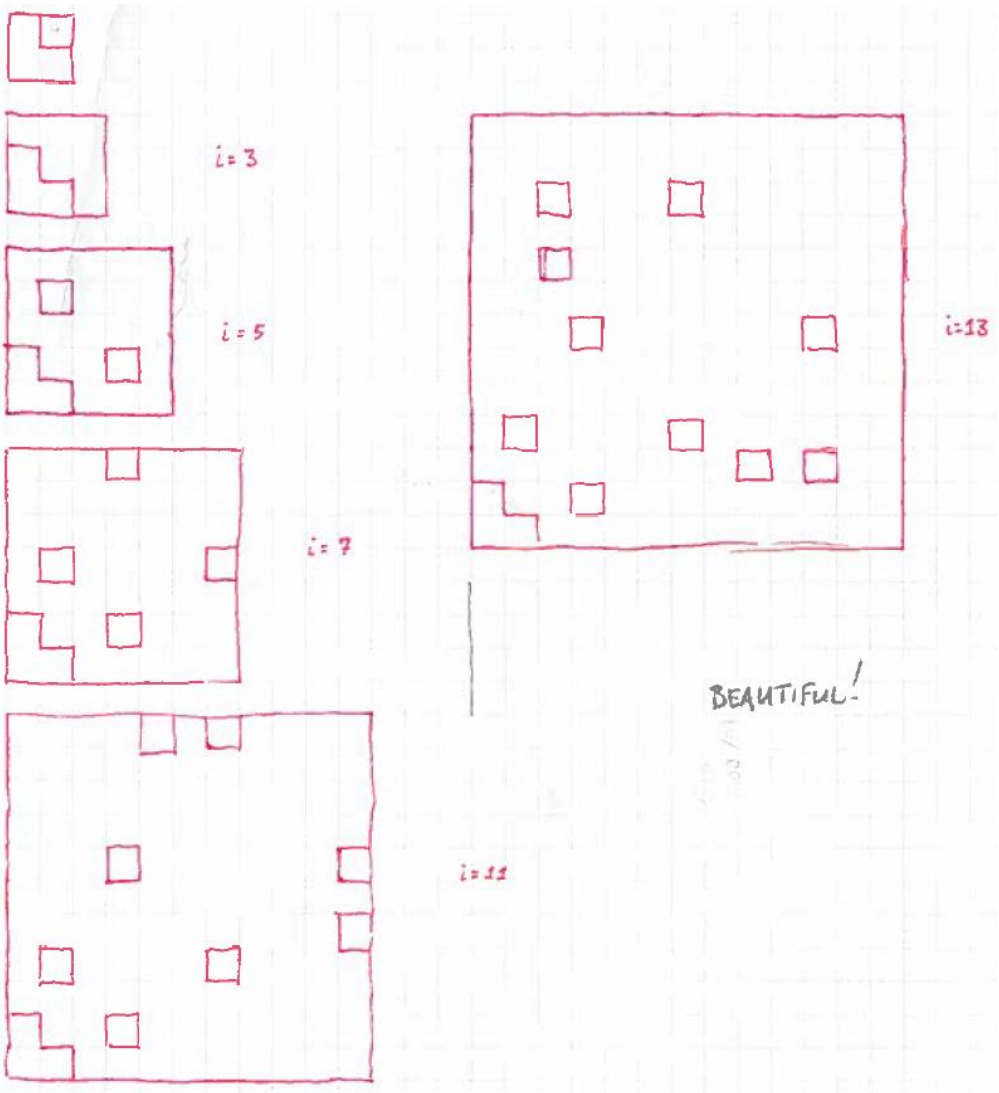

Figure 71. Patterns for $p = 2, 3, 5, 7, 11$, and 13

The author leaves this parting gift for a smarter, well-motivated posterity to analyze and articulate. The beauty of mathematics and science is surely evidence of something

simultaneously wondrous and intensely humbling. The human quest for understanding connects us in an unbroken chain to the Ancients, and will assuredly guide our collective future.

We live in a world of wonder.