



**METHODOLOGY FOR INCLUDING BASE
INFRASTRUCTURE IN CONCEPTUAL
SYSTEM ANALYSIS**

THESIS

Patrick J. Kelly IV, 1st Lt, USAF
AFIT-ENV-MS-19-M-182

**DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY**

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

DISTRIBUTION STATEMENT A
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

The views expressed in this document are those of the author and do not reflect the official policy or position of the United States Air Force, the United States Department of Defense or the United States Government. This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

AFIT-ENV-MS-19-M-182

METHODOLOGY FOR INCLUDING BASE INFRASTRUCTURE
IN CONCEPTUAL SYSTEM ANALYSIS

THESIS

Presented to the Faculty
Department of Systems Engineering and Management
Graduate School of Engineering and Management
Air Force Institute of Technology
Air University
Air Education and Training Command
in Partial Fulfillment of the Requirements for the
Degree of Master of Science in Systems Engineering

Patrick J. Kelly IV, BS

1st Lt, USAF

March 2019

DISTRIBUTION STATEMENT A
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

AFIT-ENV-MS-19-M-182

METHODOLOGY FOR INCLUDING BASE INFRASTRUCTURE
IN CONCEPTUAL SYSTEM ANALYSIS

THESIS

Patrick J. Kelly IV, BS
1st Lt, USAF

Committee Membership:

John M. Colombi, Ph.D.
Chair

Lt Col Clay M. Koschnick, Ph.D.
Member

Maj Jason R. Freels, Ph.D.
Member

Abstract

The 2018 National Defense Strategy defines a transition to agile basing, where the logistics footprint of new conceptual systems can be distributed across a set of airfields, instead of one main operating base. Currently, there is no capability to assess early concepts using airfield data. This research develops a methodology and a tool that assesses system concepts using world-wide civil and military airfield infrastructure, such as runway parameters, parking, munitions, fuel and warehouse storage, and distance to areas of interest. Specifically, the focus of the thesis is on concepts for the Intelligence, Surveillance, and Reconnaissance (ISR) Strike mission. Four concepts were assessed, a Medium-Altitude Long Endurance (MALE) ISR vehicle similar to a MQ-9 Reaper, a light attack aircraft, a light attack jet, and a low-cost attritable aircraft similar to a BQM-167A aerial drone. The tool incorporates Value Focused Thinking, with the value model conditioned by selected design parameters. The system that values a set of airfields the highest would be advantageous in an adaptive basing environment. The MALE ISR platform resulted in a statistically significant difference (nearly 10%) in median value determined by the Wilcoxon signed rank test, then the other systems across a sampled set of 1,197 CONUS airfields.

AFIT-ENV-MS-19-M-182

Dedicated to my Wife and Son.

Table of Contents

	Page
Abstract	iv
List of Figures	ix
List of Tables	xii
List of Abbreviations	xiii
I. Introduction	1
General Issue	1
Problem Statement	3
Scope	3
Research Objectives and Questions	4
Methodology	4
Assumptions and Limitations	5
Preview	6
II. Literature Review	7
Conceptual Design	7
Capability Based Assessment	8
Analysis of Alternatives	9
Military Basing	10
Basing Policies	11
Agile Basing	11
Previous Basing Studies	12
Model-Based Systems Engineering	14
Overview	14
Object-Oriented Systems Engineering Method	15
Summary	18
III. Methodology	19
Object-Oriented System Engineering Method	19
Analyze Stakeholder Needs	19
Analyze System Requirements	21
Define Logical Architecture	22
Synthesize Candidate Logical Architecture	23
Optimize and Analyze Alternatives	24
LOGICAT Analysis Overview	25
Value Model	25
Conditional Value Model Example	29

	Page
IV. Application	34
Tool Verification	34
Verify and Validate System	34
Value Model Verification	36
Scenario	38
Conceptual Systems	38
Airfield Selection	40
MALE ISR Conceptual System	41
Vehicle Description	41
Results	42
Light Attack Propeller Aircraft Conceptual System	46
Vehicle Description	46
Results	47
Light Attack Jet Conceptual System	49
Vehicle Description	49
Results	50
LCAAT Conceptual System	53
Vehicle Description	53
Results	55
Comparative Analysis	57
Sensitivity Analysis	63
Summary	64
V. Conclusion and Recommendations	65
Conclusion	65
Future Work	67
Aerospace Design	67
Value Model	68
Data	69
Cost and Performance	70
Summary	70
Appendix A Conceptual Deployed Basing; CONOPS	72
Appendix B Value Hierarchy	74
POLs	75
Runways	81
Location	92
Parking	96
Munition Storage	99
Warehouse Area	100

	Page
Appendix C Additional Figures	102
MALE ISR Conceptual System	102
Light Attack Propeller Conceptual System	113
Light Attack Jet Conceptual System	124
LCAAT Conceptual System	135
Bibliography	146

List of Figures

Figure	Page
1	Illustrative System Lifecycle 2
2	Commitment, system-specific knowledge and cost 2
3	JCIDS interaction with the DAS 7
4	Exploratory Tool Study Findings 10
5	MITRE’s Emerging, Integrated, Interdisciplinary Engineering Environment 14
6	OOSEM Specify and Design System Process 16
7	LOGICAT Use Case Diagram 20
8	Concept Assessment 21
9	LOGICAT Logical Elements 22
10	LOGICAT Data Architecture 23
11	An overview of using the LOGICAT 26
12	Value Model 27
13	Runway Length Value Function 30
14	LOGICAT Value Airfields View 35
15	LOGICAT Verification Sequence Diagram 36
16	LOGICAT Value Model Verification MQ-9 37
17	LOGICAT Value Model Verification C-5 38
18	MQ-9 Reaper 42
19	MQ-9 Colormap of Representative Airfield Set 43
20	MQ-9 Tornado of Representative Airfield Set 44
21	MALE ISR System Monte Carlo Analysis Results 45
22	A-29 Super Tucano 46

Figure		Page
23	LA Propeller Colormap of Representative Airfield Set	47
24	LA Propeller Tornado of Representative Airfield Set	48
25	LA Propeller System Monte Carlo Analysis Results	49
26	Textron AirLand Scorpion	50
27	LA Jet Colormap of Representative Airfield Set	51
28	LA Jet Tornado of Representative Airfield Set	52
29	LA Jet System Monte Carlo Analysis Results	53
30	LCAAT	54
31	LCAAT Colormap of Representative Airfield Set	55
32	LCAAT Tornado of Representative Airfield Set	56
33	LCAAT System Monte Carlo Analysis Results	57
34	CDF of Airfield Value for all four Systems	58
35	CDF of Airfield Value for all four Systems Example	59
36	PDF of all Evaluated Designs	60
37	Logarithmic Transformed PDF	61
38	Distribution of Differences between MALE ISR and LCAAT Systems	62
39	Sensitivity Analysis around the Location Branch	64
40	Value Model	74
41	Fuel Capacity Value Function	77
42	Fuel Resupply Value Function	79
43	Runway Length Calculation for a Small Aircraft	84
44	Runway Length Calculation for a Large Aircraft	85
45	Runway Width Value Function	86

Figure		Page
46	Taxiway Width Value Function	91
47	Distance Value Function	93
48	Elevation Value Function	95
49	Hangar Area Value Function	98

List of Tables

Table		Page
1	OOSEM Development Activities, Descriptions, and Examples (Friedenthal <i>et al.</i> , 2007)	17
2	Value Model Measures, Value Functions and Global Weights	28
3	Airfield Parameters and System Parameters	32
4	Specific Parameters of Evaluated Vehicles	40
5	Summary of Airfield Data	41
6	Runway Surface Value Function	88

List of Abbreviations

Abbreviation	Page
SECAF	Secretary of the Air Force 1
NDS	National Defense Strategy 1
LCC	Life Cycle Costs 1
O&S	Operations & Support 1
ODASD(SE)	Office of the Deputy Assistant Secretary of Defense for Systems Engineering 1
DES	Digital Engineering Strategy 1
MBSE	Model-Based Systems Engineering 1
OCONUS	Outside the Continental United States 3
FOL	Forward Operating Location 3
ISR	Intelligence Surveillance and Reconnaissance 3
OOSEM	Object-Oriented Systems Engineering Method..... 4
LOGICAT	Logistics and Base Infrastructure Concept Assessment Tool 4
NGA	National Geospatial-Intelligence Agency 4
AAFIF	Automated Air Field Intelligence Files 4
JROC	Joint Requirements Oversight Council..... 7
JCIDS	Joint Capabilities Integration and Development System 7
DAS	Defense Acquisition System..... 7
CBA	Capability Based Assessment 7
ICD	Initial Capability Document 7
DOTMLPF-P	Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, Facilities and Policy 8

Abbreviation		Page
MDD	Material Development Decision	8
AoA	Analysis of Alternatives	8
AF	Air Force.....	11
AFPD	Air Force Policy Directives	11
AFI	Air Force Instructions.....	11
BAS&E	Base Support and Expeditionary	11
OO	Object-Oriented.....	11
VFT	Value-Focused Thinking	13
INCOSE	International Council on Systems Engineering	14
CONOPS	Concept of Operations	21
AOI	Area of Interest	23
API	Application Programming Interface	24
MTOW	Maximum Takeoff Weight	29
AC	Advisory Circular	30
LA	Light Attack.....	39
LCAAT	Low Cost Attritable Aircraft Technology	39
CONUS	Continental U.S.	40
AOR	Area of Responsibility	40
AFRL	Air Force Research Laboratory	53
UTAP	Unmanned Tactical Aerial Platform	53
KS	Kolmogorov-Smirnov	60
MODA	Multi-Objective Decisions Analysis	65
MOG	Maximum on Ground	70
POLs	Petroleum, Oils and Lubricants	75

Abbreviation		Page
MTOW	Maximum Take Off Weight	81
LCN	Load Classification Number	87
ACN	Aircraft Classification Number	87
ToT	Time-over-Target	92
TTT	Time To Target	92

METHODOLOGY FOR INCLUDING BASE INFRASTRUCTURE IN CONCEPTUAL SYSTEM ANALYSIS

I. Introduction

General Issue

The Secretary of the Air Force (SECAF) has challenged the acquisition community by making one of her top priorities to cost effectively modernize the force for lethality (Wilson *et al.* , 2017). Historically, cost is in competition with schedule and performance, yet the 2018 National Defense Strategy (NDS) discusses prioritizing speed of delivery, continuous adaptation, and frequent modular upgrades over cost.

Figure 1 shows that the majority the Life Cycle Costs (LCC) occur later in the life cycle, during the Operations & Support (O&S) phase. However, Figure 2 shows that most of the decisions that impact the O&S costs are made early in the life cycle. With pressing schedule and budget constraints, the Air Force needs to acquire weapon systems faster and cheaper. With the majority of LCC coming from the O&S phase, logistics and infrastructure constraints need to be considered during the earliest stages of conceptual design. With the direction to develop the next generation of weapon systems with the modularity to adapt and incorporate the latest technology as fast as possible, the Office of the Deputy Assistant Secretary of Defense for Systems Engineering (ODASD(SE)) created a Digital Engineering Strategy (DES) to promote Model-Based Systems Engineering (MBSE) to meet the challenges of the SECAF and the NDS.

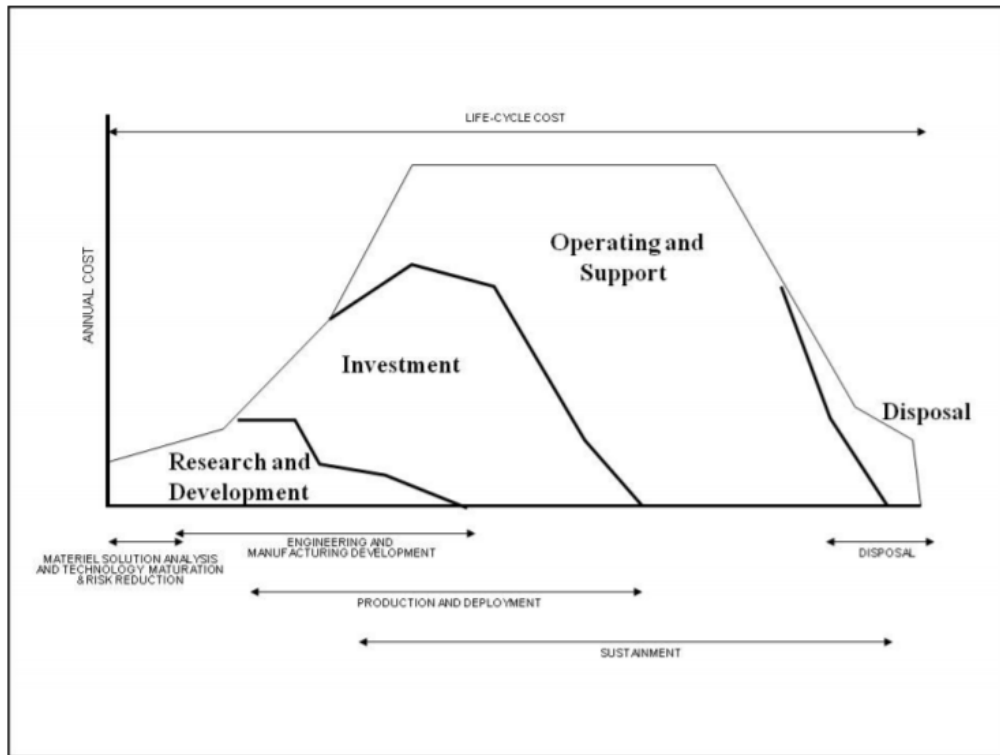


Figure 1. Illustrative System Lifecycle (CAPE, 2015)

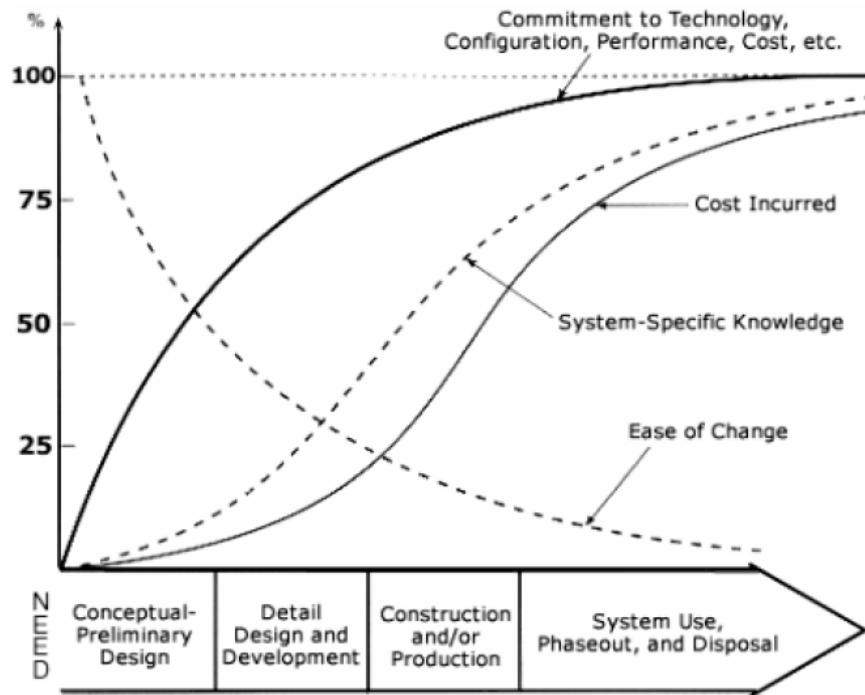


Figure 2. Commitment, system-specific knowledge and cost (Blanchard & Fabrycky, 1998)

Problem Statement

Currently the process for selecting an airfield to base a military weapon system happens late in the acquisition cycle, and there is no current process to identify and assess potential aircraft basing locations in a quantifiable and objective manner while considering base infrastructure. Without a refined process, decisions are often made exclusively by operators without cross-functional capability considerations (Way, 2018).

The transition from large, centralized, unhardened infrastructure to smaller, dispersed, resilient, adaptive basing needs to be considered in future weapon systems (DoD NDS, 2018). Discussed further in Chapter II, adaptive basing adds both flexibility and challenges to the logistics community. If the current or planned infrastructure is considered earlier in the design process, then potential savings could be realized by reducing unnecessary or unplanned infrastructure improvements and allowing for more efficient basing decisions.

Scope

To narrow down the endless possibilities of all weapon systems at all airfields, the sponsor of this research is interested in evaluating weapon system concepts for use at potential OCONUS Forward Operating Location (FOL) bases, with regards to typical operations from the FOL. However, in order to demonstrate the analysis easily, the scenario discussed in this report is focused on airfields within the United States. To further refine the scope, this research is focused on evaluating future concept weapon systems responsible for the medium-altitude Intelligence Surveillance and Reconnaissance (ISR) Strike mission set.

Research Objectives and Questions

The objective of this research is to develop a methodology for evaluating a conceptual system across the physical basing environment in which the system will likely operate. To achieve this objective, the following research questions need to be answered.

1. How can capability planning analysts evaluate competing conceptual designs, including realistic base infrastructure constraints?
2. What parameters need to be modeled for a conceptual weapon system and with what level of fidelity?
3. What airfield and logistic parameters need to be included, and how can they be related to the concept weapon system parameters?

Methodology

The Object-Oriented Systems Engineering Method (OOSEM) will be used to create the Logistics and Base Infrastructure Concept Assessment Tool (LOGICAT) that was developed to assess conceptual weapon systems on current base infrastructures. To develop this tool, this research will start with collecting base data, organizing and aggregating information from the National Geospatial-Intelligence Agency (NGA) Automated Air Field Intelligence Files (AAFIF) database (National Geospatial-Intelligence Agency, 2019). After gathering the data, the next step is to create a framework to model the conceptual weapon system. Value-Focused Thinking is applied so that various types of weapon systems can be evaluated over multiple airfields. After creating a value model, various vehicle types are evaluated across a set of airfields for a given scenario. Finally, stochastics are added to the model and

a Monte Carlo analysis captures the undefined variability in the conceptual weapon system.

Assumptions and Limitations

For the purpose of this research there are several assumptions:

- All the airfields considered are completely available for use; thus, the politics for resources, country access, environmental concerns, country overflight and munition storage are not constraints.
- Weather is also assumed out of this research. Weather patterns are important in airfield planning. Organizing, cleaning and understanding this data would fall out of the scope of this research.
- The stochastic sampling of conceptual system parameters stays within a feasible design space. The addition of more accurate aerospace parameters and their relationship is discussed in Chapter V. For conceptual planning and design, the low fidelity model is assumed to be feasible.
- Cost will not be used in the assessment of conceptual weapon systems. The LOGICAT can be used to assess various systems, and the data created from the analysis can be used to feed various cost models. Introducing cost into the analysis is discussed in Chapter V.

The unclassified AAFIF data set is highly redacted and resulted in missing data, which limited the number of airfield parameters considered for this research. The MATLAB GUI developed for this research has a scripted data ingest feature, and should be able to easily ingest a new data set with more complete data. The value model developed for this research is notional and only created to demonstrate the

methodology. The value measures in this model consist only of categorical, or linear functions, with even steps and weights through out for a simple demonstration and would need to be recalculated for further analysis.

Preview

Chapter I provided the background to the topic area and introduced the problem. Chapter II will discuss the current research, approaches, and methodologies used in concept evaluation and basing analysis. Chapter III discusses the application of the OOSEM in the development of the LOGICAT system. Chapter IV provides verification of the tool and value model, demonstrates the analysis by evaluating four conceptual designs with the tool, then compares the four conceptual systems results. Chapter V will conclude the results and the significance of the results. Chapter V will also provide recommendations for future research.

II. Literature Review

This chapter describes the background for this thesis. As this research is focused on the development and analyses of future weapon systems early in the life cycle, it made sense to start with a review of the early life cycle processes. Next, the current military basing policy and previous research is reviewed to see what is currently being done and how it could be used to constrain the design of a new system. Finally MBSE is reviewed within the DES.

Conceptual Design

The Joint Requirements Oversight Council (JROC) uses the Joint Capabilities Integration and Development System (JCIDS) to identify and validate key capability gaps for the warfighter (Joint Chiefs of Staff, 2018). JCIDS is the starting point for a potential new system to enter the Defense Acquisition System (DAS). Figure 3 depicts the JCIDS and how the needs identification and solution fits into the DAS.

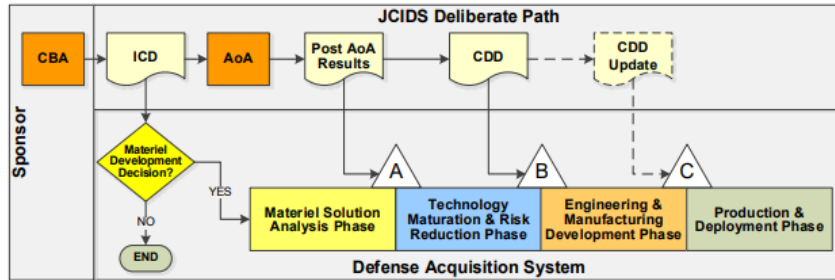


Figure 3. JCIDS interaction with the DAS (Department of Defense, 2018)

There are four main steps in the JCIDS process, two of which occur before Milestone A of the DAS and fall within the scope of this research. The JCIDS process starts with the Capability Based Assessment (CBA), which leads to the creation and approval of the Initial Capability Document (ICD). This ICD leads to either a

Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, Facilities and Policy (DOTMLPF-P) change or Material Development Decision (MDD). If a MDD is approved, an Analysis of Alternatives (AoA) is conducted during the Material Solution Analysis phase of the DAS.

The Air Force has embraced the ISR mission. General Welsh outlines the importance of ISR in the mission Global Vigilance, Global Reach, Global Power for America:

“Today, the Air Force has embraced globally integrated ISR as one of the Air Forces feature calling cards. ISR is much more than a support function. It is the foundation upon which every joint, inter-agency, and coalition operation achieves success” (Welsh, 2016).

With the ISR mission serving as the foundation of operational success, the systems that provide this capability will continue to be analyzed through the CBA and AoA analyses.

Capability Based Assessment.

The CBA serves as the starting point for a new system by assessing a mission and the DoD’s ability to complete it. The CBA formally documents any capability gaps and analyzes potential materiel and non-materiel solutions (Office of Aerospace Studies, 2014). The gaps identified fall into one of four categories:

- Recapitalization: solutions with no significant capability improvements (e.g. reopening the C-5 line in the 1980s);
- Evolutionary: solutions that upgrade existing capabilities (e.g. replacing the KC-135R tanker with a newer aircraft);
- Transformational: solutions that radically change the mix of capabilities (e.g.

conducting loitering surveillance and precision-guided weapons delivery from a single Reaper UAV); and

- Information: systems or transient solutions that have very limited lifespans (e.g. constantly revising computer network defense and attack methods).

Once the gaps have been identified, the study team analyzes the non-materiel solutions of the DOTMLPF-P for solutions that could partially or completely mitigate the gaps. If the analyses shows that a non-materiel solution cannot mitigate the gaps to an acceptable risk level, material solutions are considered. Previous versions of the instructions supported an in-depth solution analysis; this guidance has been revised to leave the solution analysis to the AoA after a MDD has been made (Office of Aerospace Studies, 2014).

Analysis of Alternatives.

The Requirement Development Handbook defines an AoA as “an analytical comparison of the operational effectiveness, suitability, risk, and life cycle cost of alternatives under consideration to satisfy validated capability needs” (Directorate of Operational Capability Requirements, 2018). To conduct this assessment, scenarios are developed to provide an operational picture for the systems to be considered.

The AoA compares alternatives in four categories; operational effectiveness; suitability, risk; and life cycle cost. The primary objective of the AoA is to identify the trade space through life cycle cost, schedule, performance, and risk analysis. The analysis needs to clearly identify the trade-offs that were evaluated, the operational risk associated with the performance, and to what degree the capability gap(s) are to be mitigated. The PERDUCO Group conducted a study on the current state of modeling and simulation tools available (The PERDUCO Group Inc., 2018). Figure 4 highlights that there are limited tools available for exploratory or conceptualization

of concepts. With more tools available in the early stages of conceptual analysis, a quantifiable and consistent analysis can occur. More on the need for tools is discussed in the MBSE section below.

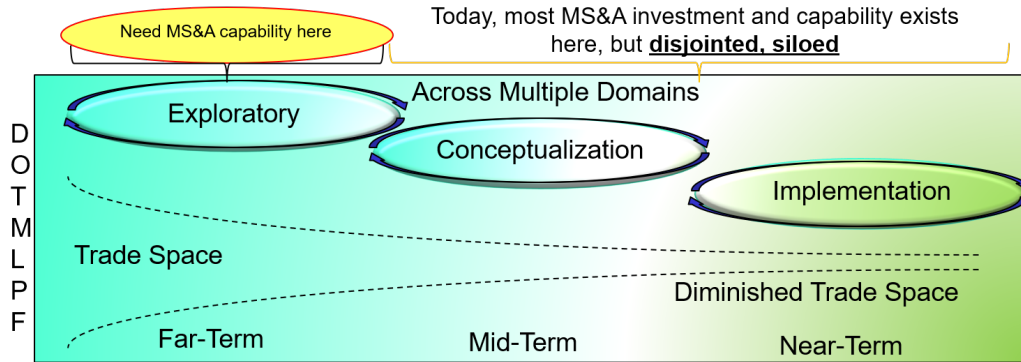


Figure 4. Exploratory Tool Study Findings (The PERDUCO Group Inc., 2018)

Military Basing

A review of military basing policy, doctrine, and previous basing research led to the understanding that basing is not used as a constraint in the conceptual design despite the importance of base infrastructure and the performance of a system described below:

“The integral relationship between an air base and the effective projection of air power was realized by Gen. Henry “Hap” Arnold in 1941. General Arnolds ideas were later translated into Air Force doctrine that stated, ‘Few effective missions can be launched without a mission-capable aircraft; a fed and rested crew; fuel, weapons, command, control and communications; a usable runway; and a secure, uncontaminated base from which to operate.’” (Dammeier *et al.* , 2016)

To project air power, the right weapon systems need to be able to operate from the right airfields. Currently, airfields are adjusted to meet the needs of a system, but if a system has yet to be built, it could be shaped to meet the needs of the mission within the constraints of the current airfields.

Basing Policies.

After reviewing AF doctrine, AFPDs, and AFIs, several points became clear in the current way basing decisions are made. The first relates to digital engineering and the second relating to the timing of basing analysis.

Before base decisions are made, multiple working groups meet to discuss and review site surveys (Department of the Air Force, 2018). These site surveys are document driven and live on digital tools such as the BAS&E Site Planning tool. The BAS&E tool does not allow, at least on the unclassified level, for full reports on multiple airfields to be generated. Some spreadsheet views currently exist but only present limited information. In a digital environment, instead of appointing someone to maintain the document through slow and costly sight surveys, a Object-Oriented (OO) model is created. This model can then be quickly utilized across the Air Force for multiple purposes besides base planning, such as concept development.

The next key point identified was that the basing policy documents are all focused on current vehicles. This makes sense in that when designing and building a new airfield it should be designed to operate the primary vehicle with room for growth (Department of the Air Force, 2013b). But it also highlights that basing considerations for a new system don't occur until after the early conceptual design and analysis of alternatives are concluded (Department of the Air Force, 2006b, 2017, 2013a).

Agile Basing.

Agile basing is the disaggregation of forces from one centralized, large airbase to several smaller airbases. Agile basing protects U.S. forces from enemy attack by basic probability. By adding additional choices, it is less likely that any one airfield has a valuable weapon system at any one time. Owen refers to this as the shell game with each vehicle representing the pea, and each airfield or even parking

spot representing a possible shell (Owen, 2015). This strategy also allows for the basing posture to become more resilient to weather or political factors by providing immediate alternating operating locations when necessary.

The drawback to agile basing is the increased workload on the logistics force. If all of the systems are located at one large operating base, the logistics force only needs to move supplies and set up facilities for one location. Once the vehicles are spread out, the support needs to spread out. The politics and physical transportation and storage of supplies now all need to be addressed across multiple locations.

Previous agile basing has been seen in sea basing efforts (Owen, 2015),

“Sea basing is the deployment, assembly, command, projection, reconstitution and reemployment of joint combat power from the sea without reliance on land bases within the [Joint Operating Area]. ...Sea basing also provides operational maneuver for ship-to-shore movement and assured access to the joint force during the action phase of amphibious operations while significantly reducing the footprint ashore, and minimizing the permissions or authorizations required to operate from host nations” (Weisz, 2012).

Sea basing in support of an on-shore agile basing operation can help mitigate the additional workload of an agile basing approach, but it’s not considered in this researchers application.

Previous Basing Studies.

Vick and Heim evaluate the current basing options against multiple scenarios in East Asia. They analyzed the currently utilized airbases and an additional 30 potential airbases; comparing threat of enemy attack, overflight requirements and force structure demand. They found that the current posture is not resilient to enemy attack or overflight restrictions, and that additional basing should be considered (Vick & Heim, 2013).

Narayanan et al. optimized the F-35a basing locations to meet training requirements while minimizing costs associated with those training actions. This study looked at the location of the base and the cost associated with flying the vehicle and sending enough support equipment to the training exercise. It did not consider the current base infrastructure, instead assuming that potential candidate bases were feasible basing options (Narayanan *et al.* , 2016).

Miravite Jr. and Schlegel created a Microsoft Excel GUI and VFT model to show limitations of the current transportation En Route System. The model evaluated airfields value toward the Rapid Global Mobility mission. This model however is built only on the use of a C-17 and it is not flexible to compare multiple types of aircraft (Miravite *et al.* , 2006).

Baker optimized the basing locations for C-17s based on 10 years of previous flights. This study only considered the current bases used and previous flights. It did not expand into additional base options and simply looked to minimize the hours flown as a estimate for cost (Baker, 2014).

Mouton and Grissom developed a tool to identify the robustness of a basing posture to the loss of one or two basing options. They discussed the politics in play with overseas basing actions, including the use of UAVs as well as armed overflight, and how this can result in the lost of access to a currently used airfield. Their tool identified potential locations to add an airfield to maintain current operations support. This tool did not look at existing airfields or logistic factors involved when recommending new locations (Mouton & Grissom, 2018).

The reviewed studies highlight that previous efforts have been focused on a single current weapon system and how to adjust the base posture; but not how to create a system that can provide a resilient basing posture. The creation of a new system that starts with a system architecture and model can allow for base infrastructure to

be considered earlier in the design process.

Model-Based Systems Engineering

Overview.

The DoD defines digital engineering as an “integrated digital approach that uses authoritative sources of system data and models as a continuum across disciplines to support life cycle activities from concept through disposal” (ODASD(SE), 2018). As a system grows from a concept to an operating system, one model can be refined and expanded throughout the life cycle.

This model, in a integrated digital environment, creates a digital thread for the system. All the data, analysis, and decisions made during the life of the system are pulled forward by the model, making necessary information available during all stages of the system life cycle. Figure 5 shows how an integrated systems engineering model can be the bridge to ensure continuity between all other engineering activities.

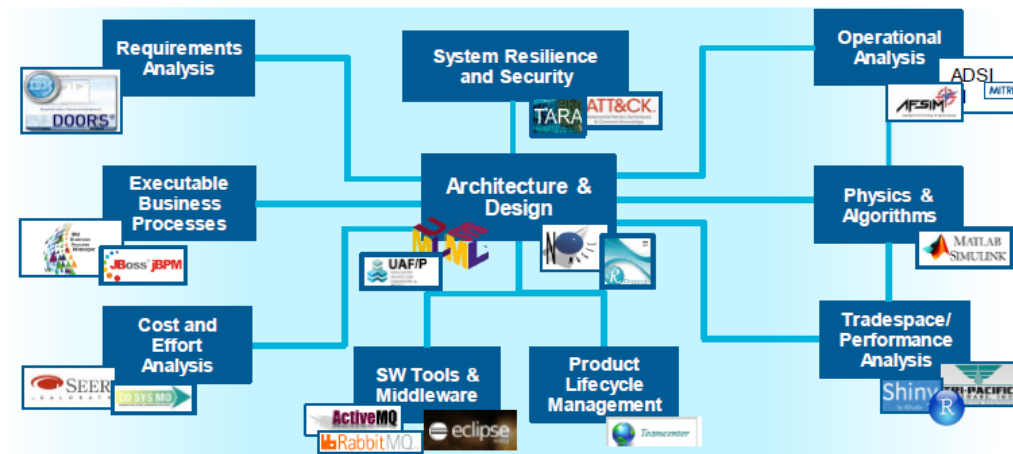


Figure 5. MITRE’s Emerging, Integrated, Interdisciplinary Engineering Environment (Wheeler, 2016)

The DES describes the “what” but does not mandate or define the “how” to accomplish this strategy. The International Council on Systems Engineering (INCOSSE)

defines MBSE as:

“The formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases. (INCOSE, 2015)”

This definition shows that MBSE can be the “how” in accomplishing the DES goals, which are:

1. Formalize the development, integration, and use of model to inform enterprise and program decision making
2. Provide an enduring, authoritative source of truth
3. Incorporate technological innovation to improve the engineering practice
4. Establish a supporting infrastructure and to perform activities, collaborate, and communicate across stakeholders
5. Transform the culture and workforce to adopt and support digital engineering across the life cycle

To better understand MBSE and its place within the DES and conceptual design, a review of the OOSEM is provided next.

Object-Oriented Systems Engineering Method.

OOSEM is a flexible and extensible top-down systems engineering method that is used for system design and evolution. (Friedenthal *et al.* , 2009a) It is applicable to the main system as well as the supporting systems around it. INCOSE defines OOSEM as:

“An MBSE method used to specify and design systems. These include not only the operational system such as an aircraft or an automobile but also systems that enable the operational system throughout its life cycle, such as manufacturing, support and verification systems” (INCOSE, 2015).

The steps of OOSEM to specify and design systems are depicted in Figure 6 and further explained by Estefan in Table 1.

OOSEM was developed from the OO software design process, which makes the OOSEM easily applicable as our systems become more software dependent (Friedenthal *et al.* , 2009a), and we transition to a model based, digital environment.

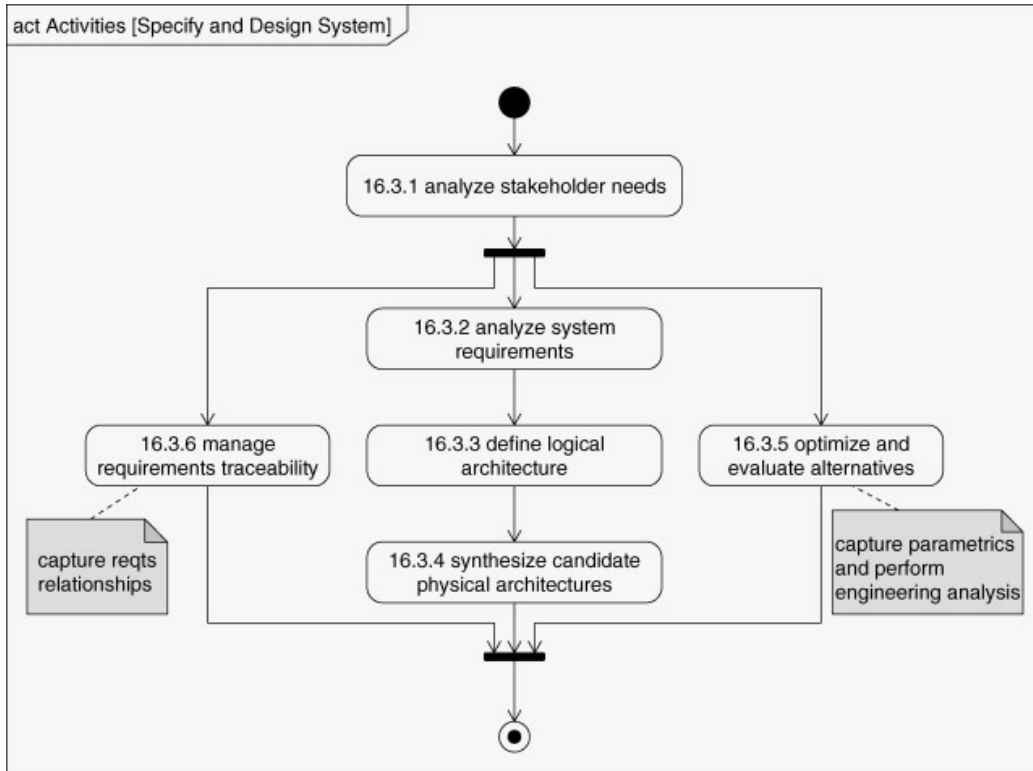


Figure 6. OOSEM Specify and Design System Process (Friedenthal *et al.* , 2009b)

The objectives of the OOSEM as defined by INCOSE are as follows:

- Capture information throughout the life cycle sufficient to specify, analyze, design, verify, and validate systems,

Table 1. OOSEM Development Activities, Descriptions, and Examples (Friedenthal *et al.* , 2007)

Activities	Description	Examples
Analyze Stakeholder Needs	Captures the as-is systems and enterprise, their limitation and potential improvement areas.	Causal analysis Mission use cases/scenarios Enterprise model
Define System Requirements	Intended to specify system requirements that support the mission requirements. System is modeled as a black box that interacts with external systems and users represented in enterprise model.	System use cases/scenarios Elaborated context Req'ts diagram
Define Logical Architecture	Includes decomposing and partitioning system into logical components that interact to satisfy system requirements.	Logical decomposition Logical scenarios Logical subsystems
Synthesize Candidate Allocated Architectures	Allocated architecture describes relationships among physical components of system including hardware, software, data and procedures.	Node Diagram HW, SW, Data arch System Deployment
Optimize and Evaluate Alternatives	Invoked throughout all other OOSEM activities to optimize candidate architectures and conduct trace studies to select preferred architecture. Parametric models for modeling performance, reliability, availability, life-cycle cost, and other specialty engineering concerns, are used to analyze and optimize candidate architecture to level needed to compare alternatives. Criteria and weighting factors used to perform trade studies are traceable to system requirements and measures of effectiveness. Also includes monitoring of technical performance measures and identifies potential risks.	Parametric diagram Trade study
Manage Requirements Traceability	Invoked throughout other OOSEM activities to ensure traceability between requirements, architecture, design, analysis, and verification elements.	Requirements diagram
Validate and Verify System	Intended to verify that system design satisfies its requirements and to validate that requirements meet stakeholder needs. It includes development of verification plans, procedures, and methods (e.g., inspection, demonstration, analysis, and test).	Test system Test cases

- Integrate MBSE methods with object-oriented software, hardware and other engineering methods,
- Support system-level reuse and design evolution.

Like all SE methods, the OOSEM should be tailored to fit the current project, to focus on the specific system, system of systems, project needs, or constraints (Friedenthal *et al.* , 2007).

Summary

This chapter provided an overview of JCIDS, a review of military basing policy and studies, and concluded with an overview of the DES and the OOSEM. The OOSEM is ideal for this thesis because its flexibility and software background allows an OOSEM model to serve as an ideal starting point for a new system in a DE environment, or a new tool to evaluate conceptual systems.

III. Methodology

This chapter describes the first five steps in the OOSEM as it was used to develop a tool to introduce base infrastructure into conceptual design. Then an overview of the methodology to use the tool to assess conceptual systems is provided. The last section explains the built-in conditional value model and provides an example. The final step of OOSEM, validate and verify the system, is discussed in the application of the tool in Chapter IV.

Object-Oriented System Engineering Method

The seven steps of OOSEM are; *analyze stakeholder needs, analyze system requirements, define logical architecture, synthesize candidate logical architecture, optimize and analyze alternates, manage requirements traceability, verify and validate system.* Manage requirements traceability is not included in this research. This activity is ongoing throughout the systems life cycle and can be used to evaluate the impact of changing requirements. The other six steps are applied to the creation of the LOGICAT, which can be used to assess a conceptual weapon system on current base infrastructure.

Analyze Stakeholder Needs.

This activity is intended to provide the analysis to understand the stakeholder problems to be solved and to specify the mission-level requirements that must be satisfied.

To understand the stakeholder needs, the analysis begins with the “as-is” system and identifies what mission requirements are missing; this identifies the “to-be” system. In the case of conceptual analysis, the “as-is” processes does not include a tool

to analyze base infrastructure. Any base information is currently available for an individual base and nothing exists that allows the analyst to examine multiple bases at once. It is in this step that the enterprise use cases are developed to define the “to-be” system. For this research the use cases are depicted in Figure 7.

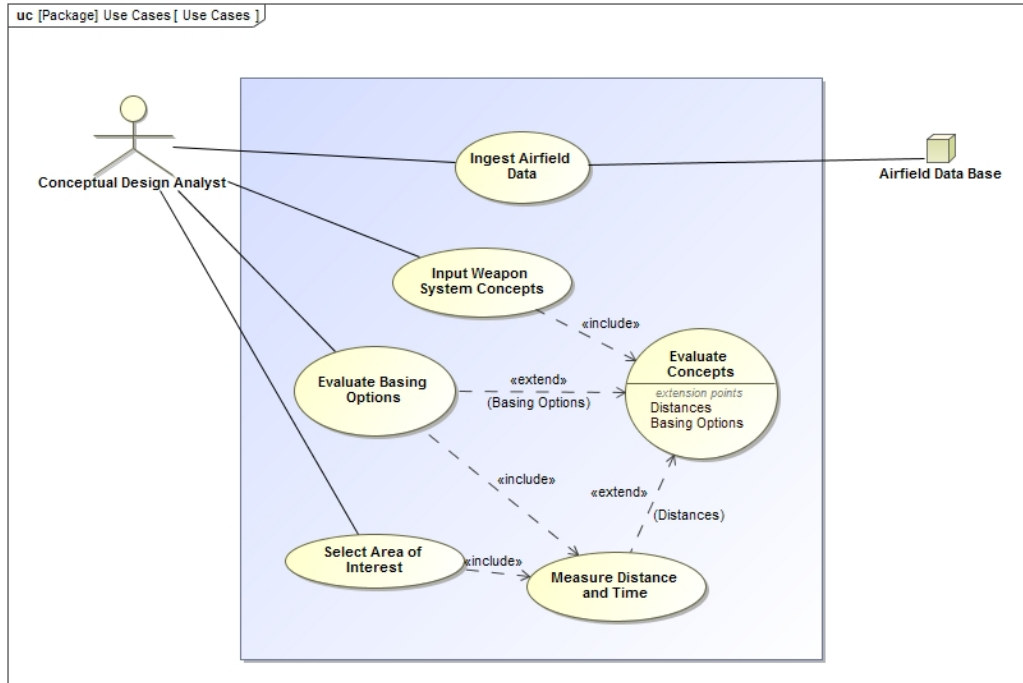
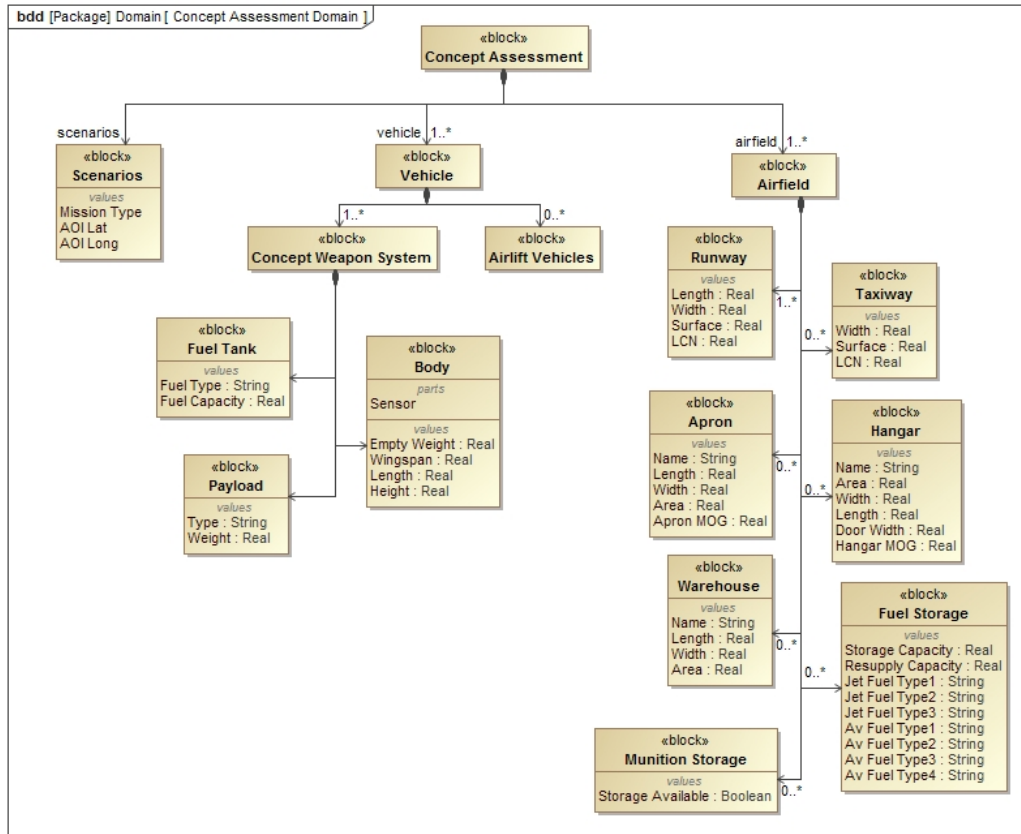


Figure 7. LOGICAT Use Case Diagram

For this research the “to-be” domain is one where the conceptual design analysts is able to evaluate a conceptual system across a set of base infrastructures at once, and it is depicted in Figure 8. The analysts can evaluate the conceptual model in the tool and visualize the potential basing options or constraints going forward.



Analyze System Requirements.

This activity specifies the system requirements, treating the system as a black box. An enterprise scenario is defined and used to evaluate the system. The enterprise scenario for this research is the need to evaluate a concept system across the base infrastructure. Appendix A includes the Concept of Operations (CONOPS) for this research provided by the sponsor. This CONOPS captures the requirements for the tool to evaluate USAF, DoD and commercial base infrastructure, to include runway length, ramp space, hangar space and fuel availability. These airfield parameters and their relationship to the concept parameters are discussed further in the value model section of this chapter.

Define Logical Architecture.

This activity decomposes the system into logical elements, the LOGICAT systems logical elements can be seen in Figure 9.

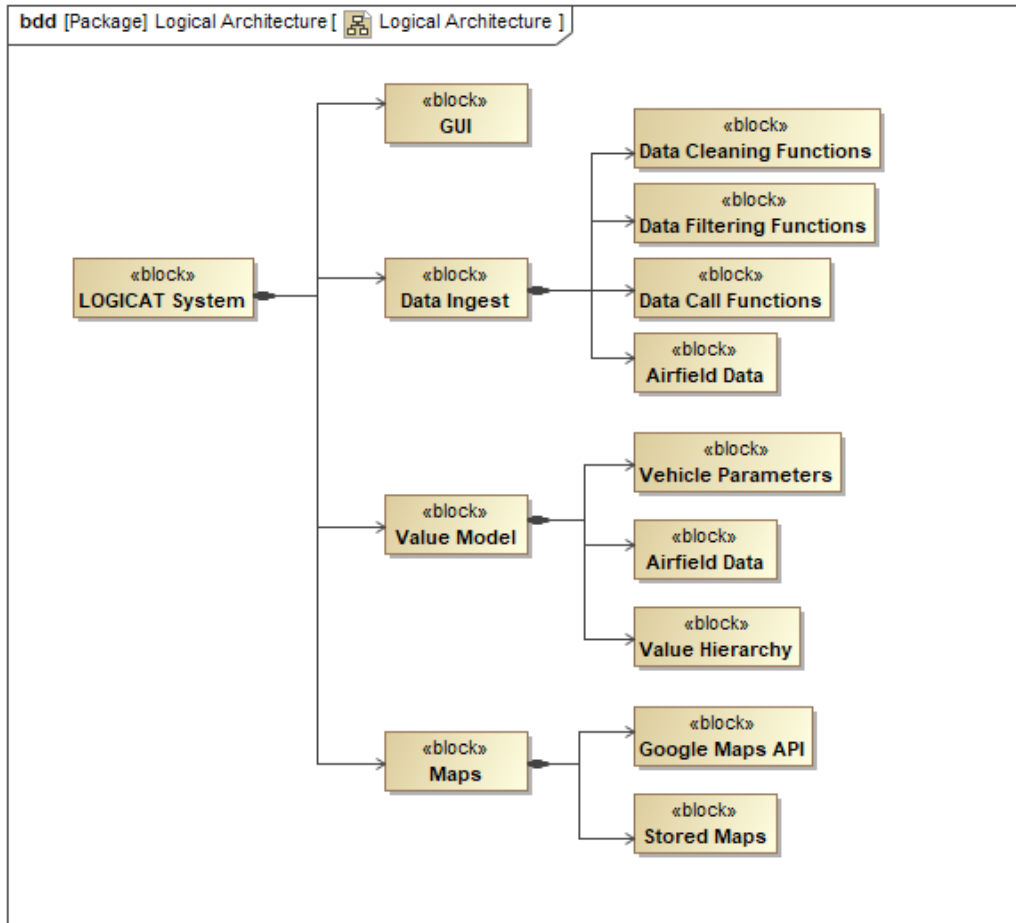


Figure 9. LOGICAT Logical Elements

The requirement for the tool to evaluate all DoD, USAF and commercial base infrastructure created the need for the tool to be able to ingest large amounts of base data. This need is met through the ingests base data functions and the interaction with the AAFIF database. The requirement for the tool to evaluate conceptual designs across base infrastructure led to the need for a value model that consists of a value hierarchy, airfield data, and vehicle parameters. The GUI is created to allow

for the analysts to interact with the system data.

Synthesize Candidate Logical Architecture.

This activity synthesizes the alternate logical architectures to satisfy the system requirements. The physical architecture includes any hardware, software, persistent data and operational procedures. For the LOGICAT, the physical components consists of the MATLAB function calls, the GUI, the AAFIF database and the value model.

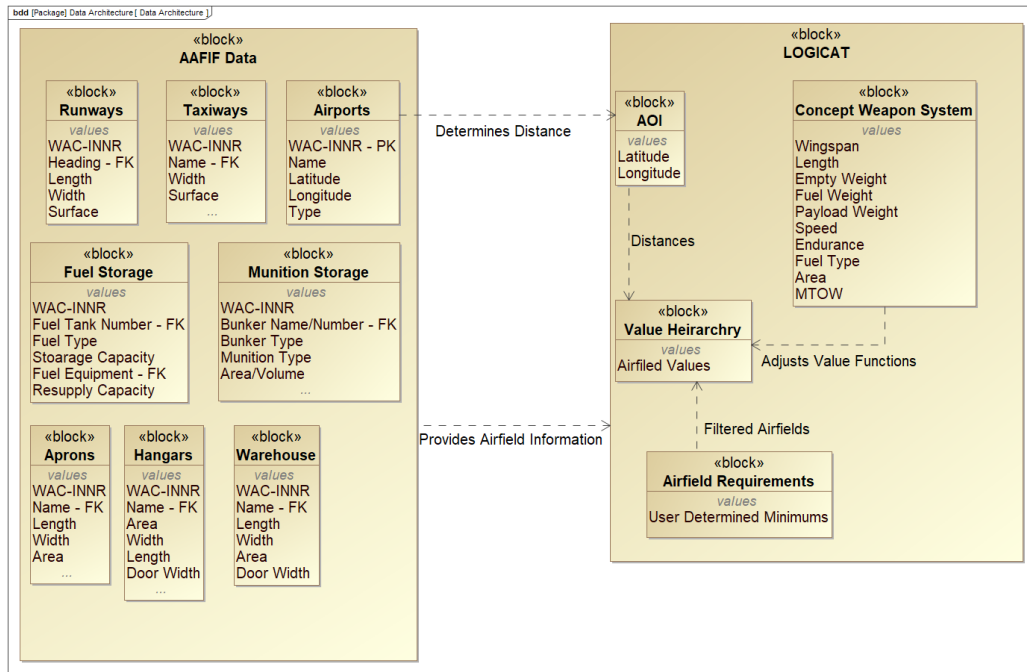


Figure 10. LOGICAT Data Architecture

Figure 10 displays the data elements of the system and how they interact. The AAFIF database provides the airfield data. The user starts by selecting an Area of Interest (AOI), determining the distance from the AOI to each airfield. The user then enters the conceptual systems parameters, which are provided to the value hierarchy. The user can then filter the airfield data to refine the search. The concept system is then assessed on the remaining airfields.

Optimize and Analyze Alternatives.

The candidate architecture represents all the elements discovered in the iterative nature of the development process. This activity happens over the life of the system, and refines the system to meet the requirements of the stakeholder. With each iteration, the tool was evaluated, identifying missing logical elements, and highlighting changes needed in the tool. The final LOGICAT considered base feasibility, static or active maps, and the use of stochastic analysis. The original tool only considered airfields that were considered feasible. All airfields that did not meet the requirements for a concept were removed from consideration. However an airfield with a runway length of 4,999 ft should still be considered if the minimum requirement was 5,000 ft. This led to the decision not to filter out infeasible airfields, but instead create a value hierarchy to score all the airfields. Effectively, the sponsors refined the concept of feasible from black and white to a literal color map of the level of feasibility for all airfields.

The next iteration of the tool introduced the value model, but the need for the tool to operate without using the Google maps Application Programming Interface (API) was discovered. A later version included stored maps that could be called if the user decided not to use an active Google map as the background.

The final version of the tool included the option to add a Monte Carlo stochastic analysis to a conceptual systems parameter. This was added to better understand the basing posture while including the uncertainty of a conceptual system. This research used a triangular distribution to randomly sample individual system parameters. The triangular distribution was selected because of the limited information known about the conceptual system. A uniform distribution would sample the entire design space evenly but it is assumed that the baseline value of the exemplar systems (discussed in Chapter IV) is most likely, and therefore the triangular distribution should be used

over the uniform. Future versions of the tool could include all distributions to improve the sampling as the fidelity of the system design is increased.

LOGICAT Analysis Overview

After the tool has been synthesized and optimized it can be used to assess conceptual weapon systems across a set of airfield data, see Figure 11. For this research, four conceptual systems were evaluated on a representative set of airfields for an ISR Strike mission. Each system was composed of seven system parameters, each of which was randomly sampled from a triangular distribution 1,000 times, creating 7,000 possible designs per system (further explained in Chapter IV). The airfield data was ingested from the NGA AAFIF database. Using the conditional value model that is explained in the next section, each possible system design is assessed across the airfield set. The results of each conceptual systems are analyzed individually, and then the results of the four systems are compared. The distribution of each of the four conceptual systems' basing value can then be compared to identify which system is best for an agile basing posture.

Value Model

Through the course of this research it became clear that an airfield's feasibility is not a boolean decision given that infrastructure changes could be scheduled in time for fielding the weapon system as needed. Each airfield has some value and should still be considered, even if the runway was too short or not rated for the anticipated load. It was decided to create a value model, scoring how a conceptual system would value each airfield, to identify which airfields were more suited to potential basing options for that conceptual system.

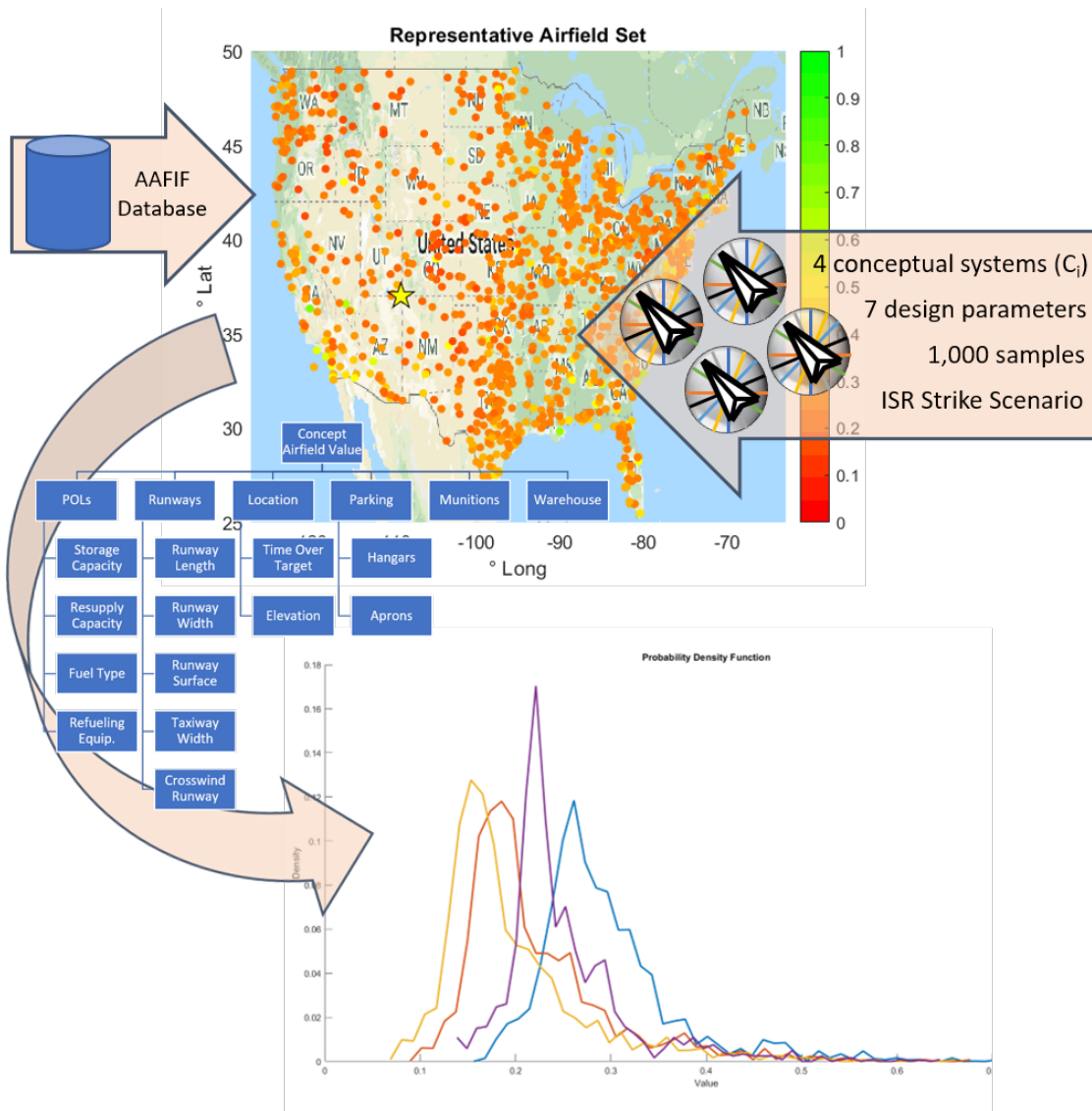


Figure 11. A story board of the using the LOGICAT for conceptual system analysis

A conceptual system that provides a greater value to a set of bases would be advantageous to an agile basing environment. If multiple systems evaluate the same set of airfields, the highest scoring system would be a better alternative to operate from all of the airfields.

The use of a value model highlights the airfields that are currently capable of fielding the system and the needed areas of improvement for the airfields that score lower. An airfield with a runway of 4,999 ft. would still be valued if the runway min-

imum was 5,000 ft. If the airfields were classified Boolean (pass/fail) with respect to the minimum requirements¹, this airfield would never be considered, but this airfield (with or without 1 ft of runway added) could be more valuable than another remote airfield that already had a 5,000 ft. runway in place.

Figure 40 shows the simple value model used to demonstrate the tool. Because the model is notional, the weights will be left equal for each branch, and for each leaf within a given branch. Table 2 lists each measure in the value model, the type of value function used and the resulting global weights.

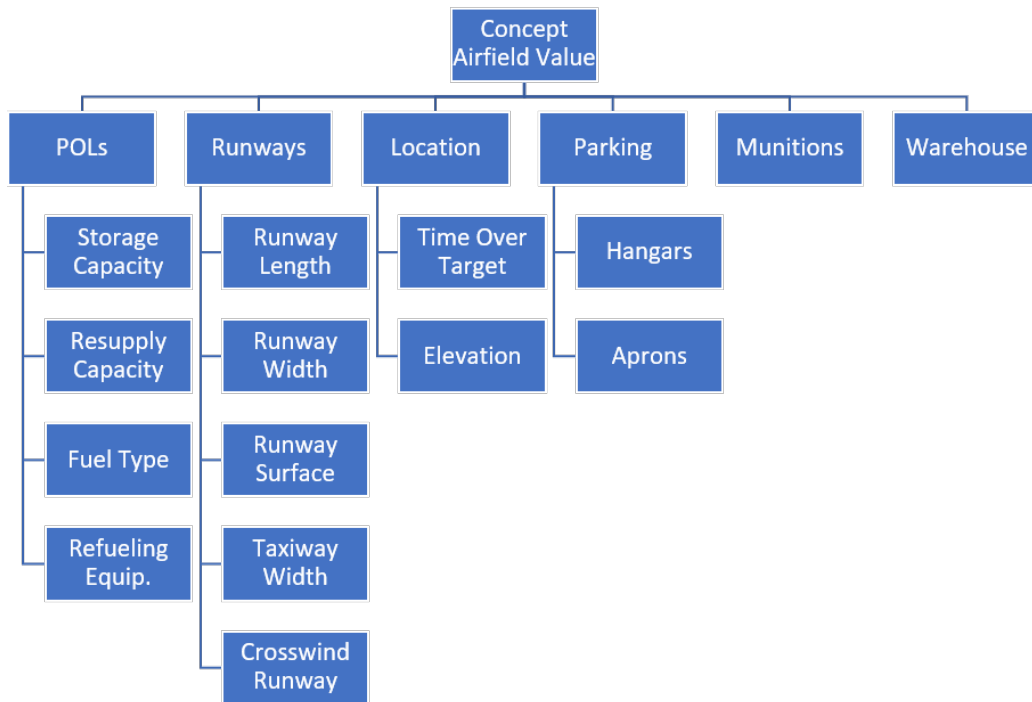


Figure 12. Value Model

¹The use of the term “requirement” in this context should be considered more as an objective, goal, or anticipated need.

Table 2. Value Model Measures, Value Functions and Global Weights

Measure	Value Function Description	Global Weight
Fuel Storage Capacity	Categorical	0.0417
Fuel Resupply Capacity	Categorical	0.0417
Current Fuel Type	Boolean	0.0417
Refueling Equipment Available	Linear Increasing	0.0417
Crosswind Runway	Boolean	0.0333
Runway Surface	Categorical	0.0333
Runway Length	Linear Increasing	0.0333
Runway Width	Categorical	0.0333
Taxiway Width	Linear Increasing	0.0333
Airfield Distance from AOI	Linear Increasing	0.0833
Airfield Elevation	Linear Decreasing	0.0833
Hangar Area	Linear Increasing	0.0833
Parking Apron Area	Linear Increasing	0.0833
Munition Storage	Boolean	0.1667
Warehouse Area	Linear Increasing	0.1667

Value Focused Thinking (VFT) was chosen because it allows the decision to be focused on the entire design space and not limited by the alternatives. Keeney explains the steps of VFT:

“First, one needs to specify the values on which the notion of better is grounded. These values are then made more precise by specifying objectives that define them. These objectives should be the basis of thinking about decisions and for appraising alternatives in that decision situation.” (Keeney, 2008)

VFT starts by developing a value hierarchy before considering different alternatives. Applied to this research, the value hierarchy needs to determine the best conceptual system to be fielded at potential airfields. However, one value measure applied for all systems to an airfield could not accurately reflect the difference in value from one system to another. This is demonstrated through the following example.

Conditional Value Model Example.

A simple example is that a C-5M Super Galaxy values an airfield different than any Cessna aircraft would. Thus the value functions must be adjusted based on the conceptual systems' parameters to reflect how the system would be valued for an airfield.²

To continue the example, the C-5M Super Galaxy has a Maximum Takeoff Weight (MTOW) of 840,000 lbs, and requires a runway length of over 8,000 ft (Department of the Air Force, 2006a). While a Cessna Skyhawk has a MTOW of 2,550 lbs and requires a runway length of only 2,500 ft (Cessna Textron Aviation, 2019). If both vehicles were assessed on the same value function, where would max value be assigned? If it is set for 2,500 ft (the length required by a Skyhawk) the Super Galaxy would be over valuing airfields that don't meet the runway requirements, and if it was set at 8,000 ft (for the Super Galaxy) airfields that have longer runways than needed for a Skyhawk would be scored lower despite being suitable. The value hierarchy proposed transforms the value function based on provided conceptual system parameters. To further demonstrate the example, both vehicles were applied to the runway length value measure.

To demonstrate the VFT method, the value of runway length is graphed as three separate linear increasing functions, one function for each aircraft category. This

²A system cannot value an airfield, but the term is used to reflect how decision makers value model would modulate by a systems parameters.

set of value functions determines how a conceptual system would value a runway length, see Figure 13. AC 150/5325-4B lists small aircraft as vehicles under 12,500 lbs MTOW, and large aircraft being over that (U.S. Department of Transportation, 2005). See figures 43 and 44 in Appendix B for the recommended runway lengths for the first two MTOW categories based on temperature and elevation. Without weather data, the average temperature on the provided curve (75 °F) was used to read the tables. With elevation already included in the value model, the sea level estimate was used. The runway length required for takeoff is used because it is longer than the runway requirements for landing. This set of value functions are expressed in Equations 1 through 3.

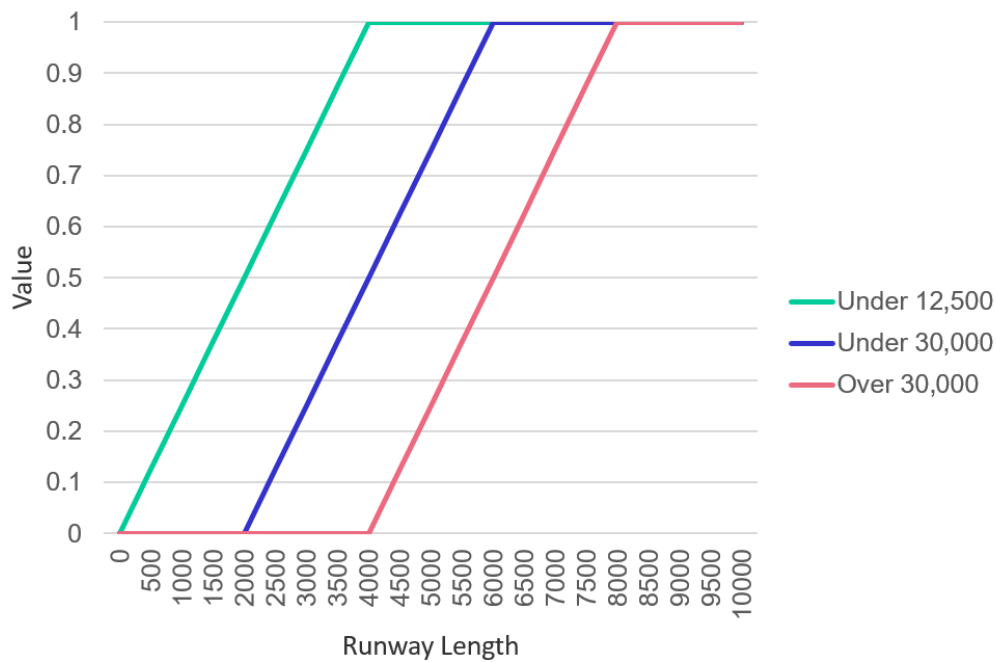


Figure 13. Runway Length Value Function

For a concept weapon system with a MTOW (C_j) $\leq 12,500$ lb

$$V_{RunwayLength}(A_i|C_j) = \begin{cases} \frac{A_i}{4,000}, & A_i \leq 4,000 \\ 1, & A_i > 4,000 \end{cases} \quad (1)$$

For a concept weapon system with $12,500 < \text{MTOW } (C_j) \leq 30,000$ lbs

$$V_{RunwayLength}(A_i|C_j) = \begin{cases} 0, & A_i \leq 2,000 \\ \frac{A_i}{6,000}, & 2,000 < A_i \leq 6,000 \\ 1, & A_i > 6,000 \end{cases} \quad (2)$$

For a concept weapon system with a MTOW (C_j) $> 30,000$ lbs

$$V_{RunwayLength}(A_i|C_j) = \begin{cases} 0, & A_i \leq 4,000 \\ \frac{A_i}{8,000}, & 4,000 < A_i \leq 8,000 \\ 1, & A_i > 8,000 \end{cases} \quad (3)$$

Where:

$V_{RunwayLength}(A_i|C_j)$ is the runway length value for an airfield based on a concepts MTOW

A_i = is the length of the runway of airfield i

C_j = is the MTOW of concept j

The conceptual systems MTOW (C_j) is the vehicle parameter used to transform the runway length value, accounting for the difference in system value. If both the Super Galaxy and the Skyhawk were to evaluate the same airfield with a 5,000 ft runway, $V_{RunwayLength}(A_i|C_j) = 1.0$ for the Skyhawk and $V_{RunwayLength}(A_i|C_j) = 0.2$

for the Super Galaxy.

This same principle is applied for seven conceptual system parameters to fifteen airfield parameters. The full value hierarchy is explained in Appendix B. Table 3 lists all the airfield parameters and what conceptual system parameters are used to condition the value model. The airfield parameters were selected through discussions with the sponsor of this research, and extracted from the criterion listed in the sponsor’s CONOPS – See Appendix A. The low fidelity of the conceptual system allowed for any potential concept to have the needed information openly available. These system parameters were chosen because there is an intuitive relationship to the airfield criterion provided by the sponsor. Expanding the concept and airfield parameters is further explained in Chapter V.

Table 3. Airfield Parameters and System Parameters

Airfield Parameter	System Parameters
Fuel Storage Capacity	Fuel Weight
Fuel Resupply Capacity	Fuel Weight
Current Fuel Type	Fuel Type
Refueling Equipment Available	Length and Wingspan
Crosswind Runway	None
Runway Surface	MTOW
Runway Length	MTOW
Runway Width	MTOW
Taxiway Width	Wingspan
Airfield Distance from AOI	Speed and Endurance
Airfield Elevation	MTOW
Hangar Area	Length and Wingspan
Parking Apron Area	Length and Wingspan
Munition Storage	None
Warehouse Area	Length and Wingspan

Chapter 3 provided a detailed explanation of applying the OOSEM steps to develop a tool for conceptual weapon system assessment across base infrastructure. After the creation of the tool, an overview of the analysis was provided. The third section walks through an in-depth look of the conditional value model applied to a

runway length, and then explained the seven system parameters and fifteen airfield parameters used to create the rest of the value model.

IV. Application

This chapter begins with the verification of the tool and value model. Once the tool is complete, four conceptual systems are individually evaluated and the results analyzed. The results of the four systems are then compared to determine the best conceptual system for an agile basing posture. The tool can be seen in Figure 14.

Tool Verification

Verify and Validate System.

This is the final activity of the OOSEM. This activity verifies that the system meets the requirements and that the requirements meet the stakeholders needs. The system level use cases when applied to a scenario can be used to develop the verification procedures. For this research, demonstration methods were used to conduct the verification and validation of the tool. Through multiple meetings with the sponsor of this research, each use case in Figure 7 was demonstrated. The demonstration followed the steps presented in the sequence diagram shown in Figure 15, and each data output was recorded to determine if the system provides the desired response.

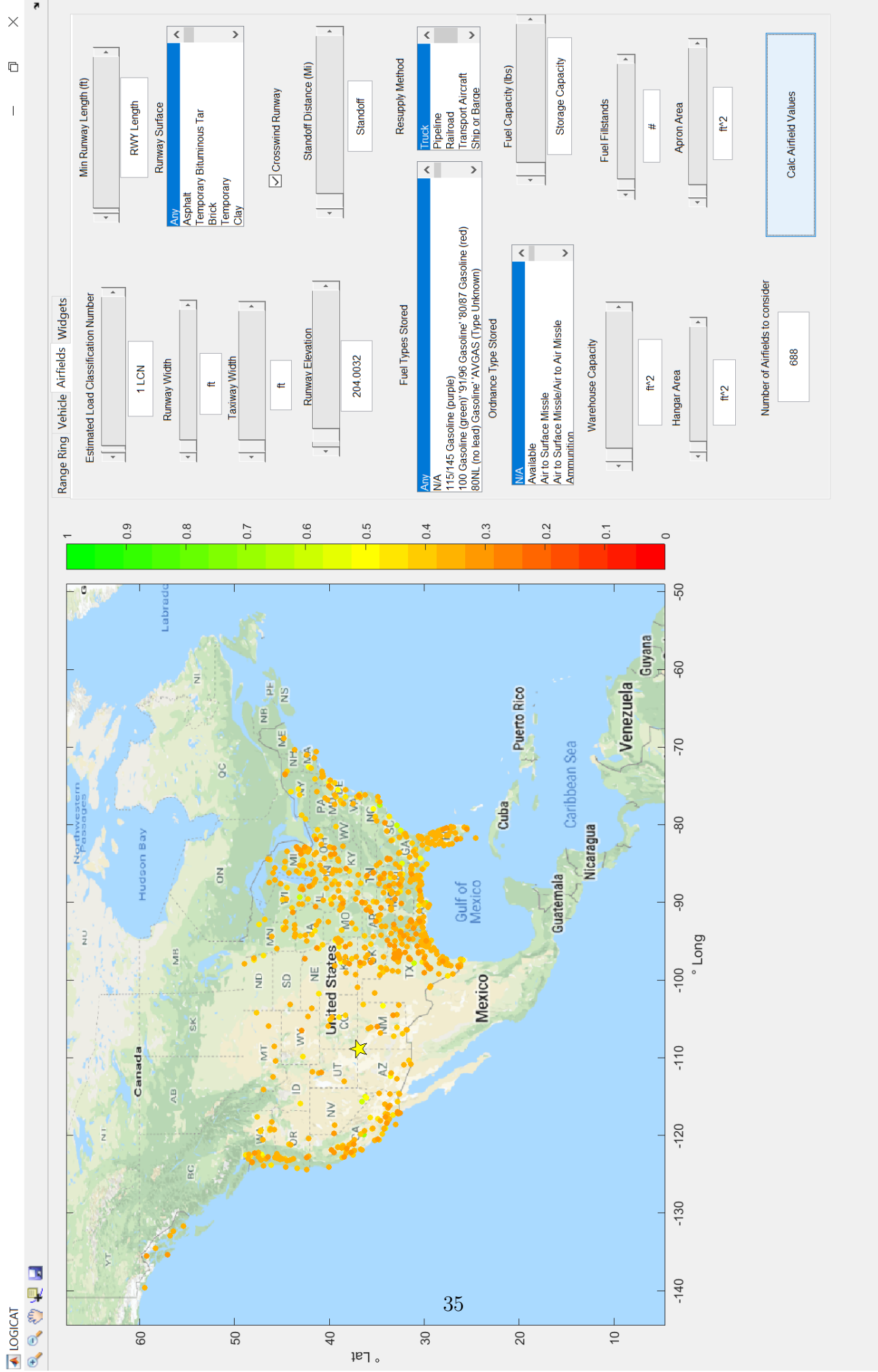


Figure 14. LOGICAT Value Airfields View

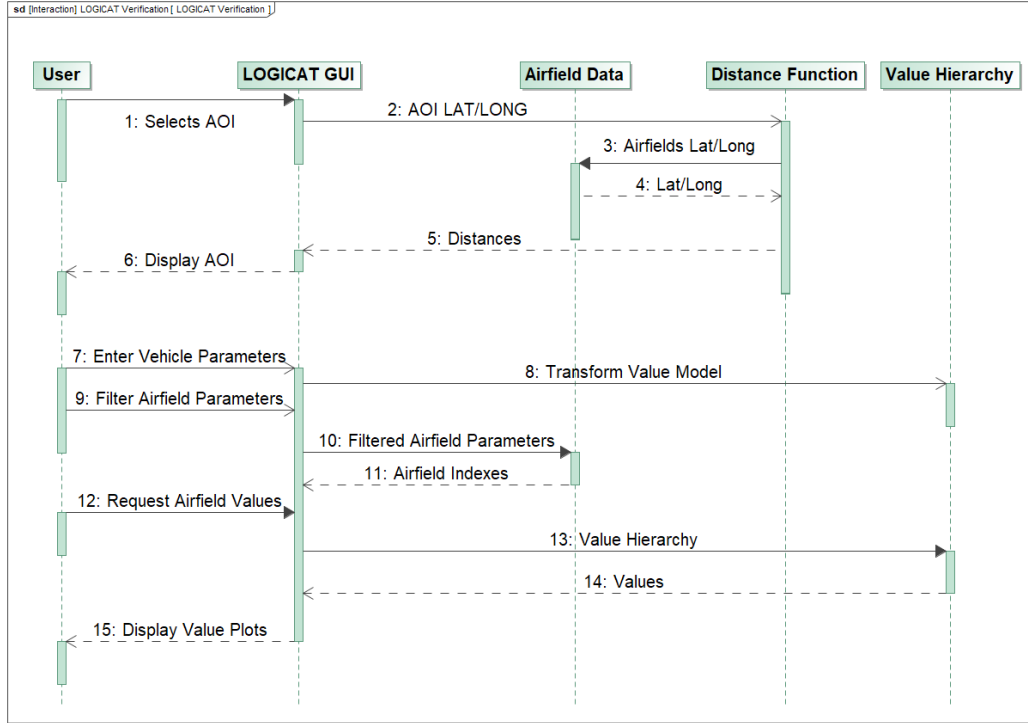


Figure 15. LOGICAT Verification Sequence Diagram

Value Model Verification.

To verify the value model embedded within the tool, a “perfect” and “worst” airfield were compared against a sample set of airfields. The MQ-9 was used as the conceptual system. The results can be seen in Figure 16. The “perfect airfield” receives a value of 1, and the “worst” airfield receives a value of zero as expected. An active military airfield (C) is valued the highest of the real data input into the model, this airfield scores well for the runway, and parking attributes it offers the MQ-9. A minimum facility airfield (D) scored the next best, this is because it is located closest to the AOI used for this research and the system values the close location for additional time over target than the two remaining airfields. A joint military and civilian airfield (B) is next. This airfield is located further away then airfield D, so it scores low for the location value. Airfield B had no information listed in the parking, munitions or warehouse variables, leaving the system to not value this airfield highly.

Scoring last is a civilian airfield (A), this airfield is similar to airfield (B) but the MQ-9 would value this airfield lower because of the shorter runway.

The same procedure was repeated with a C-5 set as the conceptual system, with the results show in Figure 17. The order of airfields does not change but when the new system is applied to the same airfields, there is a change in each airfield value. What was a perfect airfield for the MQ-9 is no longer a perfect airfield for the C-5, missing points in the location branch of the value model. The change between systems and between individual airfields confirms that the value model is providing the expected results.

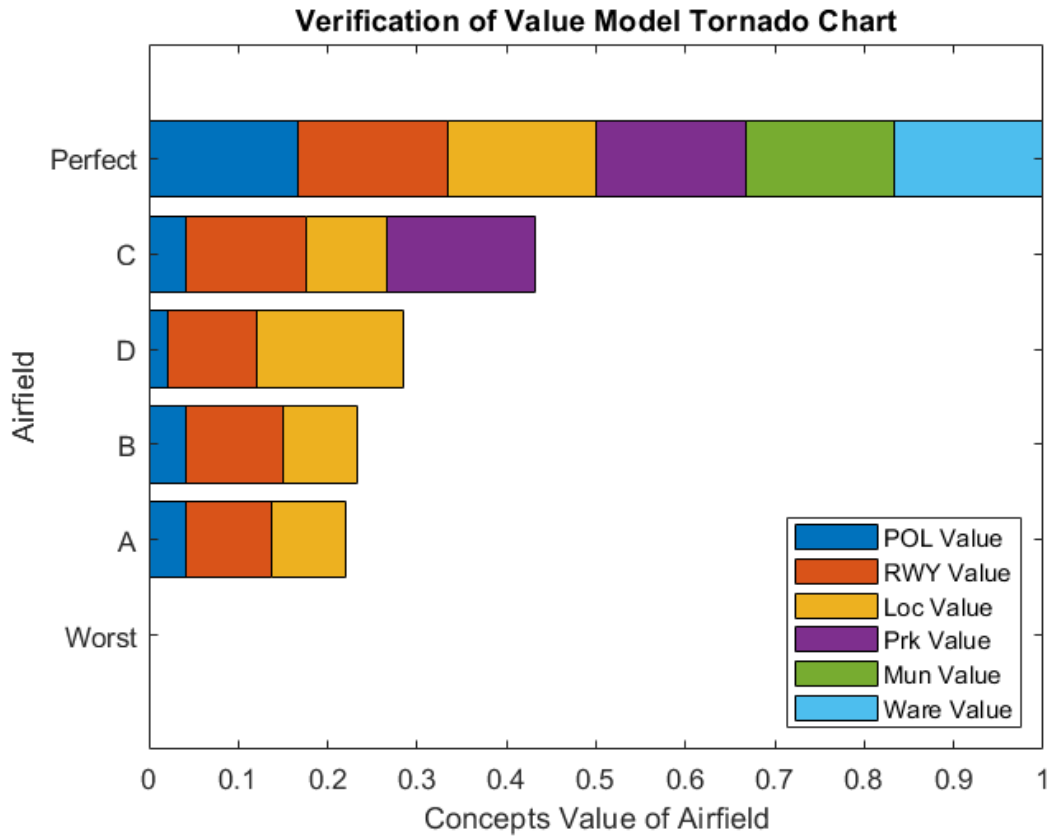


Figure 16. LOGICAT Value Model Verification Tornado Chart MQ-9

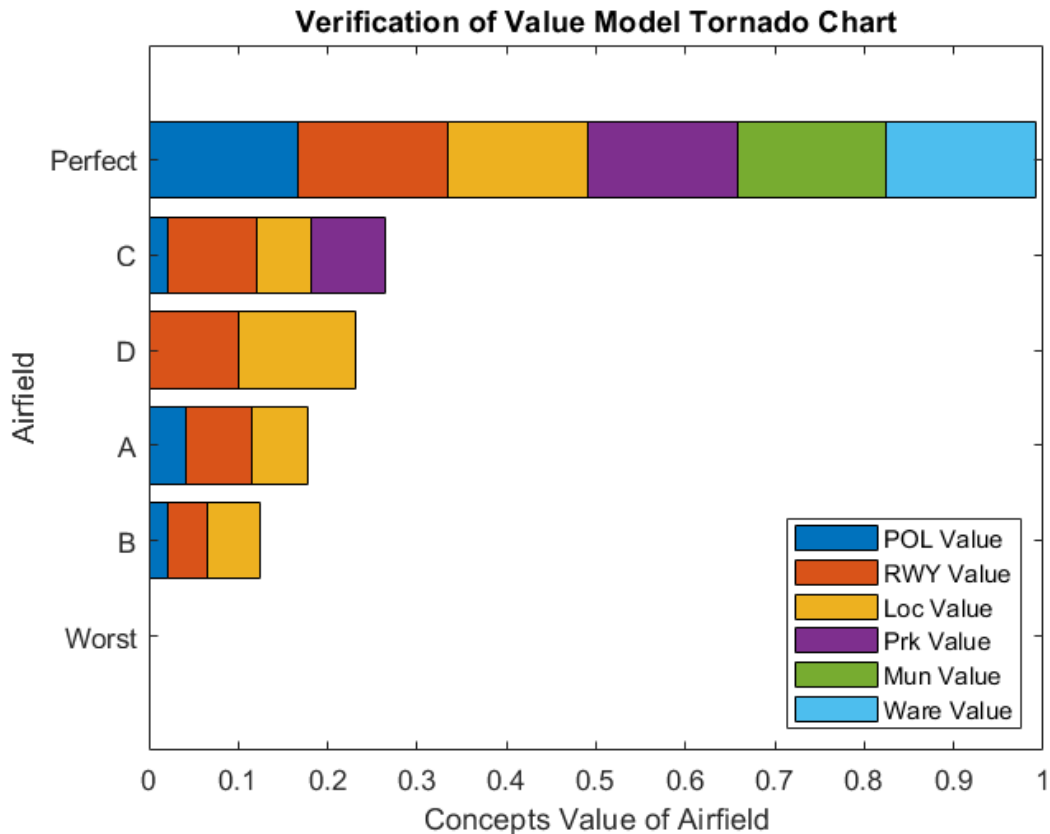


Figure 17. LOGICAT Value Model Verification Tornado Chart C-5

Scenario

The scenario created for the demonstration of the LOGICAT is to analyze multiple conceptual weapon systems to perform the MALE ISR Strike mission set from a distributed basing posture. Four weapon systems will be evaluated on a representative set of airfields to see how various concepts could operate from a basing posture. The AOI for this scenario is set as the four corners of the United States, located at a Latitude 36.9991° N, Longitude 109.0452° W.

Conceptual Systems.

For this scenario, four conceptual systems were provided by the sponsor for analysis:

1. A platform that resembles the current MQ-9, the MALE ISR
2. A Light Attack (LA) propeller aircraft that could be converted into an ISR platform that resembles the A-29 Super Tucano
3. A LA jet aircraft that could be converted into an ISR platform that resembles the Scorpion by Textron AirLand
4. A Low Cost Attritable Aircraft Technology (LCAAT) system based on the BQM-167 aerial target drone

Monte Carlo analysis was conducted to include the uncertainty of a conceptual system design in the evaluation. For this research, the triangular distribution was used to randomly sample the concept parameters. There is little information that is known about each system beyond that a subject matter expert chose the systems to serve as the baseline of each conceptual system. For this research the actual value of the baseline vehicle each conceptual system resembles is used as the most likely value. The high and low values are set as plus or minus 20% respectively. The high and low values can be individually set within the LOGICAT if there is more information available. The actual values of the baseline systems can be found in Table 4, and a description of the vehicle as well as the reason for its consideration is included in the specific section for each system later in the analysis.

Table 4. Specific Parameters of Evaluated Vehicles

Vehicle	Wingspan [ft]	Length [ft]	Empty Weight [lbs]	Fuel Weight [lbs]	Payload Weight [lbs]	Speed [MPH]	Endurance [Hr]
MQ-9	66	36	4,900	4,000	3,750	230	27
A-29	36.6	37.1	7,055	2,727	3,420	281	7.1
Scorpion	47.83	45.5	12,700	6,000	3,000	450	5
BQM-167A	10	20	690	750	500	606	2.3

(Department of the Air Force, 2015; Sierra Nevada Corporation & Embraer, 2019)

(Textron Aviation Defense LLC, 2019; Department of the Air Force, 2009b)

Airfield Selection.

The sponsor of this research is interested in the medium-altitude ISR Strike mission set in the Middle East, but to demonstrate the analysis easily, U.S airfields were used in place. CENTCOM has an area of responsibility of 4 million square miles (Department of Defense, 2008). The Continental U.S. (CONUS) with some Pacific or Atlantic ocean included, is also 4 million square miles. Using only CONUS airfield data provides a similar area for this analysis. The data set listed 1,626 airfields in the CENTCOM Area of Responsibility (AOR), and 19,468 airfields within the CONUS. The CONUS airfield data was randomly sampled by stratum to create a similar density of airfields to use for the evaluation.

The AAFIF data set grouped airfields into twelve categories which are: *Active Civilian, Active Joint, Active Military, Minimum Facilities, Highway, Military Heliport, Civilian Heliport, Minimum Facilities Military Heliport, Minimum Facilities Civilian Heliport, Decoy Airfields, Closed and Unusable*. Only Active Civilian, Active Joint, Active Military and Minimum Facilities Airfields were used for this research as the other categories fell outside the scope of this research. This left the data set with 1,197 CENTCOM airfields and 13,052 U.S Airfields. Table 5 shows the summary of airfields in CENTCOM and the Continental U.S. The 13,502 CONUS airfields were

randomly sampled by stratum to create a set of 1,197 airfields to match a similar density of airfields as the sponsors interested AOR. The missing 20 Active Joint airfields were evenly split, 10 and 10 between the Active Civilian and Active Military airfields.

Table 5. Summary of Airfield Data

Airfield Category	CENTCOM		Continental U.S.	
	Count	%	Count	%
Active Civilian	103	8.60	1,625	12.45
Active Joint	52	4.34	32	0.25
Active Military	116	9.70	180	1.38
Minimum Facilities	926	77.36	11,215	85.92
Totals	1,197	100	13,052	100

MALE ISR Conceptual System

Vehicle Description.

The MALE ISR conceptual system is based off the current MQ-9 Reaper, which is the current system the USAF relies on for ISR Strike missions. The MQ-9 Reaper can be seen in Figure 18. According to ACC fact sheets the MQ-9 Reaper is

“an armed, multi-mission, medium-altitude, long-endurance remotely piloted aircraft that is employed primarily against dynamic execution targets and secondarily as an intelligence collection asset. Given its significant loiter time, wide-range sensors, multi-mode communications suite, and precision weapons – it provides a unique capability to perform strike, coordination, and reconnaissance against high-value, fleeting, and time-sensitive targets. (Department of the Air Force, 2015)”



Figure 18. MQ-9 Reaper (Department of the Air Force, 2015)

Results.

This section discusses the results of evaluating the MALE ISR conceptual system on a representative set of 1,197 airfields. Without a higher fidelity model and the inclusion of the physical relationships between the conceptual system parameters, each system parameter was sampled individually to limit the possibility of an infeasible design. More on the random sampling and feasibility of the system is discussed in Chapter V.

To start, the baseline MQ-9 is used to evaluate the representative set of airfields. Figure 19 displays the value and location of each airfield. A breakdown of the value for each airfield can be seen in Figure 20. The highest scoring airfield was a 0.7299 and the lowest scoring airfield was a 0.1667, with a median of 0.2708, a mean of 0.2908 and a standard deviation of 0.0744. More information on the spread of the airfield data can be seen in the histograms and box plots of the airfield data by each

conceptual design, displayed in Appendix C.

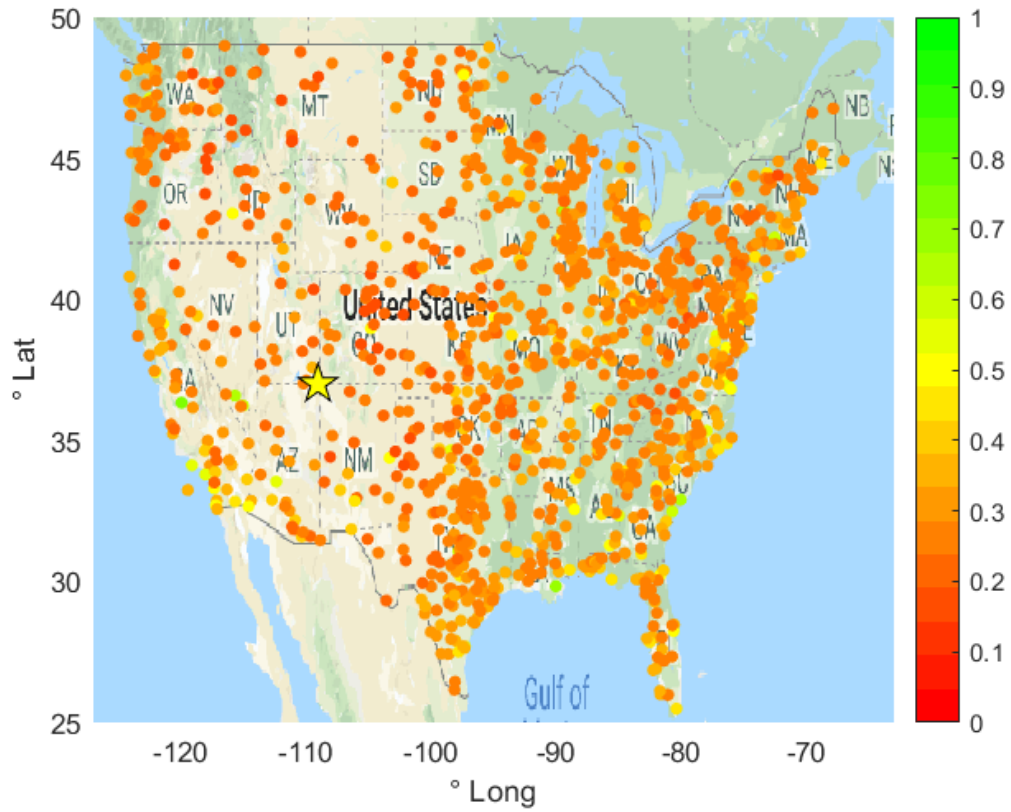


Figure 19. Baseline MQ-9 Colormap of Representative Airfield Set

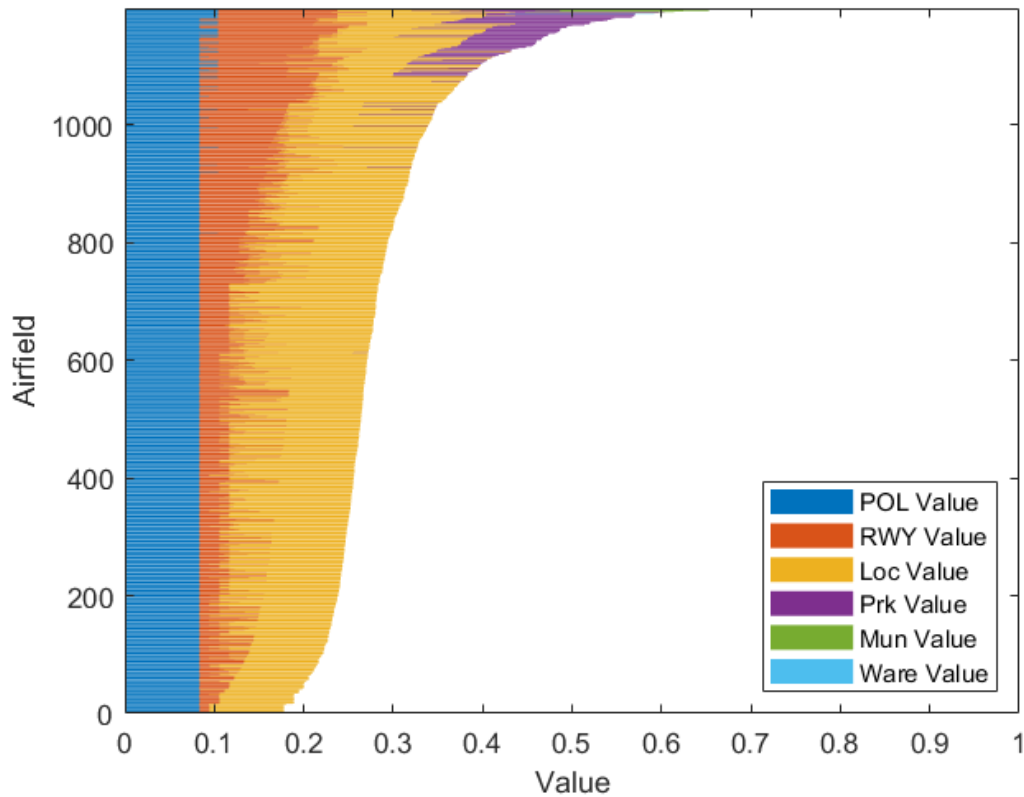


Figure 20. Baseline MQ-9 Tornado Chart of Representative Airfield Set

Each point in Figure 21 represents a possible design for the MALE ISR conceptual system that was evaluated on the set of airfields. To show all of the designs on the same figure, each system parameter is represented in its own color and the data was normalized to create consistent abscissa axis. This was accomplished by dividing the system parameter that was varied by the baseline value of that parameter, leaving the values in a range from 0.8 to 1.2. The ordinate axis shows the average value of the representative airfield set, instead of showing all 1,197 values, 7,000 times. Looking at the three weight parameters, an increase in the average value of the set of airfields was observed when a system weight parameter was reduced. This result is expected, as the MQ-9 total weight is 12,650 lbs, and the vehicle weight category changes at 12,500 lbs. System designs with a weight parameter that was a decrease around 5%

from the baseline resulted in the system design changing categories. This moved the system into the lighter category, where more value is assigned for the same airfield attributes. The MQ-9 has a long enough endurance that all airfields in the sample set received value for Time-over-Target resulting in only a small decrease or increase in value as the endurance or speed parameters were changed. This figure also shows that there is minimal change of a concepts value of the entire airfield set across all the evaluated conceptual designs. Appendix C provides additional figures generated for each conceptual system and sampled parameter.

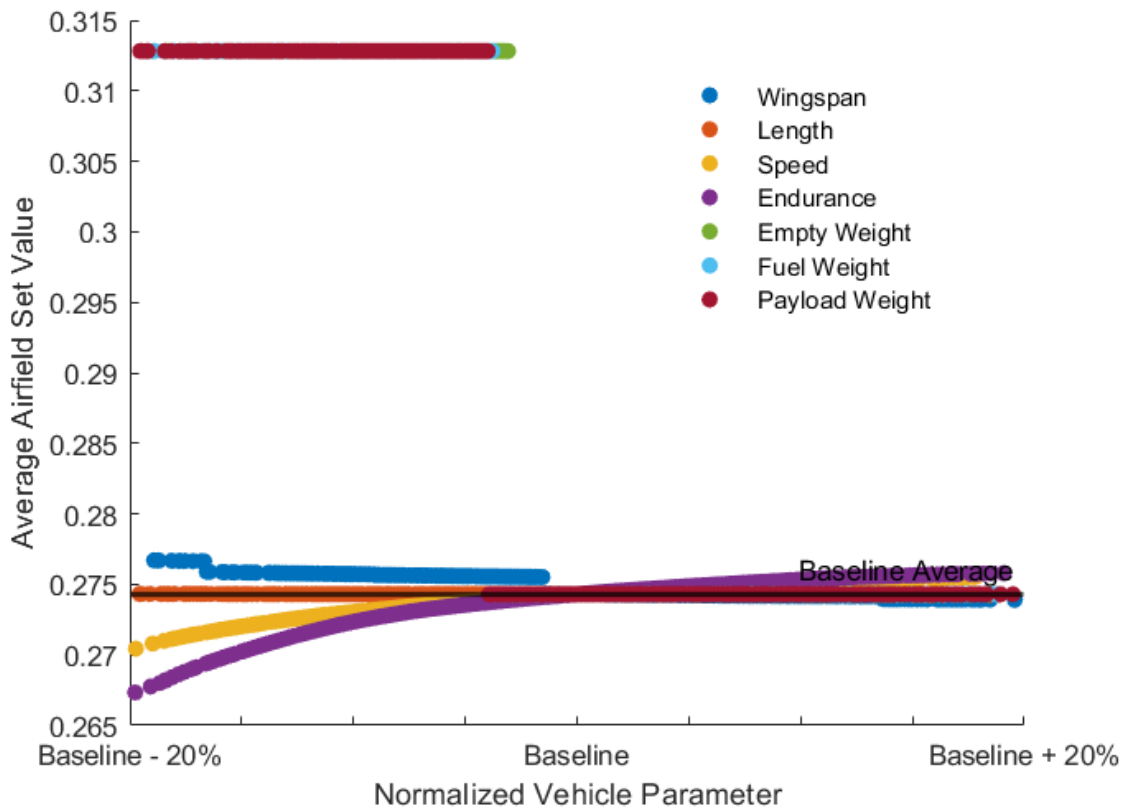


Figure 21. MALE ISR System Monte Carlo Analysis Results

Light Attack Propeller Aircraft Conceptual System

Vehicle Description.

The LA propeller aircraft conceptual system is based off the A-29 Super Tucano, which can be seen in Figure 22. “[Used] by 13 air forces worldwide, the A-29 is a durable, versatile and powerful turboprop aircraft capable of carrying out a wide range of fighter and ISR missions. The A-29 is combat-proven in Afghanistan and in theaters around the globe.” (Sierra Nevada Corporation & Embraer, 2019) The USAF has considered the A-29 as a system that could potentially provide a lower cost per flight hour for training, combat or ISR missions with a reduced level of performance. The Super Tucano is a smaller but heavier aircraft than the MQ-9; the Tucano also has a higher cruise speed but shorter endurance time. The results of the Super Tucano on the sample data set are discussed next.



Figure 22. A-29 Super Tucano (Sierra Nevada Corporation & Embraer, 2019)

Results.

This section discusses the results of evaluating the LA propeller aircraft conceptual system on the same representative set of 1,197 airfields. To start, the baseline A-29 is used to evaluate the representative set of airfields. Figure 23 displays the value and location of each airfield. A breakdown of the value for each airfield can be seen in Figure 24. The highest scoring airfield was a 0.6715 and the lowest scoring airfield was a 0.0966, with a median of 0.197, a mean of 0.2198 and a standard deviation of 0.0764. More information on the spread of the airfield data can be seen in the histograms and box plots of the airfield data by each conceptual design, displayed in Appendix C.

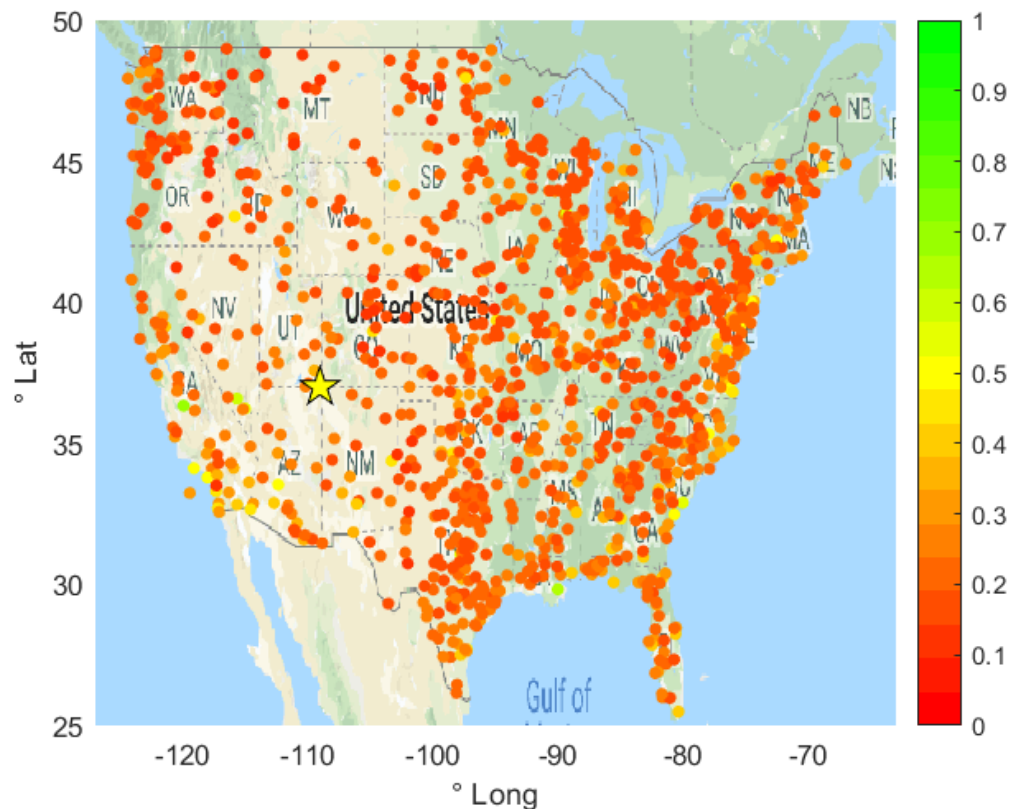


Figure 23. Baseline LA Propeller Colormap of Representative Airfield Set

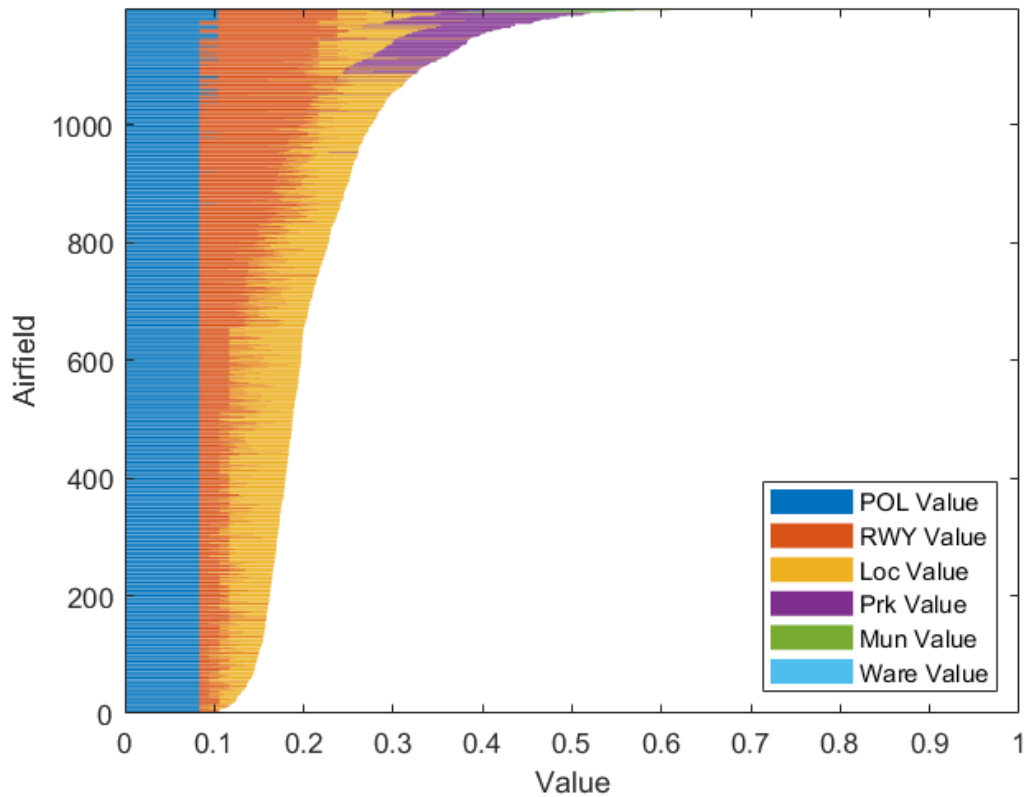


Figure 24. Baseline LA Propeller Tornado Chart of Representative Airfield Set

Figure 25 shows the results of each possible LA propeller system design compared to the average value for the representative set of airfields. This figure shows the same small increase in airfield value for the empty weight parameter as the MALE ISR did. This is because the LA propeller system can only enter the lighter category with a large enough change to empty weight. The system does not have enough fuel or payload weight for a 20% reduction to create a change in MTOW category. This figure also shows that there is minimal change of a concepts value of the entire airfield set across all the evaluated conceptual designs.

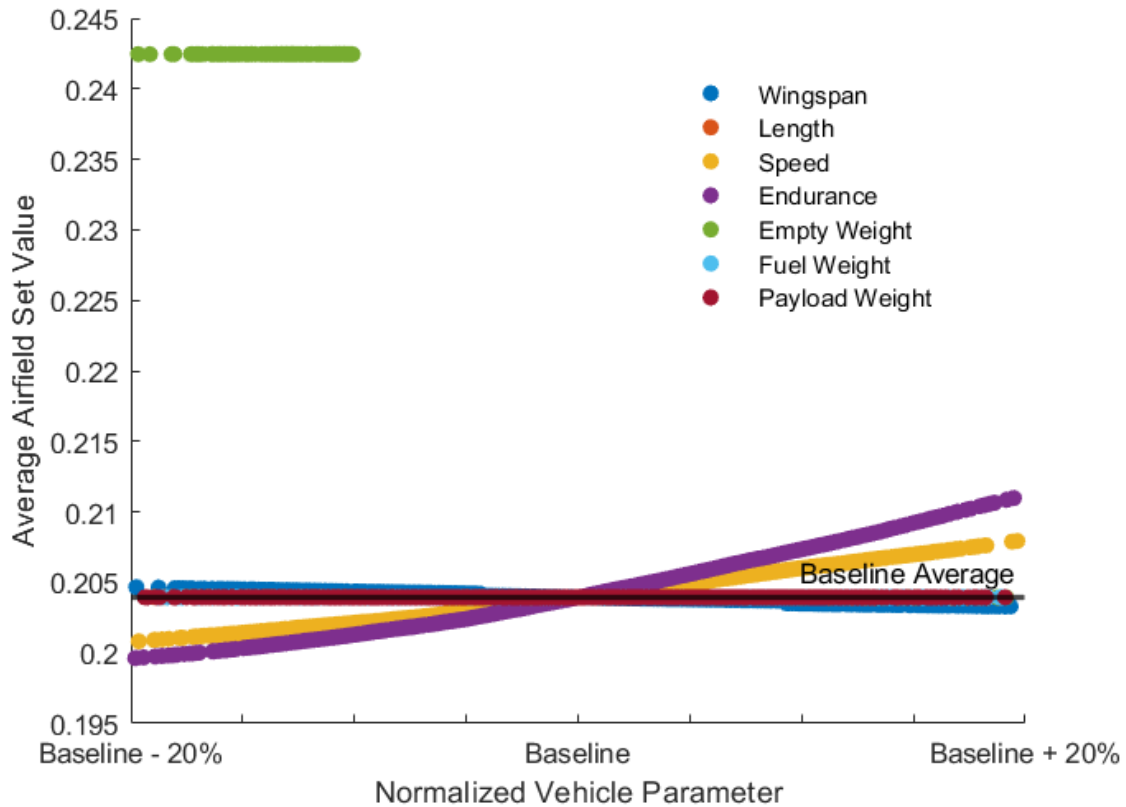


Figure 25. LA Propeller System Monte Carlo Analysis Results

Light Attack Jet Conceptual System

Vehicle Description.

The LA jet conceptual system is based on the Textron AirLand Scorpion – see Figure 26. This system is being evaluated on the same principle as the LA Propeller system, where life cycle cost savings can potentially be seen with performance trades as needed. The Scorpion is the heaviest vehicle evaluated in this research. As a jet aircraft, it is significantly faster than both the MQ-9 or the A-29 vehicles it is being evaluated against but the Scorpion has a shorter endurance. The maintenance schedule and costs associated with a jet aircraft vs a propeller aircraft are not included in this research but discussed further in Chapter V.



Figure 26. Textron AirLand Scorpion (Textron Aviation Defense LLC, 2019)

Results.

This section discusses the results of evaluating the LA jet aircraft conceptual system on the representative set of airfields. To start, the baseline Scorpion is used to evaluate the representative set of airfields. Figure 27 displays the value and location of each airfield. A breakdown of the value for each airfield can be seen in Figure 28. The highest scoring airfield scored a 0.6565, and the lowest scoring airfield was a 0.0736, with a median of 0.1728, a mean of 0.0.1953 and a standard deviation of 0.0768. More information on the spread of the airfield data can be seen in the histograms and box plots of the airfield data by each conceptual design, displayed in Appendix C.

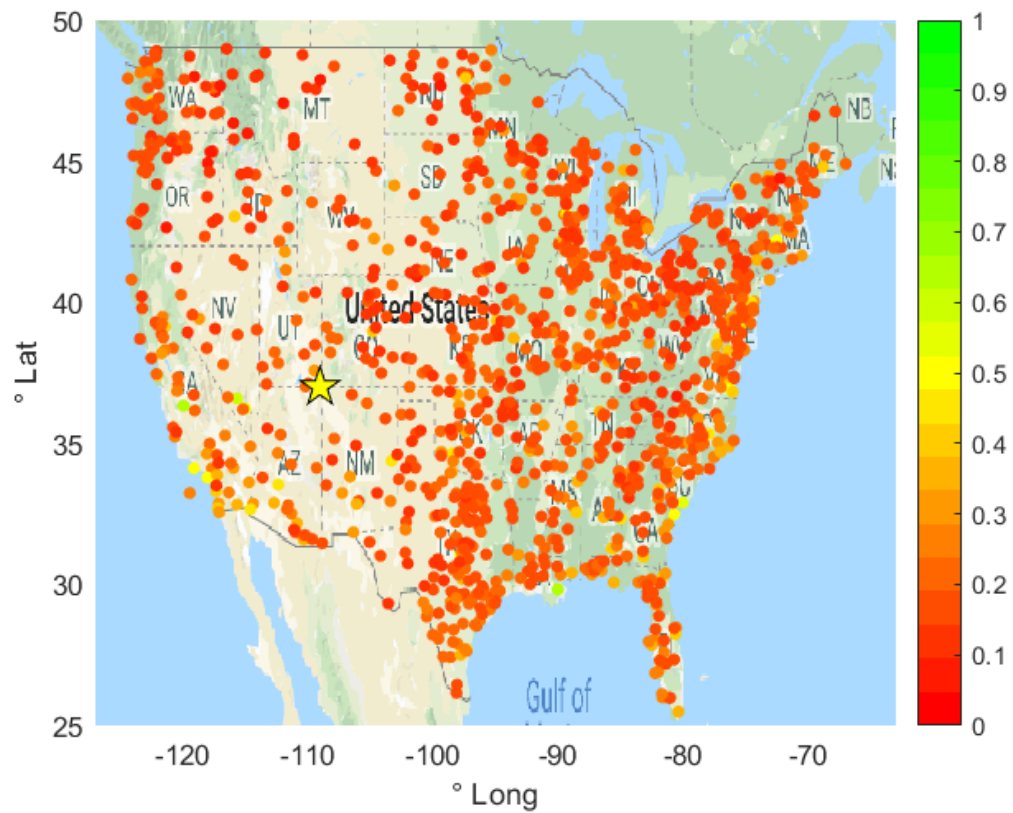


Figure 27. Baseline LA Jet Colormap of Representative Airfield Set

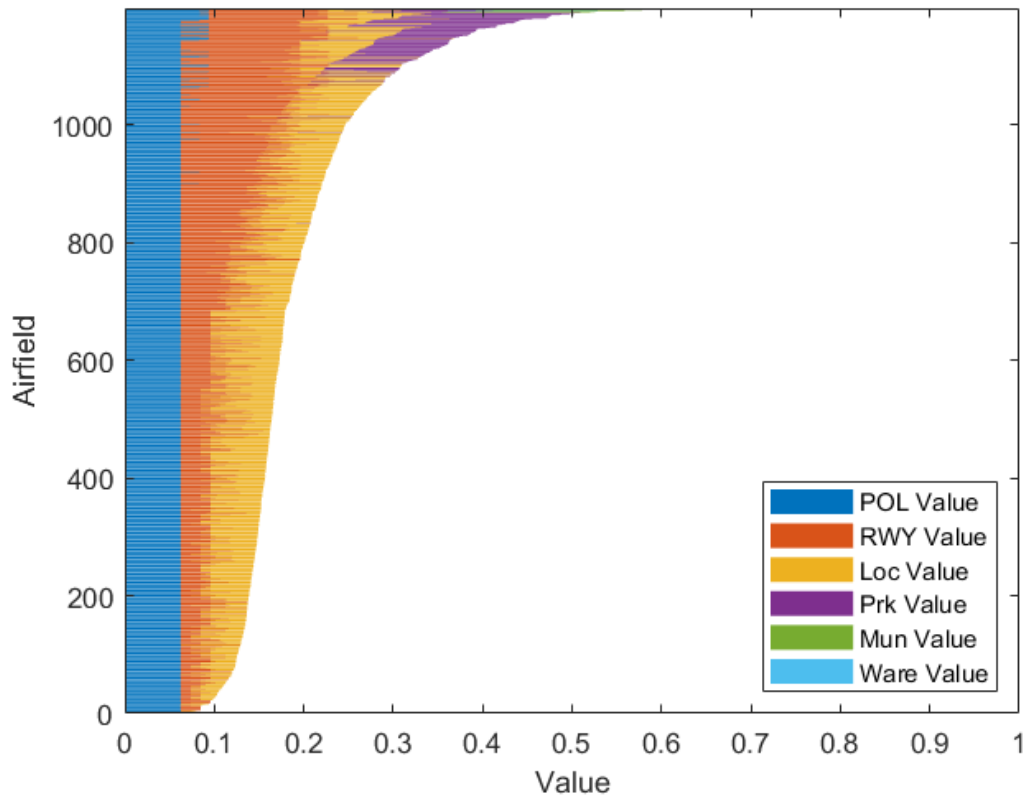


Figure 28. Baseline LA Jet Tornado Chart of Representative Airfield Set

Figure 29 shows the results of each possible LA jet system design compared to the average value for the representative set of airfields. Very little change in airfield value is seen for this system as it falls into the heavier category for almost all sampled designs. This systems value varies almost 10% across the designs when the speed or endurance parameters were varied. This change in value could be used to drive a requirement for increased range for this system. Comparing these result with both the MALE ISR and the LA jet systems, this system has shown the most variability across the various system designs.

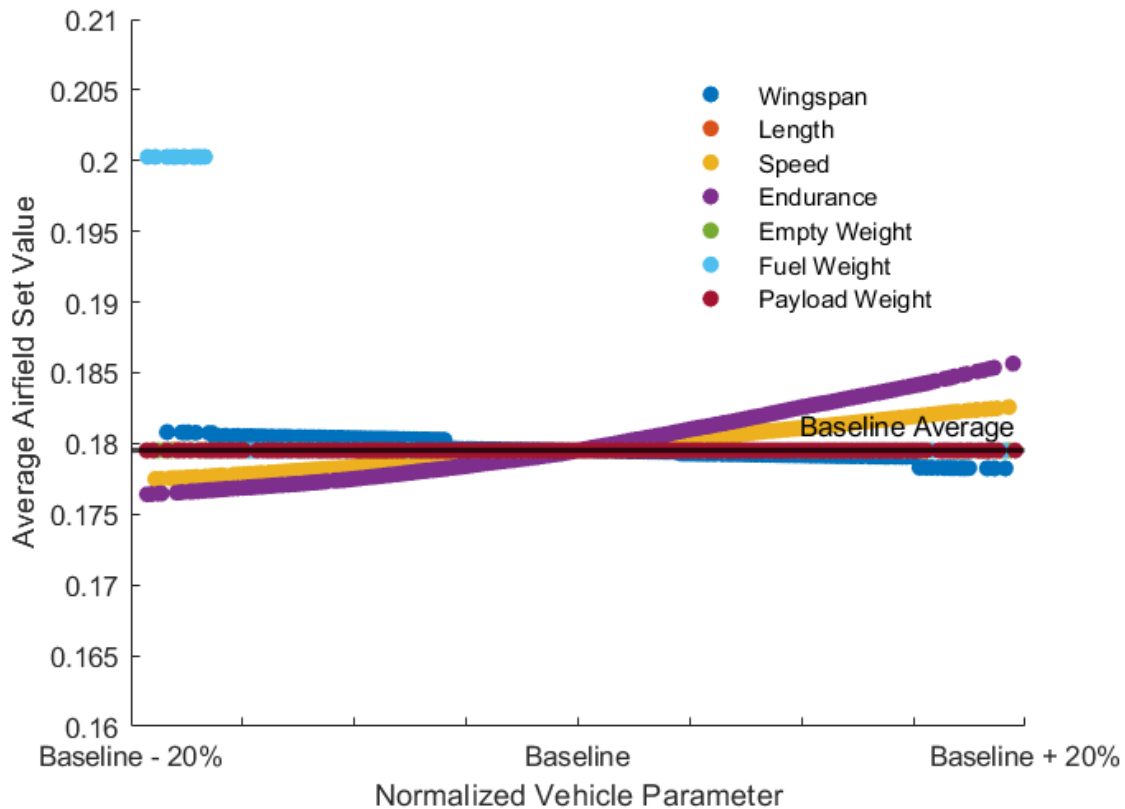


Figure 29. LA Jet System Monte Carlo Analysis Results

LCAAT Conceptual System

Vehicle Description.

The LCAAT system considered in this research is based of the BQM-167A which is an aerial target drone created by Kratos. The target drone is being considered by the Air Force Research Laboratory (AFRL) for modification to act as either a system with a modular payload to perform various missions as needed, including ISR or Strike missions. The BQM-167A, converted into a LCAAT system is named the Unmanned Tactical Aerial Platform (UTAP) Mako, and a conceptual image of the LCAAT system can be seen in Figure 30.



Figure 30. LCAAT (Department of Defense, 2017)

The conceptual system shown is displayed with landing gear, but the BQM-167A is a rail launched vehicle, and the LCAAT systems that have been demonstrated are all rail launched, parachute recovery vehicles. As a rail launched vehicle, very little runway is needed for this system. The value model in future work could be adjusted to accurately reflect the limited runway space needed, but currently is left as a light vehicle, valuing a runway similarly to other light vehicles. This could be used to represent the needed support airlift vehicles or manned vehicles this system would be supporting.

As an attritable system, this platform was design to keep costs low. With a low procurement cost, this system could possibly be used for a one way missions; effectively doubling the range of the LCAAT. However, this is out of the scope of this research and this system was considered as is with the need to return home. The LCAAT is the lightest and fastest system evaluated but has the shortest endurance flight time.

Results.

This section discusses the results of evaluating the LCAAT conceptual system on a representative set of airfields. Starting with the baseline LCAAT is used to evaluate the representative set of airfields. Figure 31 displays the value and location of each airfield. A breakdown of the value for each airfield can be seen in Figure 32. The highest scoring airfield was a 0.6504 and the lowest scoring airfield was a 0.0651, with a median of 0.2317, a mean of 0.2502 and a standard deviation of 0.0651. More information on the spread of the airfield data can be seen in the histograms and box plots of the airfield data by each conceptual design, displayed in Appendix C.

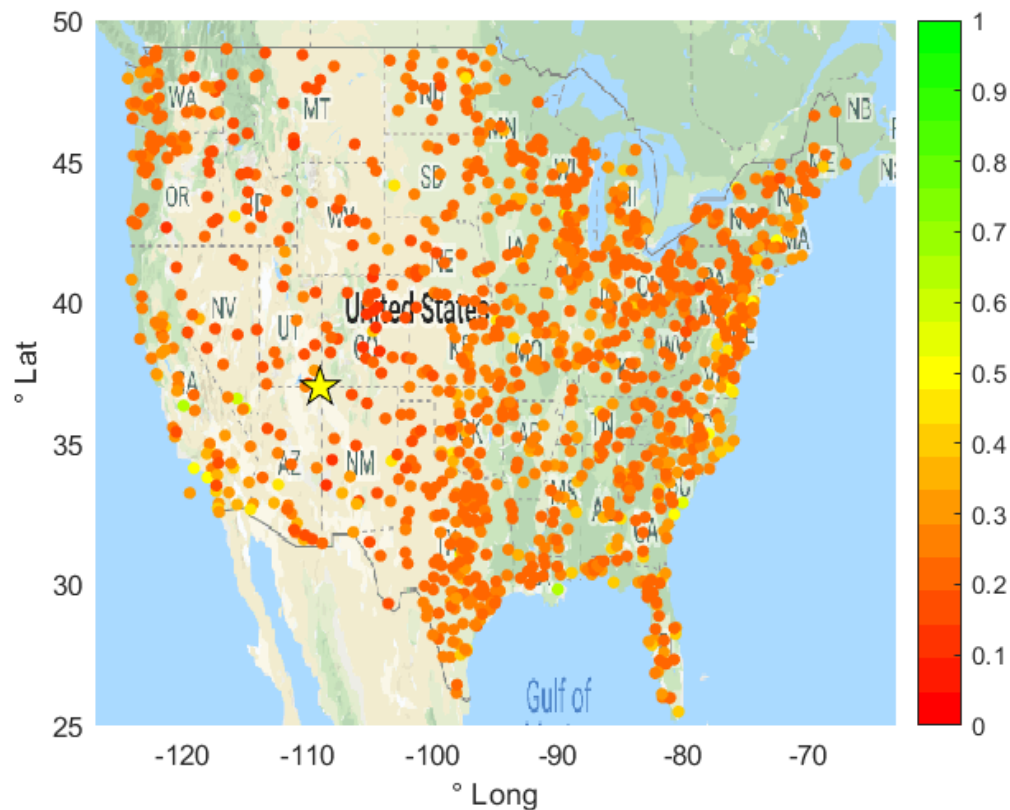


Figure 31. Baseline LCAAT Colormap of Representative Airfield Set

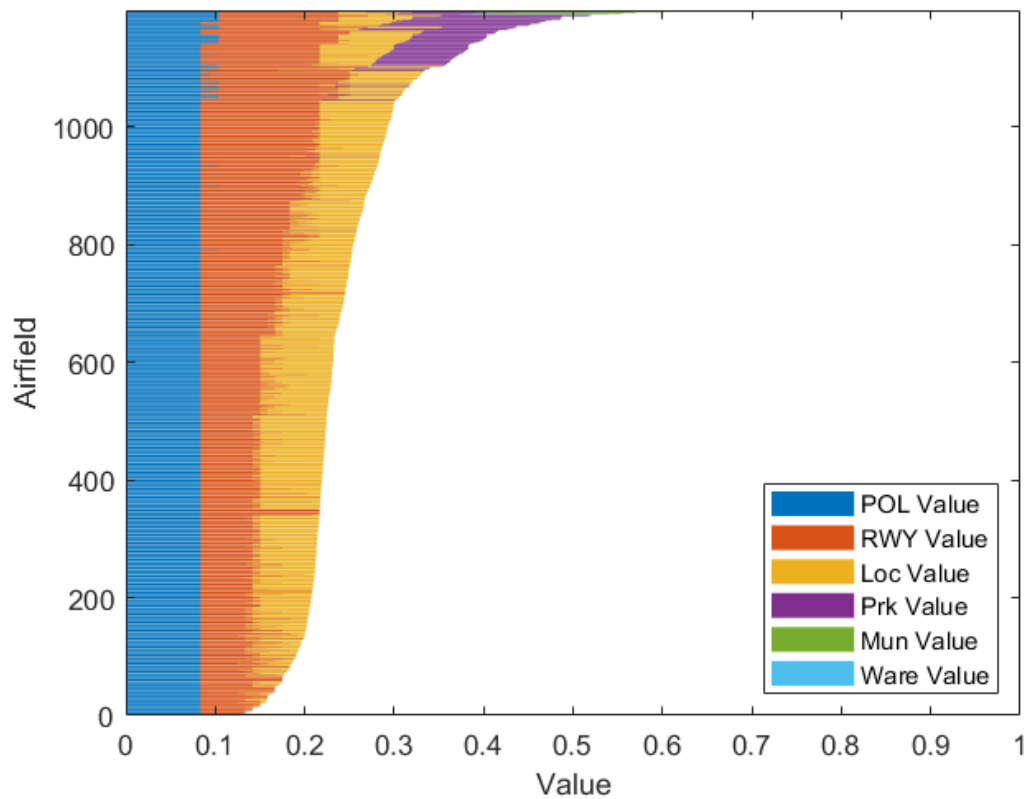


Figure 32. Baseline LCAAT Tornado Chart of Representative Airfield Set

Figure 33 show the results of each LCAAT conceptual system design. This figure shows that there is no variation in the systems value across the evaluated system designs.

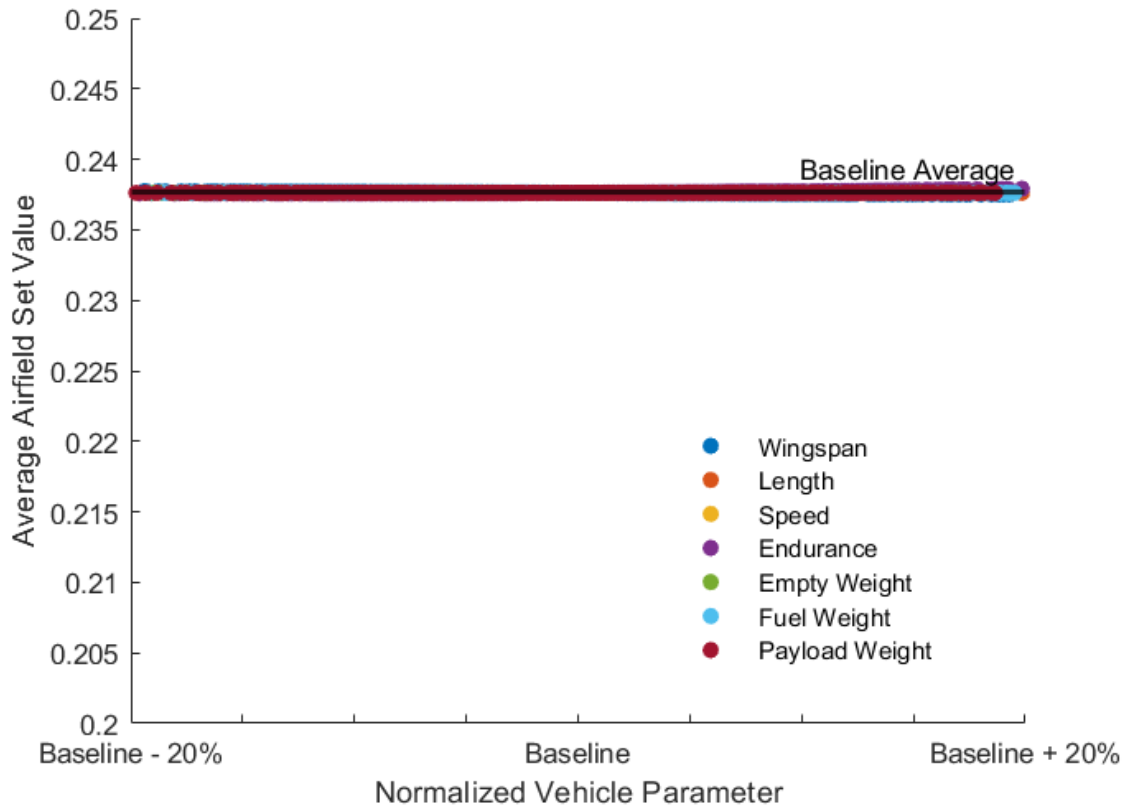


Figure 33. LCAAT System Monte Carlo Analysis Results

Comparative Analysis

The four conceptual systems individual results were then compared to each other across the representative set of airfields. Figure 34 shows the CDF of each baseline system. A system that would support an adaptive basing strategy, and provide a more resilient basing posture than other systems would be valued higher on the same set of airfields. This is shown in the CDF as a curve that is further to the right on the abscissa axis before it rises on the ordinate axis. This figure resembles overlaying each systems tornado chart, showing that the the MALE ISR system has a higher value than the other systems.

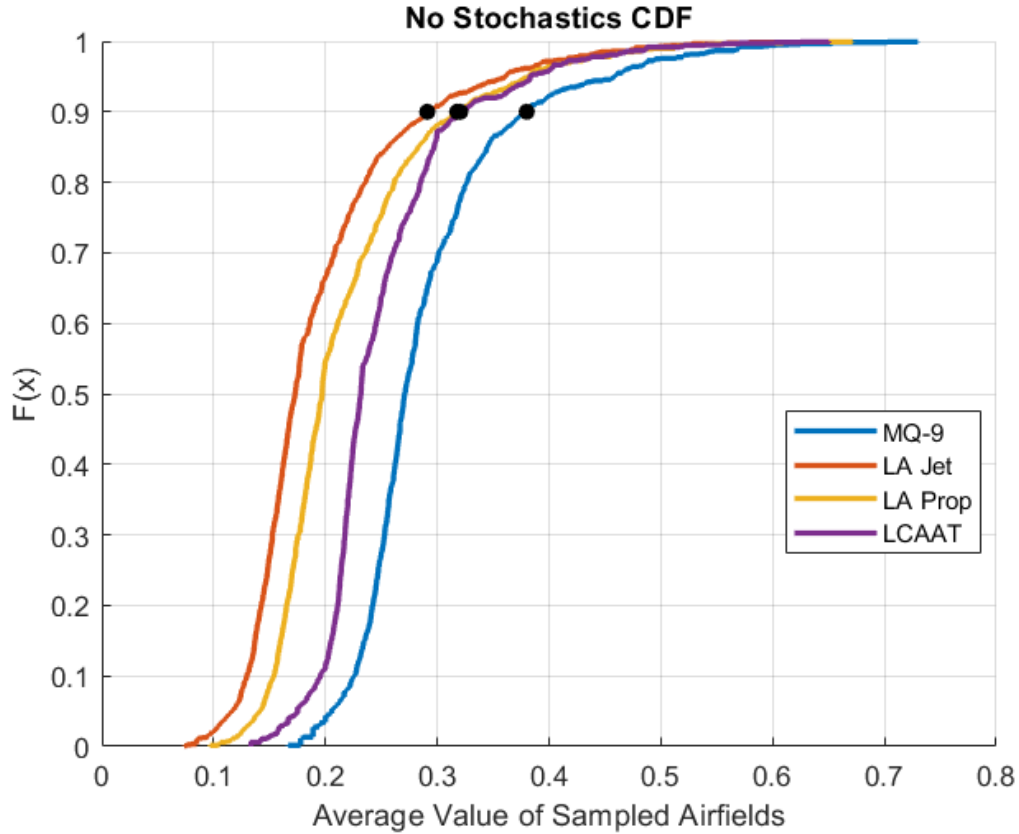


Figure 34. Cumulative Distribution Function Comparing all four Systems

Figure 35 shows a zoomed in view around the 90% percentile of the CDFs from Figure 34. Reading this graph, 90% of the airfields for the LA jet system would have a value of less than 0.291, but for the MALE ISR system, 90% of the airfields have a value less than 0.38. This shift of almost 10% in the systems basing value along the majority of the curves in Figure 34.

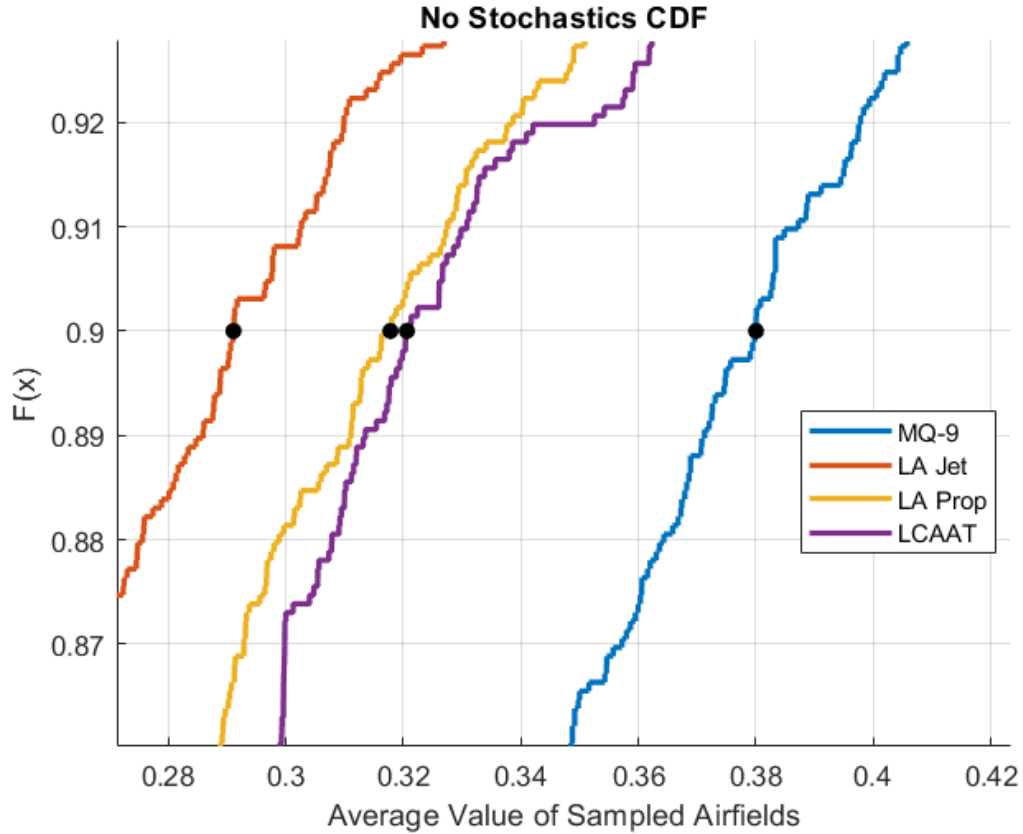


Figure 35. Cumulative Distribution Function Comparing all four Systems Zoomed in

The value of all 7,000 conceptual system designs for all 1,197 airfields were aggregated and placed into the probability density functions seen in Figure 36. The MALE ISR system is shown to have a shift in density to the right of the graph, showing a higher probability of a better value. After visualizing the data in Figure 36, normality cannot be assumed.

To test for a statistical difference between the MALE ISR system and the LCAAT system, a difference of means test could not be conducted without normality. The Wilcoxon signed rank test is used to test a shift in median difference for data that cannot assume normality, but this test assumes symmetry of the differences of data (Box *et al.* , 1978). When the differences were plotted in the top chart in Figure 38, it became clear the differences were not symmetric. A logarithmic transformation

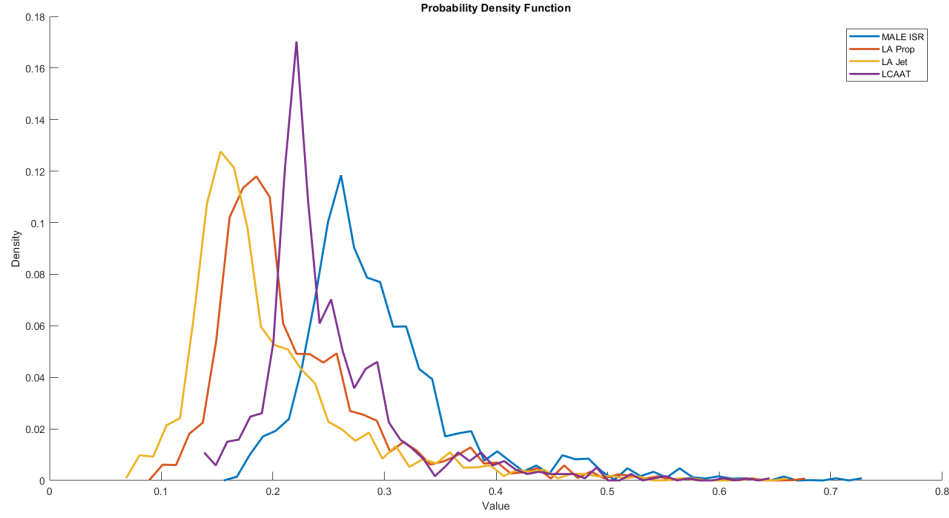


Figure 36. Probability Density Function of all Evaluated Designs

was then applied to the original data – See Figure 37. After transforming the data, a Kolmogorov-Smirnov (KS) test was applied to test the data for normality before conducting a difference of means test. The null hypothesis for the KS test is shown below:

H_o : The data follows the standard normal distribution

H_1 : The data do not follow the standard normal distribution

The KS test is used to test if data fits the standard normal distribution, the MALE ISR and LCAAT data was shifted to fit the standard normal with Equation 4:

$$X = \frac{(A - \mu)}{\sigma} \quad (4)$$

Where:

A is the MALE ISR or LCAAT Data

$\mu = -1.243$ and -1.414 for the transformed MALE ISR and LCAAT respectively

$\sigma = 0.221$ and 0.229 for the transformed MALE ISR and LCAAT respectively

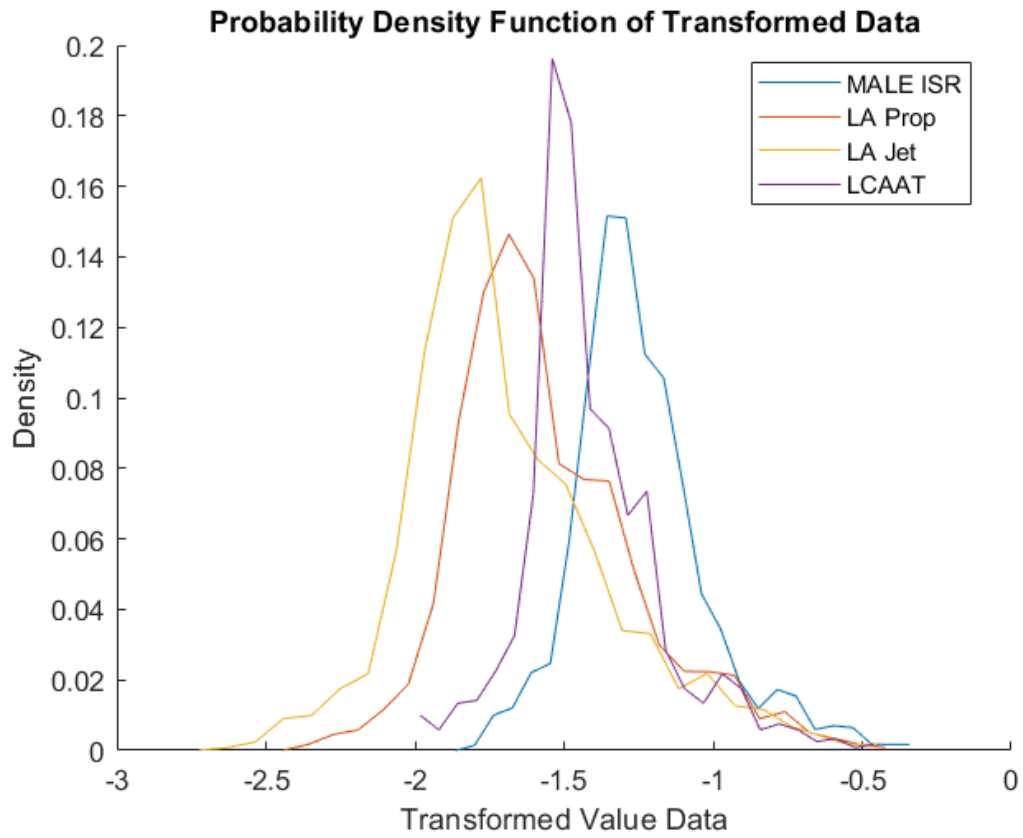


Figure 37. Logarithmic Transformed PDF

The KS test was conducted for both the MALE ISR and LCAAT transformed data, and both rejected the null hypothesis. Because the transformed data are non-normal, the Wilcoxon signed rank test was revisited. The differences of the transformed data shown in the bottom graph in Figure 38. The null hypothesis of the Wilcoxon signed

rank test is shown below:

$$H_o : \tilde{d} = 0$$

$$H_1 : \tilde{d} > 0$$

Where:

$\tilde{d} =$ The median of the differences

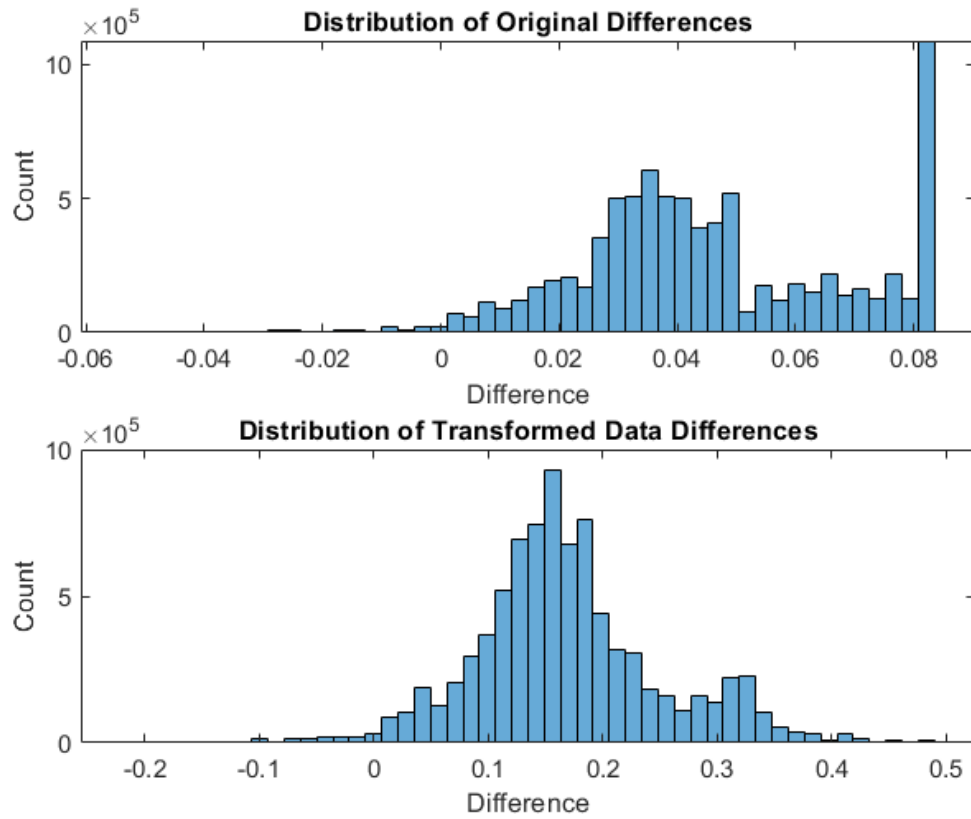


Figure 38. Distribution of Differences between MALE ISR and LCAAT Systems

With a symmetric distribution of the differences, MATLAB's signrank function was called to calculate a one sided Wilcoxon signed rank test. This test resulted in a

p-value of 0, rejecting the null hypothesis that there is no difference in the medians of that data. This concludes that there is significant difference between the MALE ISR systems value and the LCAAT systems value. Otherwise saying that the MALE ISR conceptual system is the best system evaluated for a agile basing posture.

Sensitivity Analysis

Finally sensitivity analysis is conducted on the weights at the branch level of the value hierarchy to see how sensitive the results are to the current weights. Figure 39 shows the results of varying the weight of the location branch from zero to one, and adjusting the weights of the other five branches equally. As the location branch weight is reduced from 0.1667, the LCCAT conceptual system becomes the preferred system. When the location weight is reduced, the importance of time over target is reduced. The LCAAT system is the lightest and smallest, and therefore can maximize its agile basing value at every airfield when the LCAAT's limited range is considered weighted lower. As the weight of the location branch is increased, the MALE ISR system pulls away from the other considered systems. This is because as the importance on time over target is increased, the long endurance of the MQ-9 is receiving more value and the other systems cannot compete.

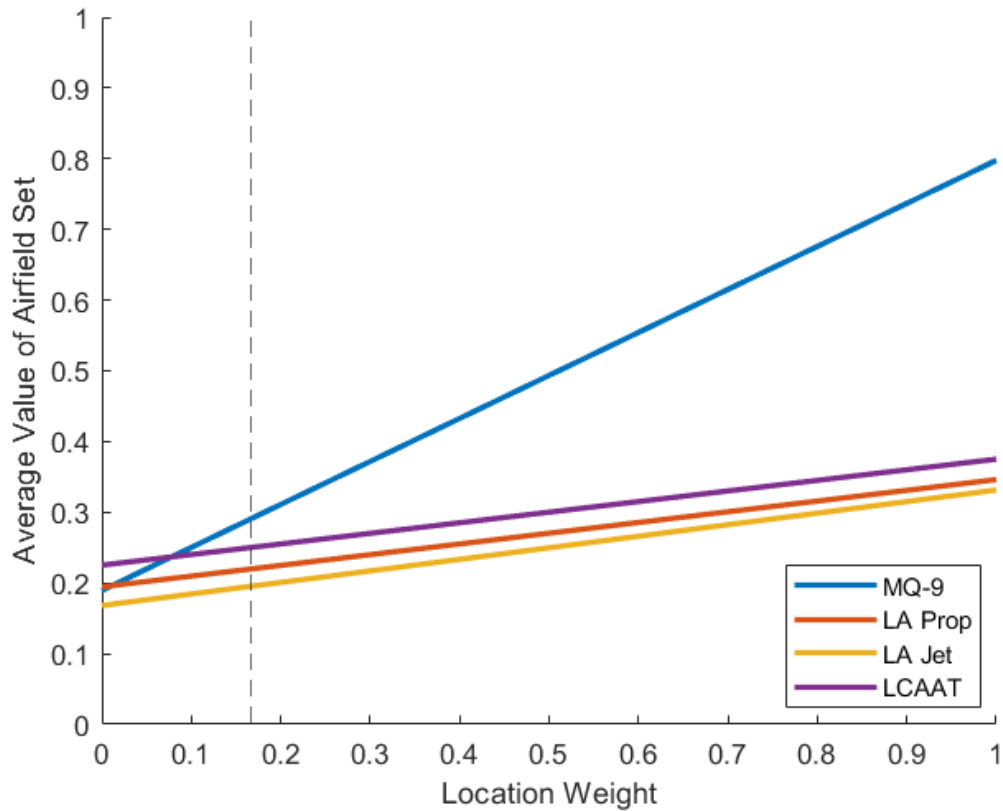


Figure 39. Sensitivity Analysis around the Location Branch

Summary

This chapter began by verifying the LOGICAT and a built in value hierarchy. The second section explained the scenario used to evaluate four conceptual systems. The chapter then discussed the four systems and the individual results of those systems. The last section compared the four systems across the sample data set, finding statistical difference in the value of the MALE ISR system over the other systems. Finally the sensitivity of the results to the current weights of the value model were analyzed.

V. Conclusion and Recommendations

This chapter begins with a review of the research questions and answers them found in the analysis. Potential topics for future work and extensions of this research are discussed in the second section. This chapter concludes with a summary of this research.

Conclusion

The objective of this research was to develop a methodology for evaluating a conceptual system across the physical basing environment the system will likely operate in. This research goal was achieved with the development of the LOGICAT and a built-in conditional value model to assess conceptual systems for agile basing value. This research used a notional model to demonstrate the tool; further refinement of the data and value hierarchy is discussed in the next section.

Research Question 1.

How can capability planning analysts evaluate competing conceptual designs, including realistic base infrastructure constraints?

It was found that the use of Multi-Objective Decisions Analysis (MODA) is currently used in conceptual analysis by the sponsor. Using VFT allowed the tool to value any conceptual system for an agile basing value. The conditional value model allows the conceptual planning analysts to provide consistent analysis across various designs. The conditional properties, keep each value measure relevant to the concept considered. Base infrastructure was added through the creation of the tool to filter airfields based on desired parameters.

Research Question 2.

What parameters need to be modeled for a conceptual weapon system and with what level of fidelity?

To keep consistent analysis across different conceptual systems, the systems were modeled with a low level of fidelity. Some conceptual designs are further along in the design process and have more information available, but this left missing values for the designs that were not as developed. By using the same information across each system the analysis is consistent. For this research eight vehicle parameters were modeled. The vehicles wingspan, length, speed, endurance, empty weight, fuel weight, payload weight and anticipated fuel type. These system parameters were selected from discussion with the sponsor and the information available in Appendix A.

Research Question 3.

What airfield and logistics parameters need to be included, and how can they be related to the concept weapon system parameters?

The sponsor requested the consideration of all USAF, DoD and commercial base infrastructures. For this research it was decided to include fifteen airfield parameters in the analysis. These parameters are listed in Table 3 (from Chapter III, reprinted below) with the associated system parameter used in the value model.

How each airfield parameter is adjusted by a vehicle parameters is further explain in Appendix B. These airfield parameters were selected as an initial exploration of how an airfield could constrain a conceptual system design. The next section discusses expanding the value model to include additional parameters.

Table 3. Airfield Parameters and System Parameters

Airfield Parameter	System Parameters
Fuel Storage Capacity	Fuel Weight
Fuel Resupply Capacity	Fuel Weight
Current Fuel Type	Fuel Type
Refueling Equipment Available	Length and Wingspan
Crosswind Runway	None
Runway Surface	MTOW
Runway Length	MTOW
Runway Width	MTOW
Taxiway Width	Wingspan
Airfield Distance from AOI	Speed and Endurance
Airfield Elevation	MTOW
Hangar Area	Length and Wingspan
Parking Apron Area	Length and Wingspan
Munition Storage	None
Warehouse Area	Length and Wingspan

Future Work

This research developed a tool to include base infrastructure and logistics in conceptual system analysis, there are multiple areas for future work to continue or expand on this research. This section will describe each area.

Aerospace Design.

This project considered a small set of variables for early conceptual design; the inclusion of more vehicle parameters would allow for a higher fidelity model. Additionally, a higher fidelity model could use more physics based analysis tools to model the interdependency of design parameters. Including additional parameters and constraints would change the stochastic sampling conducted. Instead of assuming all designs are feasible, sampling could be conducted so the entire design space can be evaluated while maintaining a feasible design with the underlying equations between parameters. For instance, this could take one randomly sampled value for wingspan

and calculate how the other vehicle parameters would be adjusted if the wingspan was increased or decreased – e.g. the empty weight of the system would change as the vehicle changed size. This would need to be repeated across all the vehicle parameters to ensure the design stays feasible and the entire design space is considered.

This research began with the intent to optimize a system using the airfield parameters as a constraint. The optimization problem would seek to maximize the value of a set of airfields, minimize variation of the airfield values, and maximize the performance of the system. More on the inclusion of performance is included in a following section. The multi-objective optimization would become possible with the inclusion of the aerospace design perspective. In the early attempts at the optimization of the system design, without the relationship between parameters, the model always selected the upper or lower bounds for each parameter. A higher fidelity model would allow the optimization algorithms to find a mathematical optimum within the bounds of a feasible aircraft.

Value Model.

With a higher fidelity model, specifics like minimum runway length could be calculated and these values could be used in place of vehicle categories in the value model. Consider the runway length example demonstrated in Chapter III. Instead of placing the Cessna Skyhawk and the Super Galaxy in the light and giant categories respectively, the calculated minimum runway length could be set as a point in the curve, $-V_{RunwayLength}(A_i|C_j) = 0.8$. Then C_j could represent the runway length requirement instead of the MTOW thus transforming the value measure by individual concept instead of category. In this case, the airfield with a 5,000 ft. runway would still score a 1 for the Skyhawk. The Super Galaxy would adjust the curve so 8,000 ft is set at 0.8 value, resulting in a score of 0.5 instead of 0.2 in the current model.

The value model would also need to be recreated with the use of a senior decision maker as the current value model embedded in the tool is a notional example to demonstrate the methodology. If the value functions are changed so that they are not all linear or a simple categorical examples and the weights are appropriately selected instead of being left equal to each other, the results could change and would be more meaningful than the notional example demonstrated. Sensitivity analysis should then be conducted on the new value hierarchy to see how the solution is effected by the model's weights.

Data.

As with most analysis, the results can only be as good as the information being fed into it. The AAFIF data set contains hundreds of variables that could be considered in the analysis. Only 15 airfield parameters were considered because of this study's scope and time limitations. The value model could be expanded to include additional parameters, especially if the conceptual systems model fidelity level is increased. The AAFIF data set also includes a remarks section; this section contains text data that often has more valuable information than what is within the defined variables. The ability to ingest, manipulate, and understand this data would also provide more valuable information in the design and airfield planning processes.

Weather was assumed out because of the scope and time limitations of this study, but certain vehicle designs perform better in various weather conditions. The current MQ-9 was never designed to fly in poor weather because of its ISR mission; but as technology and operational scenarios change, weather information could influence the design process. The inclusion of weather data in the airfield value model would provide further constraints on a system design. If weather data could be used to filter out airfields, the remaining set of airfields would be a more valuable set of airfields.

Cost and Performance.

This research did not include costs. The LOGICAT tool provides information about selected airfields and can display the value of airfields based on conceptual system parameters. This information can be used to support separate cost analysis studies. Cost would be an important factor to consider in a conceptual design. If a change in a vehicle parameter resulted in a significant increase or decrease in base value, the cost associated with that change might be justified. Also if the set of airfields that provided the best basing value needed infrastructure improvements to meet operational needs, a gap analysis of the value model would identify where costs could be applied to improve the basing posture.

The inclusion of performance models or simulations into the analysis would allow for the trade off of fuel and payload weight to be further examined beyond its airfield value. The current model does not change the speed or endurance of the system as the payload and fuel weights are changed. If various sensors and flight paths could be simulated to provide an estimation of the potential surveillance of an area beyond a time over target estimation, the number of vehicles needed to accomplish a specific mission could be determined. This would make the Maximum on Ground (MOG) numbers of an airfield more important as the number of vehicles needed is better defined. The number of vehicles needed would be valuable in cost analysis of the system.

Summary

This research presented a methodology and tool for using current base infrastructure to inform conceptual system analysis in the early design stages of the life cycle. Chapter I presented the background information and motivation for this research and posed three research questions. Chapter II reviewed the beginning of the

defense acquisition process, current military basing policy and research, DE and the OOSEM. Chapter III described the application of the OOSEM in the creation of a tool to assess the impact of base infrastructure on conceptual design. The conditional value model was demonstrated and the full value model is provided in Appendix B. The verification of the tool and value model are shown in the start of Chapter IV. Four different conceptual systems are then evaluated with the tool, and the results compared. This research identified a tool and methodology that was able to find a statistically significant improvement in value for the MALE ISR system over the other three systems evaluated. Chapter V answers the research questions posed in Chapter I and discussed possible future research areas.

Appendix A. Conceptual Deployed Basing; CONOPS

Given weapon system conceptual design fundamental factors, we desire a tool to help understand a concepts deployed basing limitations and typical radius of operations within a given deployed theater. The study should focus upon OCONUS Forward Operating Location (FOL) base potentials, with regards to two major CONOPS events: 1) deployment to the FOL, and 2) typical operations from the FOL. Ideally, this tool will be universal to apply to most, if not all, potential USAF weapon systems. For study scope purposes, the focus will be limited to concepts applicable to the medium-altitude ISR Strike mission (e.g. MQ-9 successor), and the hunter-killer mission as the deployed operation. Note AFLCMC/XZ will provide concept descriptions.

The tool should consider current USAF, DoD, and commercial base infrastructures using specific criterion such as, but not limited to, runway length, ramp space, hangar space, and fuels available. The criterion will directly relate to concept design factors, such as the concept anticipated fuel type, serving requirements (oils; oxygen; nitrogen, etc.), gross takeoff and landing weights, runway length required, FOL munition requirements, and anticipated support equipment. The tool outcome should help identify CONOPS expectations and limitations for a given FOL such as feasible FOL bases, deployment leg duration, FOL Maximum on Ground (MOG), FOL radius of operations given a specific mission profile, fuel availability and FOL munitions storage. Additionally, the outcome could help highlight unique considerations, such as SAP/SAR materials storage or shelter requirements for maintenance practices.

Study could consider, but not limited to, the following related efforts:

- USAF "Base Support & Expeditionary (BaS&E) Planning Tool" database populated for USAF (and some DoD) bases for deployment purposes. Format for

the information consistent; actual information entered not consistent in comparison of all the bases.

- “Adaptive Basing” which is an USAF enterprise-level approach to sustain operations through logistics and base support. The concept requires the effective movement and maneuver of operational forces, including Air Force combat support units, through a robust network of forward bases to improve survivability and enable positional advantage.
- Overseas Basing of U.S. Military Forces, RAND’s National Defense Research Institute conducted an independent assessment of the advisability of changes in the overseas basing presence of U.S. forces based on an evaluation of strategic benefits, risks, and costs. Though the study focuses upon personnel stationed overseas, useful information is included. (Lostumbo *et al.* , 2013)

Appendix B. Value Hierarchy

This appendix provides a detailed description of the value model included in the LOGICAT system. The value model values airfields, but the value functions are conditioned based on the specific conceptual systems parameter. In the future work section, it was discussed that this adjustment can be calculated through physics and engineering equations if the level of fidelity of the concept is high enough to support the calculation. At the current level of fidelity, the airfield are valued in categories that are explained through each value function.

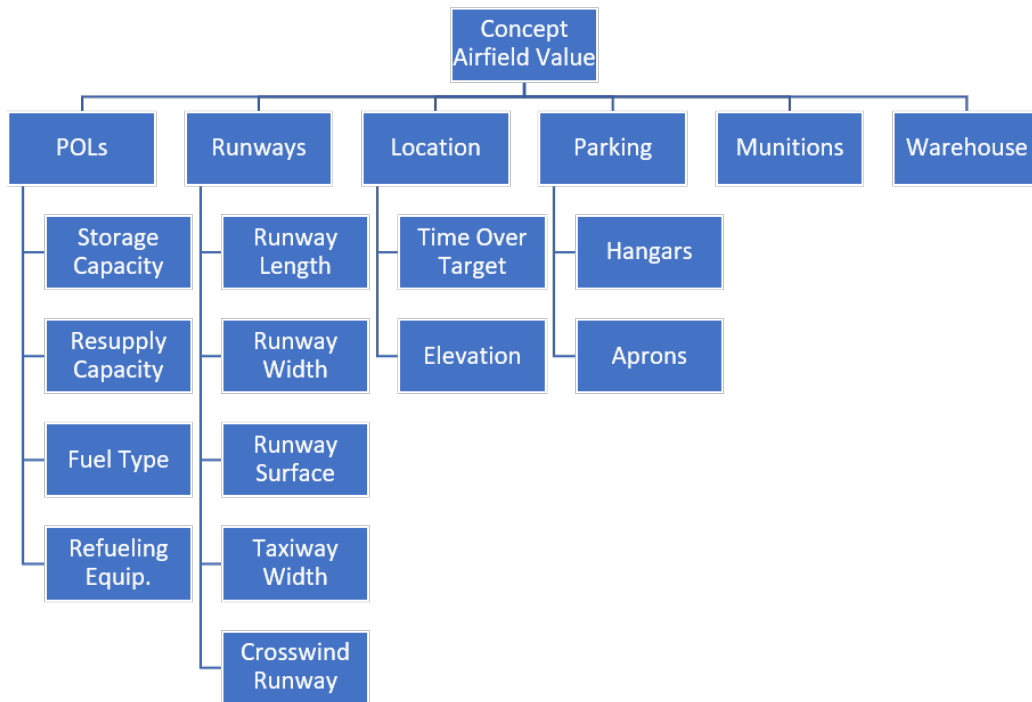


Figure 40. Value Model

POLs

The POLs branch contains four leafs under it. The fuel storage capacity at an airfield, the resupply capacity, the current fuel types stored and the refueling equipment available.

Fuel Storage Capacity.

The fuel storage capacity measure is a categorical value function that bins the total fuel storage capacity of the airfield into 5 bins. The value function is created using the vehicles fuel weight. A concept that has a smaller fuel tank would value an airfield with less storage more than a concept with a larger tank. This is because in the event that the fuel resupply is disrupted or late, normal operations can be maintained for a longer interval until the fuel supply is depleted or resupply is re-established. The concept fuel capacity bins and airfield storage capacity bins are depicted in Figure 41. Equations 5 to 7 represent the value function for the fuel storage capacity.

For a concept weapon system with a fuel tank capacity $(C_j) \leq 5,000$ lbs

$$V_{FuelStorage}(A_i|C_j) = \begin{cases} 0.5, & A_i < 50,000 \\ 0.75, & 50,000 \leq A_i < 100,000 \\ 1, & 100,000 \leq A_i \end{cases} \quad (5)$$

For a concept weapon system with a fuel tank capacity $(C_j) \leq 10,000$ lbs

$$V_{FuelStorage}(A_i|C_j) = \begin{cases} 0.25, & A_i < 50,000 \\ 0.5, & 50,000 \leq A_i < 100,000 \\ 0.75, & 100,000 \leq A_i < 500,000 \\ 1, & 500,000 \leq A_i \end{cases} \quad (6)$$

And for a concept weapon system with a fuel tank capacity $(C_j) > 10,000$ lbs

$$V_{FuelStorage}(A_i|C_j) = \begin{cases} 0, & A_i < 50,000 \\ 0.25, & 50,000 \leq A_i < 100,000 \\ 0.5, & 100,000 \leq A_i < 500,000 \\ 0.75, & 500,000 \leq A_i < 1,000,000 \\ 1, & 1,000,000 \leq A_i \end{cases} \quad (7)$$

Where:

$V_{FuelStorage}(A_i|C_j)$ is the fuel storage value an airfield receives for a concepts fuel tank capacity

A_i = is the fuel storage capacity of airfield i

C_j = is the fuel tank capacity of concept j

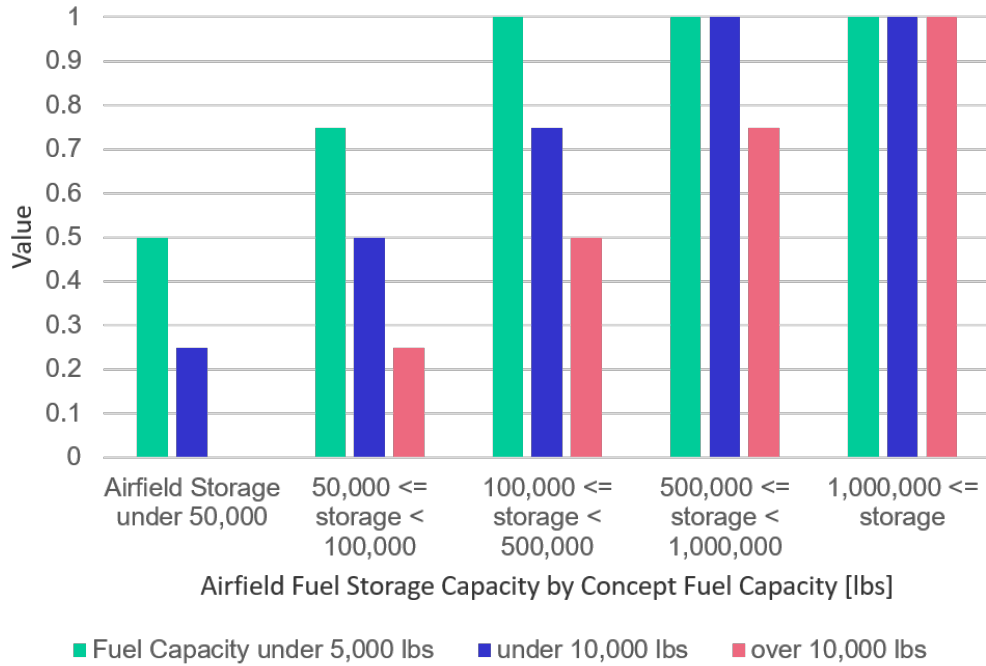


Figure 41. Fuel Capacity Value Function

Fuel Resupply Capacity.

The fuel resupply capacity measure is a categorical value function that bins the fuel resupply capacity of the airfield into the same 5 bins as fuel storage capacity. The fuel resupply capacity is defined as the amount of fuel in pounds that an airfield can receive in 24 hours. The same concept vehicle fuel capacity bins are used as well. A concept system that has a smaller tank would value an airfield with a lower resupply capacity more than a concept with a larger tank. The larger concept vehicle would be more dependent on fuel resupply because of its larger tank. The categories can be seen in Figure 42. The fuel resupply value functions are represented with Equations 8 to 10

For a concept weapon system with a fuel tank capacity $(C_j) \leq 5,000$ lbs

$$V_{FuelResupply}(A_i|C_j) = \begin{cases} 0.5, & A_i < 50,000 \\ 0.75, & 50,000 \leq A_i < 100,000 \\ 1, & 100,000 \leq A_i \end{cases} \quad (8)$$

For a concept weapon system with a fuel tank capacity $(C_j) \leq 10,000$ lbs

$$V_{FuelResupply}(A_i|C_j) = \begin{cases} 0.25, & A_i < 50,000 \\ 0.5, & 50,000 \leq A_i < 100,000 \\ 0.75, & 100,000 \leq A_i < 500,000 \\ 1, & 500,000 \leq A_i \end{cases} \quad (9)$$

And for a concept weapon system with a fuel tank capacity $(C_j) > 10,000$ lbs

$$V_{FuelResupply}(A_i|C_j) = \begin{cases} 0, & A_i < 50,000 \\ 0.25, & 50,000 \leq A_i < 100,000 \\ 0.5, & 100,000 \leq A_i < 500,000 \\ 0.75, & 500,000 \leq A_i < 1,000,000 \\ 1, & 1,000,000 \leq A_i \end{cases} \quad (10)$$

Where:

$V_{FuelResupply}(A_i|C_j)$ is the fuel resupply value an airfield receives for a concepts fuel tank capacity

A_i = is the fuel resupply capacity of airfield i

C_j = is the fuel tank capacity of concept j

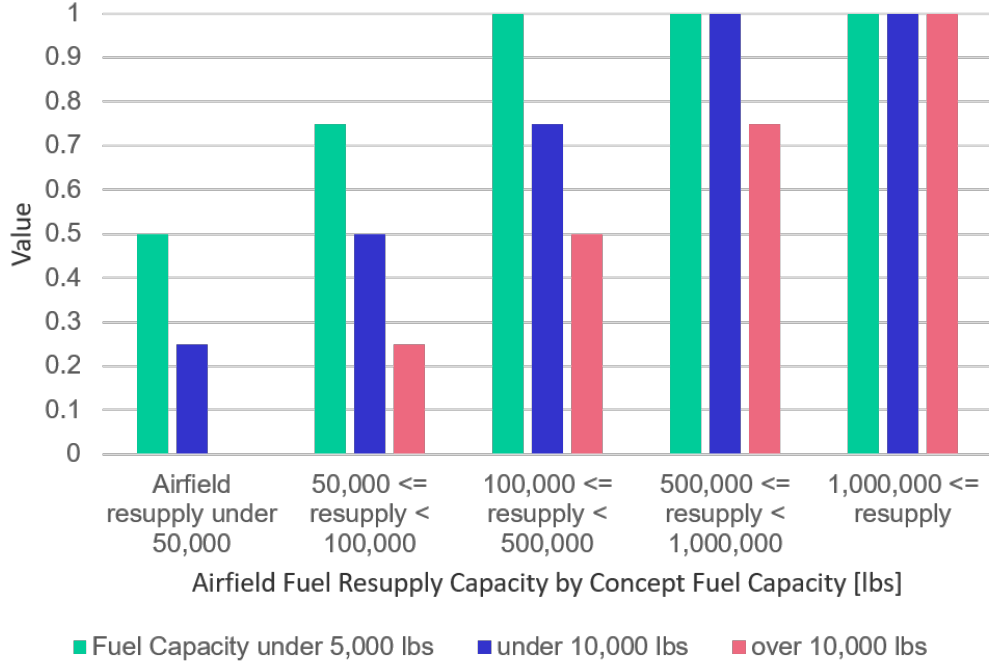


Figure 42. Fuel Resupply Value Function

Fuel Types Available.

The fuel types available leaf measures if the concept weapon systems anticipated fuel type is currently stored at the airfield. This assumes that to store this fuel the needed logistics supply chains are in place, and gives value to an airfield that has the right fuel type available. The value function for available fuel types is captured in Equation 11:

$$V_{FuelType}(A_i|C_j) = \begin{cases} 1, & \text{Fuel Type Match} \\ 0, & \text{Otherwise} \end{cases} \quad (11)$$

Where:

$V_{FuelType}(A_i|C_j)$ is the fuel type value an airfield receives for a concept

A_i = is the fuel types stored at the airfield i

C_j = is the fuel type of the concept j

Refueling Equipment.

Having the fuel at the airfield is not useful without the equipment to move the fuel from storage into the vehicle. This measure is used to understand what airfields already have equipment in place. For this research, refueling equipment is defined as only the number of fillstands. This measure assumes that there is no value in having no fillstands, as well as max value is achieved when there is a fillstand for every single parking spot, so vehicles don't need to be repositioned or wait for refueling. This measure is a linear increasing function expressed in Equation 12.

The MOG for this research is assumed to be equal to the maximum of the apron and hangar MOG. The apron and hangar MOG numbers are estimated by dividing the total hangar or apron area by the area of one conceptual system. This number is rounded down to a whole number to represent the maximum number of systems that could fit in the available area.

$$V_{FuelEquip}(A_i|C_J) = \begin{cases} 1, & A_i \geq MOG \\ \frac{A_i}{MOG}, & 0 < A_i \leq MOG \\ 0, & A_i = 0 \end{cases} \quad (12)$$

Where:

$V_{FuelEquip}(A_i|C_j)$ is the refuel equipment value for an airfield based on a concepts area

A_i = is the number of fillstands at airfield i

C_j = is the area of concept j

MOG = is the Maximum on Ground for airfield i

The POL branch value function is composed of equations 5 through 12. Each weight variable was equal, with a value of 0.25. The POL branch value function is expressed in equation 13:

$$V_{Fuels} = W_{FuelStorage} * V_{FuelStorage} + W_{FuelType} * V_{FuelType} + W_{FuelResupplyCapacity} * \dots \\ V_{FuelResupplyCapacity} + W_{FuelEquip} * V_{FuelEquip} \quad (13)$$

Runways

The runways branch contains five measures, runway length, runway width, runway surface material, taxiway width, and if the airfield has a crosswind runway. For this branch, concept vehicles were binned into 3 groups, The first being a vehicle with a MTOW under 12,500 lbs, the second for vehicles with a MTOW under 30,000 lbs, and the third for vehicles greater than or equal to 30,000 lbs. These categories were created by referencing Runway Length Requirements for Airport Design (U.S. Department of Transportation, 2005).

Some Airfields have multiple runways and others do not. This research evaluates all the runways at each airfield and uses the maximum value runway as the value for the airfield.

Runway Length.

The runway length measure is a linear increasing function that is separated into 3 aircraft categories to determine how a concept would value the runway length. AC 150/5325-4B lists small aircraft as vehicles under 12,500 lbs MTOW, and large aircraft being over that. See figures 43 and 44 for the recommended runway lengths for the first two MTOW categories based on temperature and elevation. Without weather data, the average temperature on the provided curve (75 °F) was used to read the tables. With elevation already included in the value model, the sea level estimate was used. The runway length required for takeoff is used because they are longer than the runway requirements for landing. This value measure can be seen in Figure 13 and Equations 14 through 16.

For a concept weapon system with a MTOW $(C_j) \leq 12,500$ lb

$$V_{RunwayLength}(A_i|C_j) = \begin{cases} \frac{A_i}{4,000}, & A_i \leq 4,000 \\ 1, & A_i > 4,000 \end{cases} \quad (14)$$

For a concept weapon system with $12,500 < \text{MTOW } (C_j) \leq 30,000$ lbs

$$V_{RunwayLength}(A_i|C_j) = \begin{cases} 0, & A_i \leq 2,000 \\ \frac{A_i}{6,000}, & 2,000 < A_i \leq 6,000 \\ 1, & A_i > 6,000 \end{cases} \quad (15)$$

For a concept weapon system with a MTOW (C_j) > 30,000 lbs

$$V_{RunwayLength}(A_i|C_j) = \begin{cases} 0, & A_i \leq 4,000 \\ \frac{A_i}{8,000}, & 4,000 < A_i \leq 8,000 \\ 1, & A_i > 8,000 \end{cases} \quad (16)$$

Where:

$V_{RunwayLength}(A_i|C_j)$ is the runway length value for an airfield based on a concepts MTOW

A_i = is the length of the runway of airfield i

C_j = is the MTOW of concept j

Runway Length Curves

Example: Temperature (mean day max hot month) 90° F (32° C)
 Airport Elevation (msl) 1,000 feet (328 m)
 Recommended Runway Length 4,400 feet (1,341 m)

Note: For airport elevations above 3,000 feet (915 m), use the 100 percent of fleet grouping in figure 2-1.

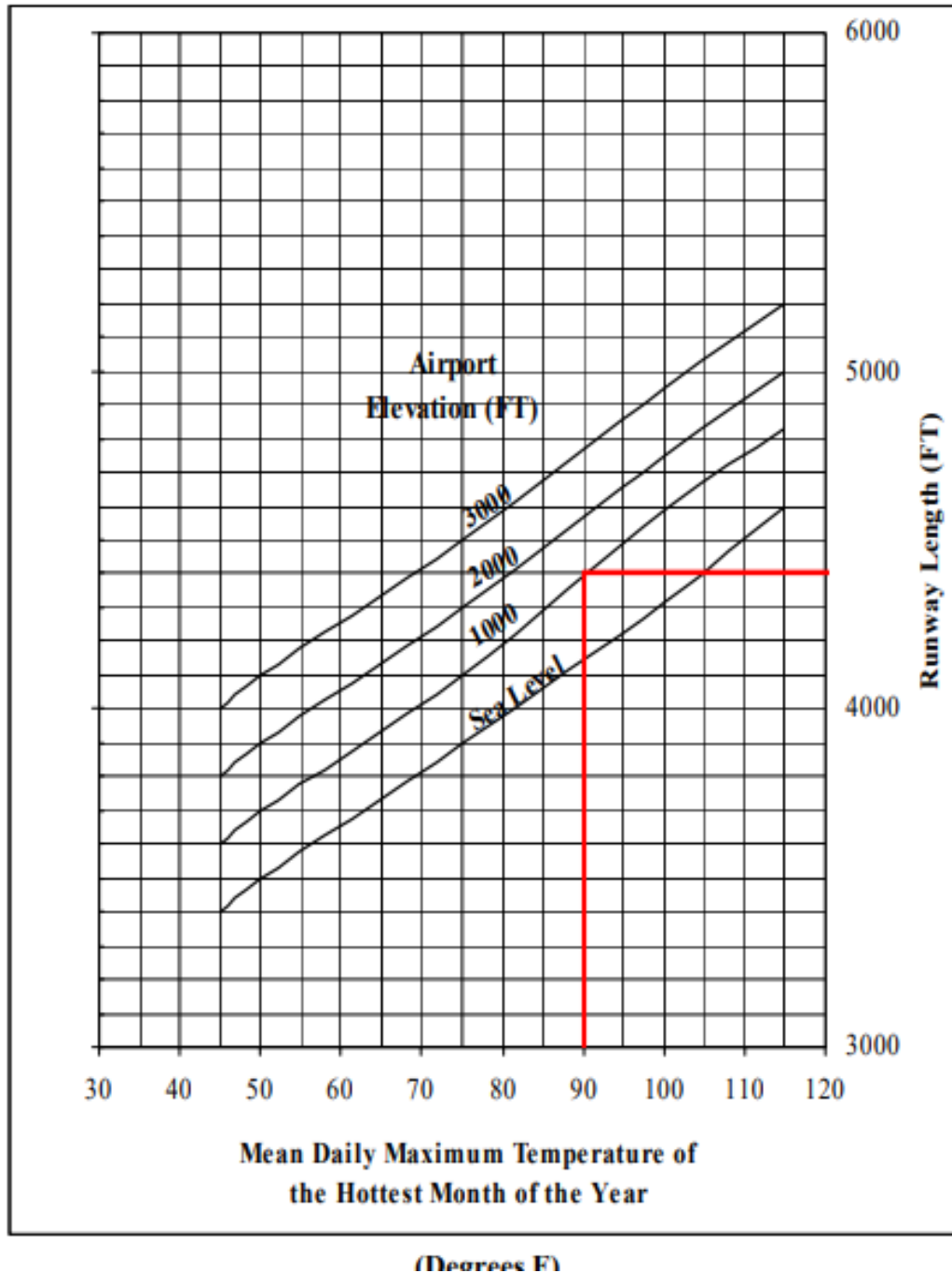


Figure 43. Runway Length Calculation for Small Aircraft (U.S. Department of Transportation, 2005)

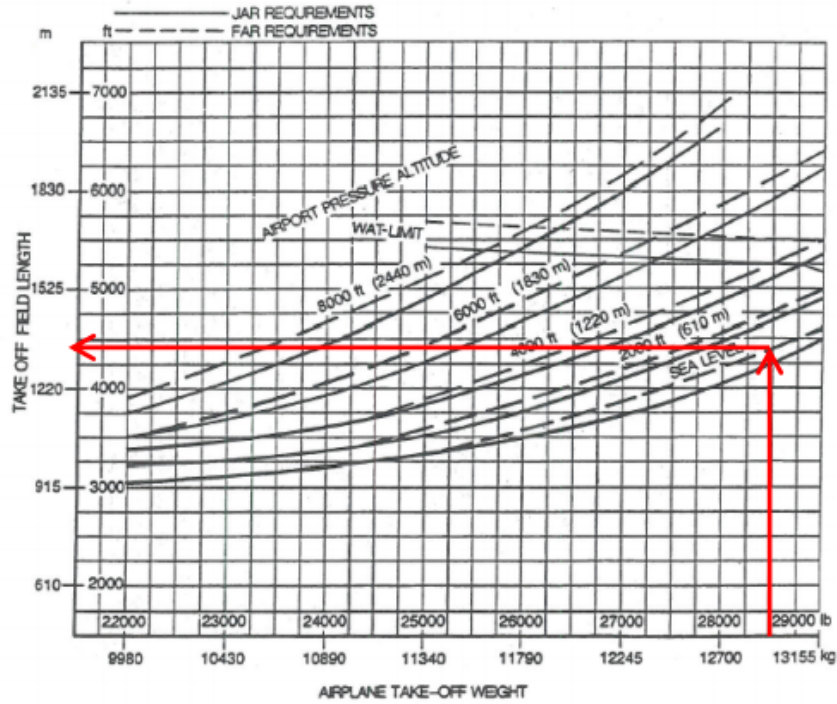


Figure 44. Runway Length Calculation for a Large Aircraft (U.S. Department of Transportation, 2005)

Runway Width.

The runway width value measure is a categorical value function. This function assigns value to an airfield's runway width based on the MTOW of the concept vehicle. This assumes that a heavier vehicle will be larger and require a wider runway. This value measure is seen in Figure 45. The value function is expressed in Equations 17 through 19.

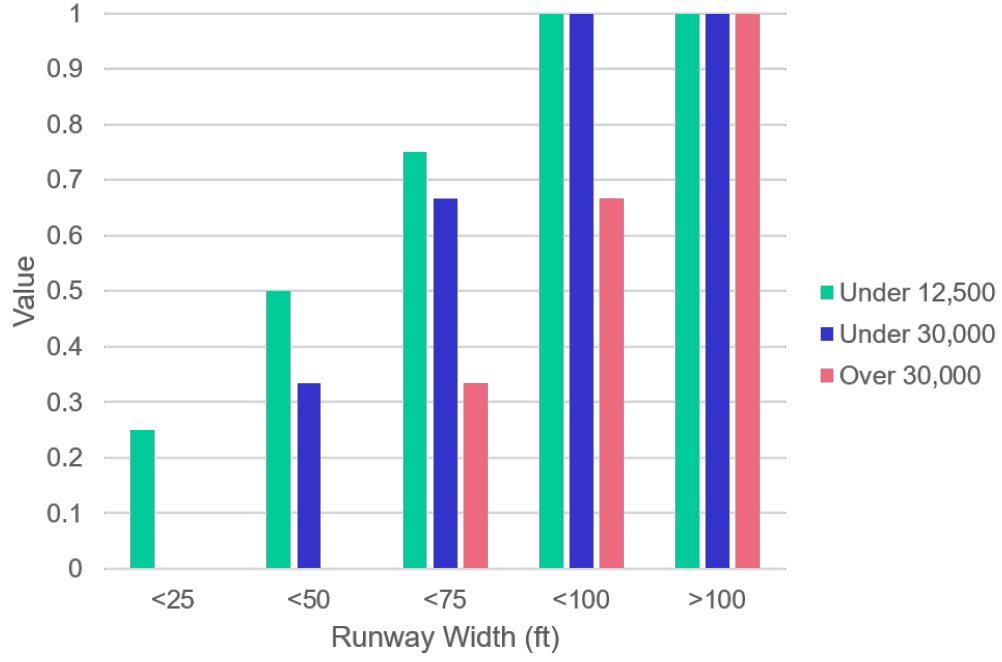


Figure 45. Runway Width Value Function

For a concept weapon system with a MTOW (C_j) $\leq 12,500$ lbs

$$V_{RunwayWidth}(A_i|C_j) = \begin{cases} 0.25, & A_i \leq 25 \\ 0.5, & 25 < A_i \leq 50 \\ 0.75, & 50 < A_i \leq 75 \\ 1, & A_i \geq 75 \end{cases} \quad (17)$$

For a concept weapon system with $12,500 < \text{MTOW } (C_j) \leq 30,000$ lbs

$$V_{RunwayWidth}(A_i|C_j) = \begin{cases} 0, & A_i \leq 25 \\ 0.333, & 25 < A_i \leq 50 \\ 0.667, & 50 < A_i \leq 75 \\ 1, & A_i \geq 75 \end{cases} \quad (18)$$

For a concept weapon system with a MTOW (C_j) > 30,000 lbs

$$V_{RunwayWidth}(A_i|C_j) = \begin{cases} 0, & A_i \leq 50 \\ 0.333, & 50 < A_i \leq 75 \\ 0.667, & 75 < A_i \leq 100 \\ 1, & A_i \geq 100 \end{cases} \quad (19)$$

Where:

$V_{RunwayLength}(A_i|C_j)$ is the runway length value for an airfield based on a concepts MTOW

A_i = is the length of the runway of airfield i

C_j = is the MTOW of concept j

Runway Surface.

The runway surface value measure is a categorical value function that categorizes the 23 different surface materials listed in the AAFIF database. This measure serves as an approximation for an aircraft Load Classification Number (LCN) or Aircraft Classification Number (ACN). These values determine if the runway surface is strong enough to support load of an aircraft. The LCN and ACN calculations involve aircraft geometry, number of wheels, and tire pressure; this level of fidelity could not be reach while evaluating an early conceptual system. The approximate measure can also be valuable because some aircraft cannot operate on certain surface. For example *Airfield Planning and Design Criteria for Unmanned Aircraft Systems* states that it is expected that the predator will only operate on paved surfaces. (Department of the Air Force, 2009a) The categories for runway surfaces and the respective value received is listed in Table 6 and Equations 20 through 22.

Table 6. Runway Surface Value Function

Airfield Runway Surface	Vehicle MTOW (lbs)		
	$C_j < 12,500$	$C_j < 30,000$	$30,000 \leq C_j$
Bin 1 Unknown, Other	0	0	0
Bin 2 Sand, Snow, Grass, Gravel, Ice	0.2	0	0
Bin 3 Brick, Composite, Temporary clay, Temporary composite, Graded earth, Temporary coral, Temporary membrane Mix-in-place, pierced-steel planking	1	0.8	0.5
Bin 4 Asphalt, Laterite, Permanent surface, Temporary bituminous tar, Portland cement concrete, Crushed rock or tarmac Permanent part portland cement	1	1	1

For a concept weapon system with a MTOW (C_j) $\leq 12,500$ lbs

$$V_{RunwaySurface}(A_i|C_j) = \begin{cases} 0, & A_i \in \text{Bin 1} \\ 0.2, & A_i \in \text{Bin 2} \\ 1, & A_i \in \text{Bin 3} \\ 1, & A_i \in \text{Bin 4} \end{cases} \quad (20)$$

For a concept weapon system with $12,500 < \text{MTOW } (C_j) \leq 30,000 \text{ lbs}$

$$V_{RunwaySurface}(A_i|C_j) = \begin{cases} 0, & A_i \in \text{Bin 1} \\ 0, & A_i \in \text{Bin 2} \\ 0.8, & A_i \in \text{Bin 3} \\ 1, & A_i \in \text{Bin 4} \end{cases} \quad (21)$$

For a concept weapon system with a MTOW $(C_j) > 30,000 \text{ lbs}$

$$V_{RunwaySurface}(A_i|C_j) = \begin{cases} 0, & A_i \in \text{Bin 1} \\ 0, & A_i \in \text{Bin 2} \\ 0.5, & A_i \in \text{Bin 3} \\ 1, & A_i \in \text{Bin 4} \end{cases} \quad (22)$$

Where:

$V_{RunwaySurface}(A_i|C_j)$ is the runway surface value for an airfield based on a concepts j MTOW

A_i = is the surface material of the runway of airfield i

C_j = is the MTOW of concept j

Crosswind Runway.

A crosswind runway is “an additional runway built to compensate primary runways that provide less than the recommended 95 percent wind coverage for the airplanes forecasted to use the airport” (U.S. Department of Transportation, 2005). Wind coverage is highly dependant on the current wind direction and wind speed. This research does not use any weather data and so assumed that any airfield with

a runway that is offset by at least 70 degrees in heading could serve as a crosswind runway. This value measure is boolean where an airfield receives the value regardless of the concept being assessed. It is included in the value model to help identify better airfield options against other airfields. This value measure is expressed in Equation 23.

$$V_{Crosswind}(A_i) = \begin{cases} 1, & A_i \text{ has a crosswind runway} \\ 0, & A_i \text{ does not have a crosswind runway} \end{cases} \quad (23)$$

Where:

$V_{Crosswind}(A_i)$ is the crosswind runway value

A_i = is the boolean if an airfield has a crosswind runway

Taxiway Width.

The taxiway width value function is a linear increasing value function that assigns value based on the taxiway with the greatest width. It is assumed that the widest taxiway can accommodate vehicle movement to the needed runway. The value function is built in consideration of AFI 11-2 and AFI 11-218 to determine when a wing walker would be needed and to ensure the vehicle can safely maneuver around the airfield when needed. The value function is seen in Figure 46 and in Equation 24.

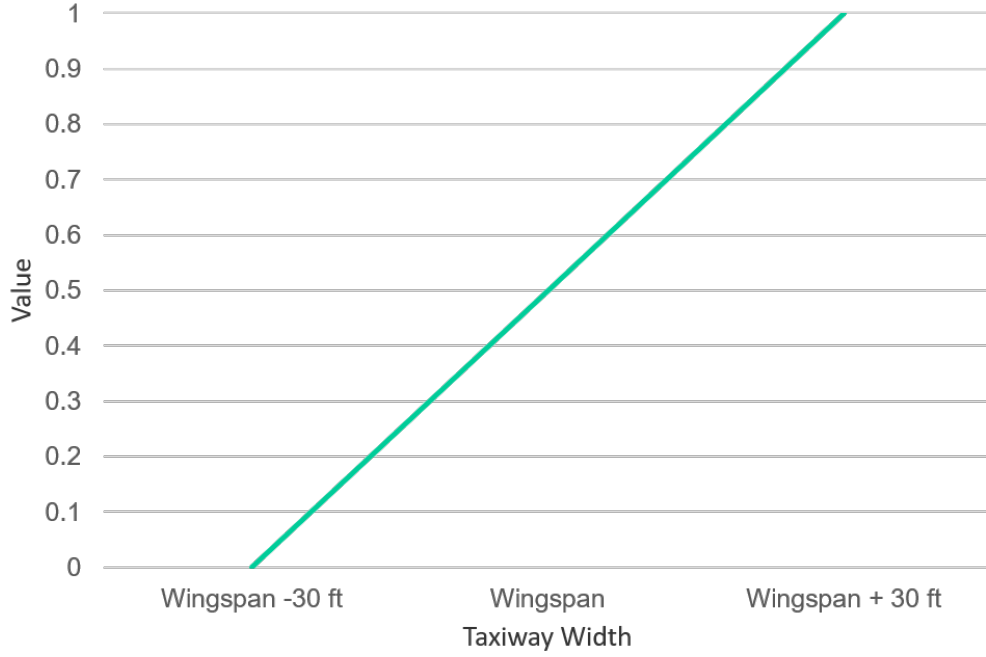


Figure 46. Taxiway Width Value Function

$$V_{TaxiwayWidth}(A_i|C_j) = \begin{cases} 1, & A_i > C_j + 30 \\ \frac{A_i}{C_i+30} & A_i - 30 < C_j \leq A_i + 30 \\ 0, & A_i \leq C_j - 30 \end{cases} \quad (24)$$

Where:

$V_{TaxiwayWidth}(A_i|C_j)$ is the taxiway width value for airfield i on concepts j wingspan

A_i = is the maximum width of an airfields taxiway

C_j = is the concepts j wingspan

The runway branch value function is composed of Equations 14 through 24 and

is displayed in Equation 25. The value of each weight in Equation 25 is 0.2.

$$V_{Runways} = W_{RWYLength} * V_{RWYLength} + W_{RWYWidth} * V_{RWYWidth} + W_{RWYSurface} * \dots \\ V_{RWYSurface} + W_{TWYWidth} * V_{TWYWidth} + W_{Crosswind} * V_{Crosswind} \quad (25)$$

Location

The location branch contains two leafs, distance and elevation. This branch is used to value the physical location of the airfield.

Distance.

The distance value measure is a linear increasing value function that assigns value to an airfield based on the conceptual systems estimated Time-over-Target (ToT) at the AOI. The ToT is calculated from an estimate made from the concepts speed and endurance parameters – see Equations 26 and 27.

$$TTT = \frac{\frac{1.15078Mi}{1NMi} * D}{C_{1j}} \quad (26)$$

$$ToT = C_{2j} - (2 * TTT) * 0.95 \quad (27)$$

Where:

TTT = time the system requires to reach the AOI from airfield A_i

D = distance from A_i to the AOI (nautical miles)

C_{1j} = concept j speed (MPH)

C_{2j} = concept j endurance (hours)

The TTT is estimated based on a simple distance and speed calculation; it is

adjusted so that distance in nautical miles is converted into hours. TTT is then doubled to include the flight time home, and subsequently reduced by 5% to account for emergency fuel and other variations in the flight. This time is then subtracted from the systems endurance estimate resulting in an estimate for the ToT.

The distance value function provides value based on ToT instead of distance. An airfield that is out of range of one concept would receive less value than the same airfield with a concept with a greater range. If the value function was defined by distance, the airfield would receive the same value without consideration of the systems range. The value function can be seen in Figure 47 and is expressed in Equation 28.

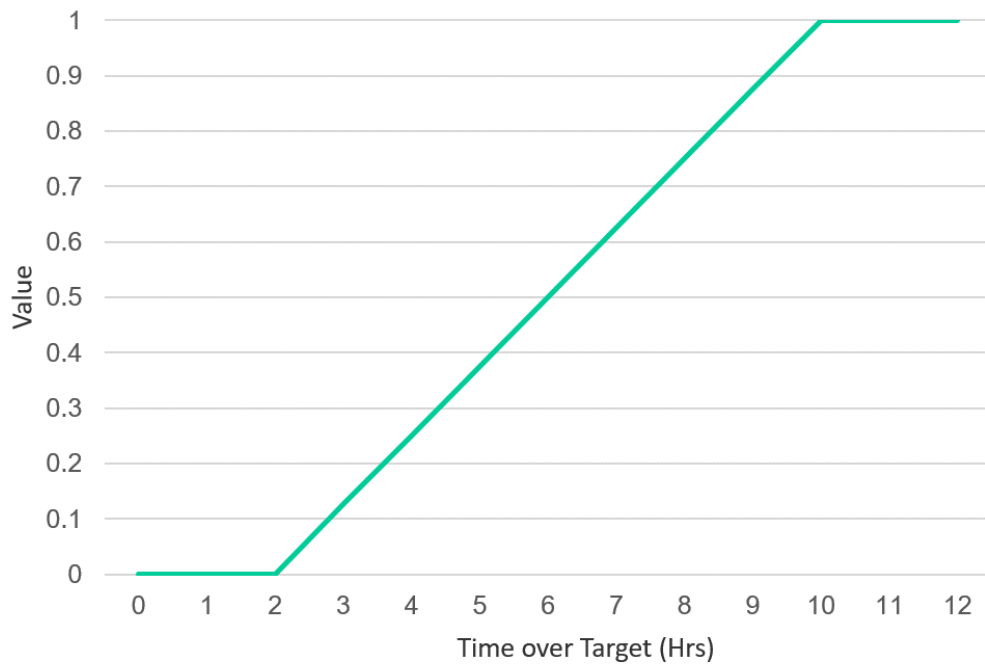


Figure 47. Distance Value Function

$$V_{Distance}(A_i|C_{1j}, C_{2j}) = \begin{cases} 1, & ToT \geq 10 \\ \frac{ToT}{10}, & 2 < ToT < 10 \\ 0, & ToT \leq 2 \end{cases} \quad (28)$$

Where:

$V_{Distance}(A_i|C_{1j}, C_{2j})$ the distance value for airfield i

calculated from concept j speed and endurance

A_i = distance from airfield i to the AOI

C_{1j} = concepts j speed

C_{2j} = concepts j endurance

Elevation.

The elevation value measure is a linear decreasing value function. This value measure uses the MTOW categories from the runway functions. As an airfield gains elevation the air is thinner and the required runway length is increased. The elevation value member is seen in Figure 48 and Equations 29 through 31.

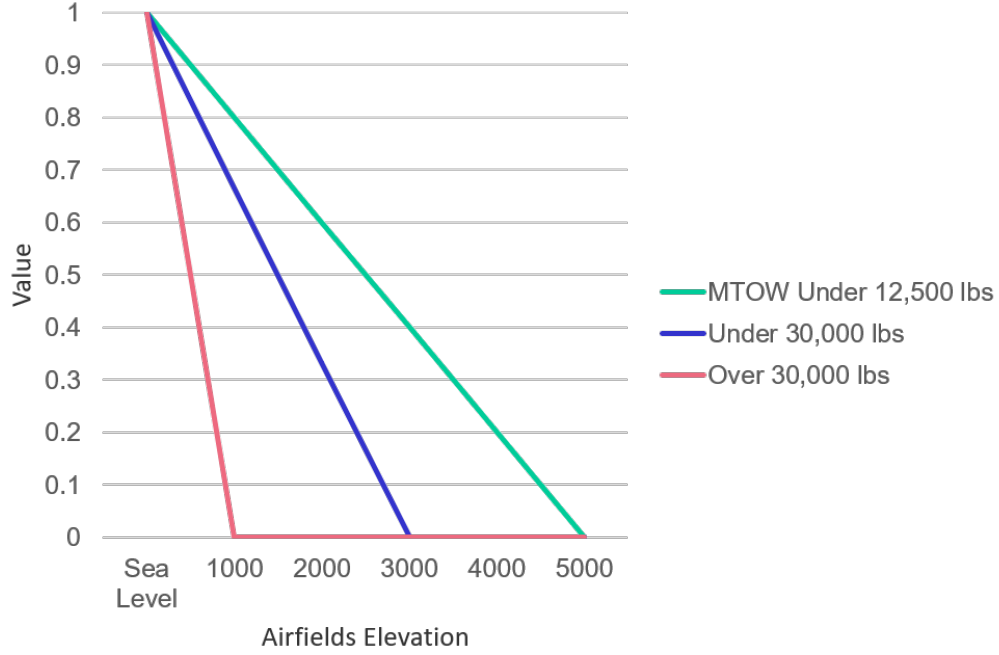


Figure 48. Elevation Value Function

For a concept weapon system with a MTOW (C_j)/ $\leq$ 12,500 lb

$$V_{Elevation}(A_i|C_j) = \begin{cases} 1, & A_i = SeaLevel \\ \frac{-(A_i+5,000)}{5,000}, & A_i \leq 5,000 \\ 0, & A_i > 5,000 \end{cases} \quad (29)$$

For a concept weapon system with $12,500 < \text{MTOW } (C_j) / \leq 30,000$ lbs

$$V_{Elevation}(A_i|C_j) = \begin{cases} 1, & A_i = SeaLevel \\ \frac{-(A_i+3,000)}{3,000}, & A_i \leq 3,000 \\ 0, & A_i > 3,000 \end{cases} \quad (30)$$

For a concept weapon system with a MTOW (C_j) > 30,000 lbs

$$V_{Elevation}(A_i|C_j) = \begin{cases} 1, & A_i = SeaLevel \\ \frac{-(A_i+1,000)}{1,000}, & A_i \leq 1,000 \\ 0, & A_i > 1,000 \end{cases} \quad (31)$$

Where:

$V_{Elevation}(A_i|C_j)$ is the elevation value for an airfield i based on a concepts MTOW

A_i = elevation of airfield i

C_j = MTOW of concept j

The location branch value function is composed of Equations 28 through 31 and expressed in Equation 32. Each weight variable in Equation 32 is equal to 0.5.

$$V_{Location} = W_{Distance} * V_{Distance} + W_{Elevation} * V_{Elevation} \quad (32)$$

Parking

The parking branch is composed of two value functions, the hangar parking area and the apron parking area. This branch is used to value the airfields MOG. This research estimates the MOG by calculating the concept systems ground footprint by multiplying the wingspan by the fuselage length. This area is then divided into the total area of the respective category.

$$A_i = \Sigma \text{ area} \quad (33)$$

$$C_j = C_{1j} * C_{2j} \quad (34)$$

$$MOG = \left\lfloor \frac{A_i}{C_j} \right\rfloor \quad (35)$$

Where:

A_i = the sum of the area of each parking area for airfield i

C_j = the ground footprint of concept j area

C_{1j} = concept j wingspan

C_{2j} = concept j length

MOG = Maximum on Ground for airfield i

Hangar Area.

The hangar area value measure is a linear increasing value function that assigns value to an airfield based on the number of concept systems that could be parked in hangars available at the airfield. This value function is seen in Figure 49 and Equation 36.

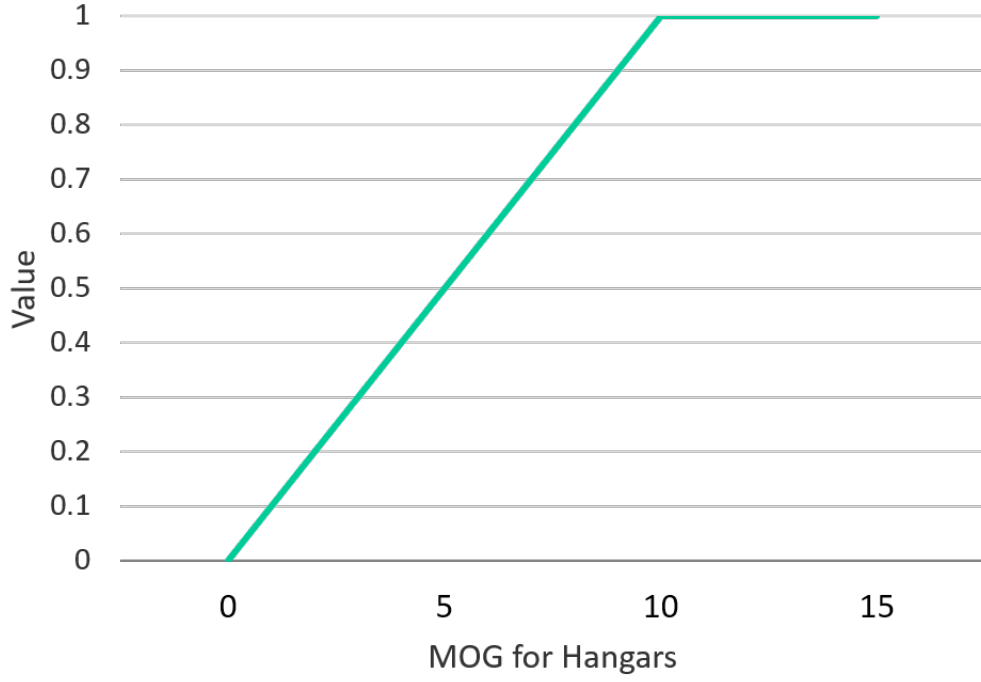


Figure 49. Hangar Area Value Function

$$V_{Hangar}(A_i|C_J) = \begin{cases} 1, & A_i \geq MOG \\ \frac{A_i}{MOG}, & 0 < A_i \leq MOG \\ 0, & A_i = 0 \end{cases} \quad (36)$$

Where:

$V_{Hangar}(A_i|C_J)$ = is the hangar parking value for airfield i based on concept j

A_i = the total area hangar area for airfield i

C_j = the ground footprint of concept j area

MOG = The hangar Maximum on Ground for airfield i

Apron Area.

The apron parking area value function is linear increasing. It is the same as the hangar parking area except that it uses the total apron area to estimate the MOG. The value function is expressed in Equation 37.

$$V_{Apron}(A_i|C_J) = \begin{cases} 1, & A_i \geq MOG \\ \frac{A_i}{MOG}, & 0 < A_i \leq MOG \\ 0, & A_i = 0 \end{cases} \quad (37)$$

Where:

$V_{Apron}(A_i|C_J)$ = is the apron parking value for airfield i based on concept j

A_i = the total area apron area for airfield i

C_j = the ground footprint of concept j area

MOG = The hangar Maximum on Ground for airfield i

The parking branch value function is composed of Equations 36 and 37 and is expressed in Equation 38. Each weight variable in Equation 38 is equal to 0.5.

$$V_{Parking} = W_{Hangars} * V_{Hangars} + W_{Aprons} * V_{Aprons} \quad (38)$$

Munition Storage

The munitions value function is boolean, where the airfield receives value if it has the ability to store munitions. This means the airfield has ordnance bunkers available and assumes the politics of storing munitions is in place. The munition value function

is expressed in Equation 39.

$$V_{Munitions}(A_i) = \begin{cases} 1, & A_i \text{ has munition storage} \\ 0, & A_i \text{ does not have munition storage} \end{cases} \quad (39)$$

Where:

$V_{Munition}(A_i)$ is the munition storage value for airfield i

$A_i =$ the boolean if an airfield has munition storage

Warehouse Area

The warehouse value function is a linear increasing value function. The airfield receives value for having warehouse area equivalent to the area of one concept system. This assumes that maintenance shops or required storage would value area by number of vehicles that there is space for. The warehouse value function is therefor based on the MOG calculated the same way as the apron or hangar MOG but using the total warehouse area. The warehouse storage value function is expressed in Equation 40.

$$V_{Warehouse}(A_i|C_J) = \begin{cases} 1, & A_i \geq MOG \\ \frac{A_i}{MOG}, & 0 < A_i \leq MOG \\ 0, & A_i = 0 \end{cases} \quad (40)$$

Where:

$V_{Warehouse}(A_i|C_j) =$ is the warehouse value for airfield i based on concept j

$A_i =$ the total warehouse area for airfield i

$C_j =$ the ground footprint of concept j area

$MOG =$ The warehouse Maximum on Ground for airfield i

Equations 13, 25, 32, 38, 39, and 40 are combined and weighted to calculate the final airfield value in Equation 41. The weight variables in Equation 41 are equal to 0.167.

$$V(A_i|C_j) = W_{Parking} * V_{Parking} + W_{POLs} * V_{POLs} + W_{Runways} * V_{Runways} + W_{Location} * \dots \\ V_{Location} + W_{Munition} * V_{Munition} + W_{Warehouse} * V_{Warehouse} \quad (41)$$

Appendix C. Additional Figures

This chapter provides the figures created for all the possible vehicle stochastic parameters that were not covered in the main text for readability.

MALE ISR Conceptual System

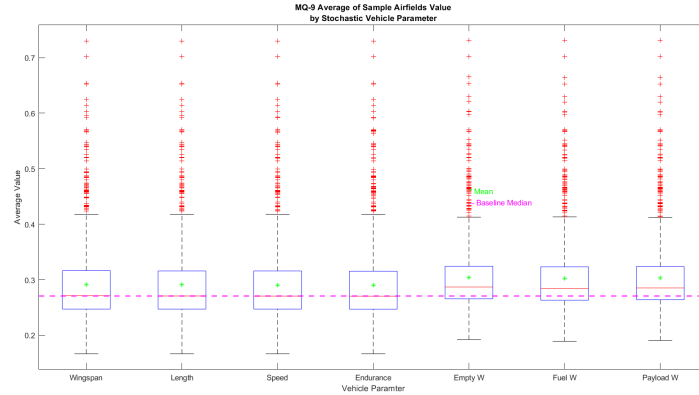


Figure 50. Boxplots for MALE ISR System MC Results

Wingspan.

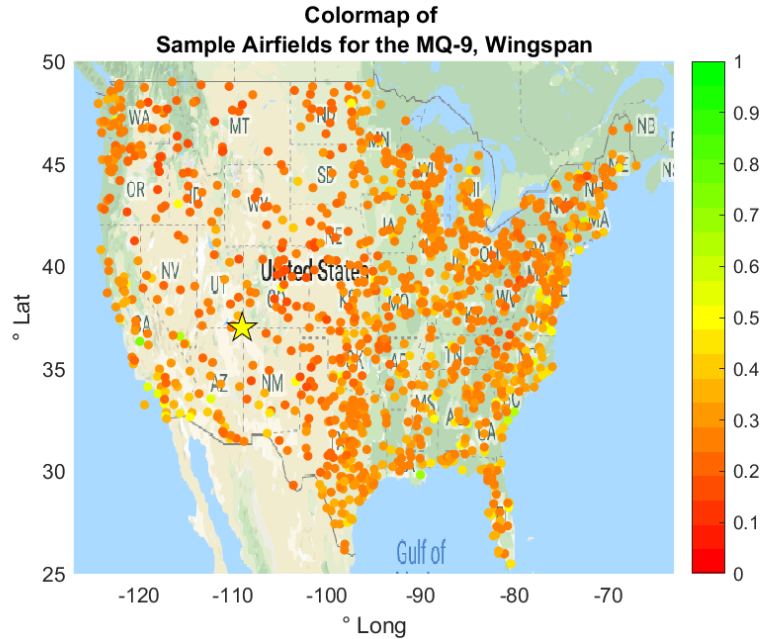


Figure 51. Colormap for the MALE ISR System, Wingspan

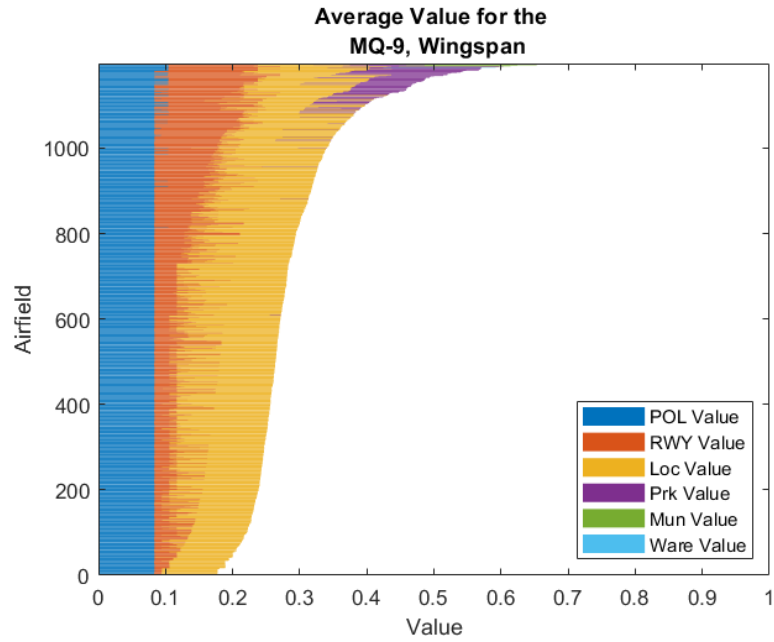


Figure 52. Tornado Chart for the MALE ISR System, Wingspan

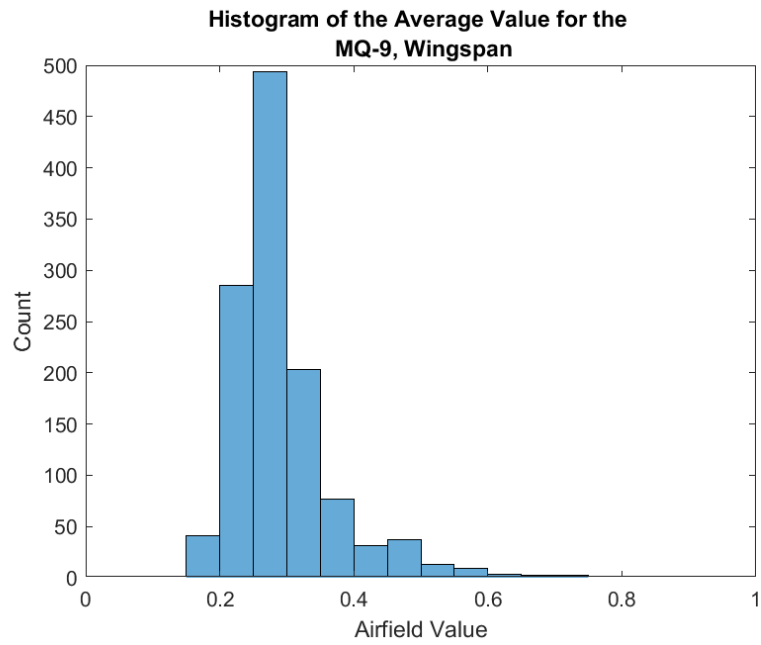


Figure 53. Histogram for the MALE ISR System, Wingspan

Length.

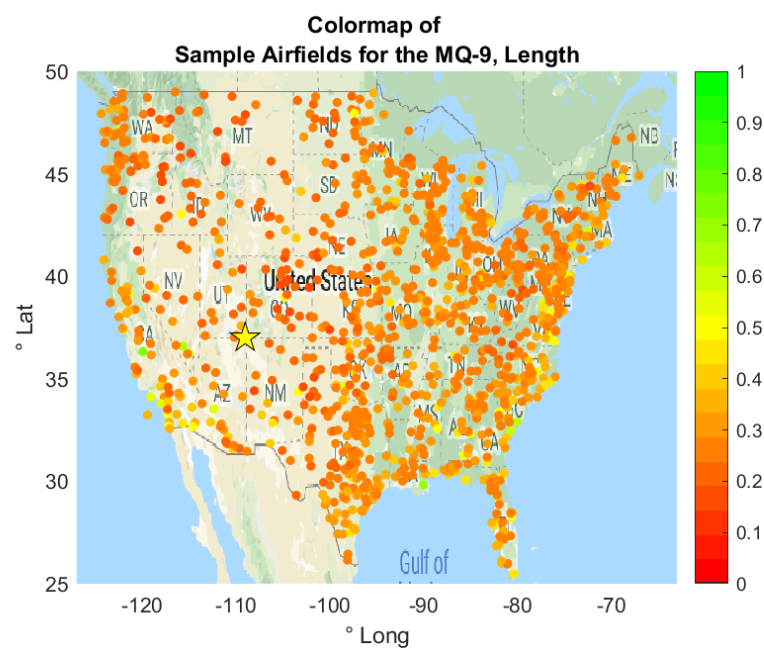


Figure 54. Colormap for the MALE ISR System, Length

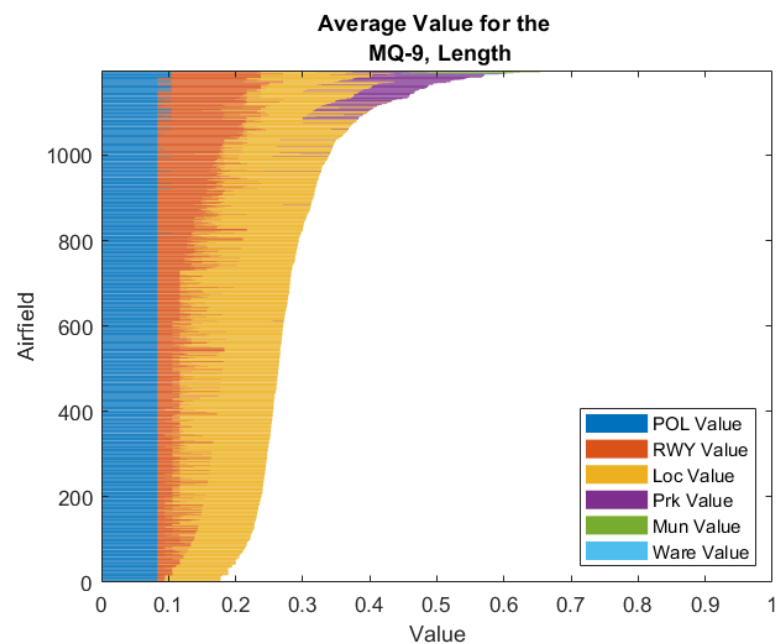


Figure 55. Tornado Chart for the MALE ISR System, Length

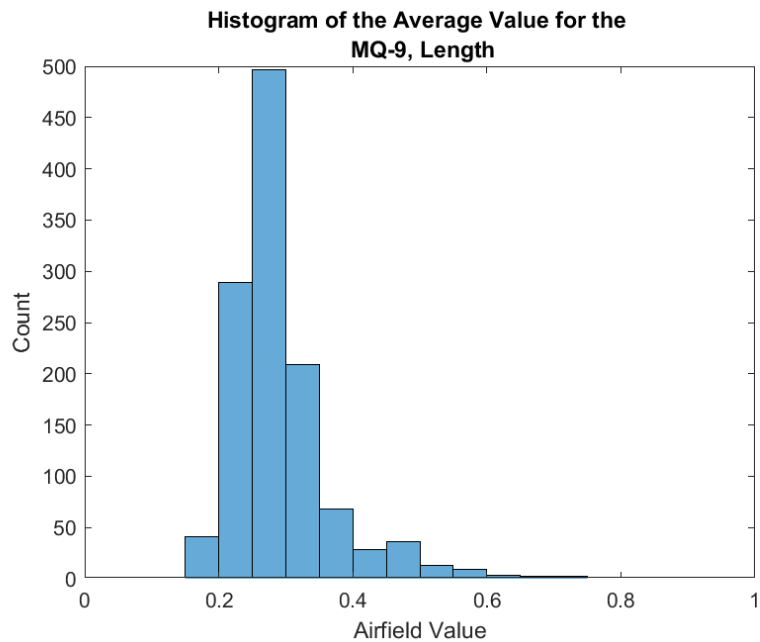


Figure 56. Histogram for the MALE ISR System, Length

Endurance.

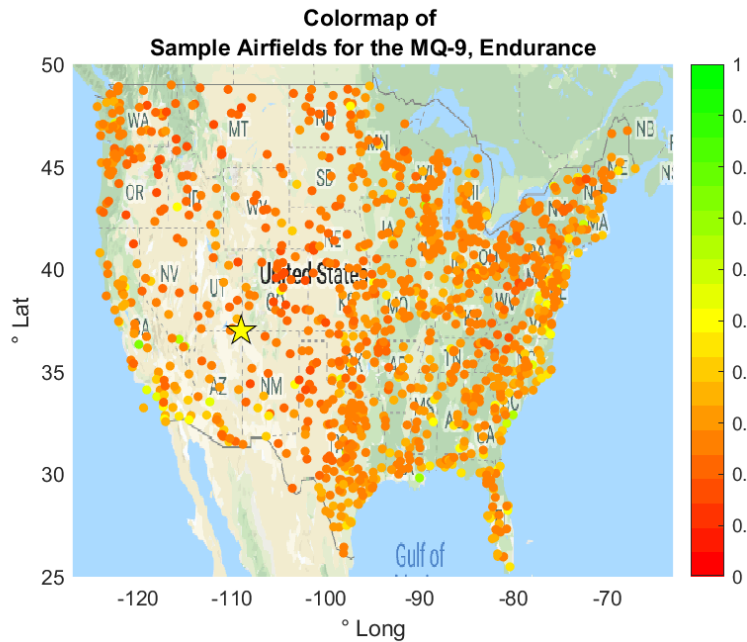


Figure 57. Colormap for the MALE ISR System, Endurance

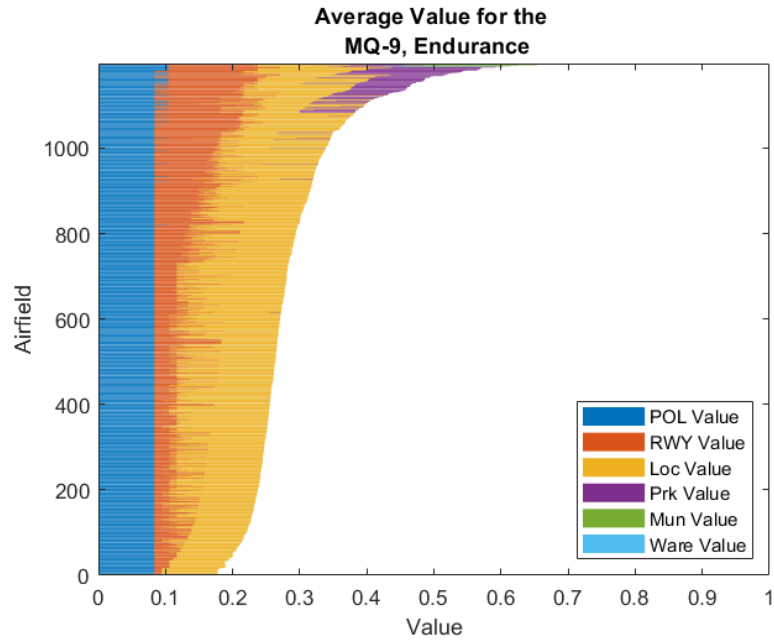


Figure 58. Tornado Chart for the MALE ISR System, Endurance

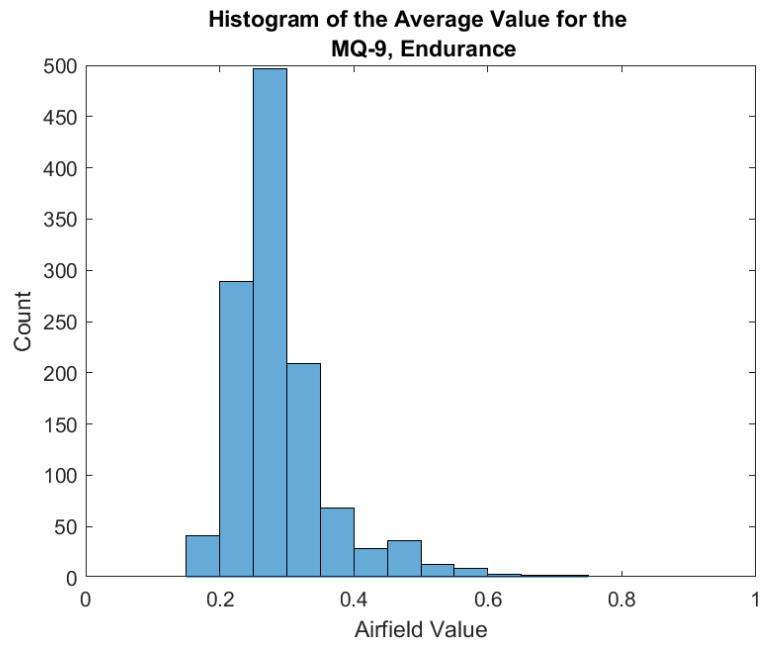


Figure 59. Histogram for the MALE ISR System, Endurance

Speed.

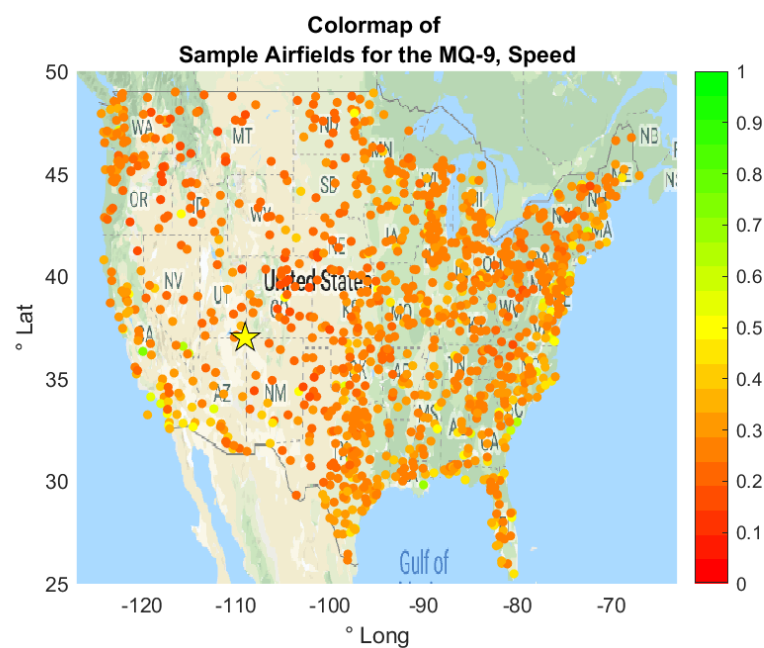


Figure 60. Colormap for the MALE ISR System, Speed

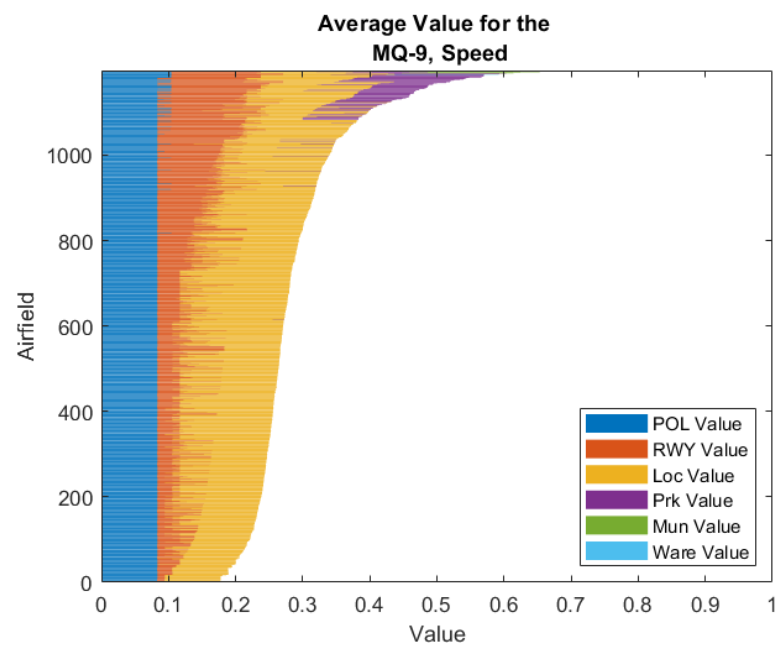


Figure 61. Tornado Chart for the MALE ISR System, Speed

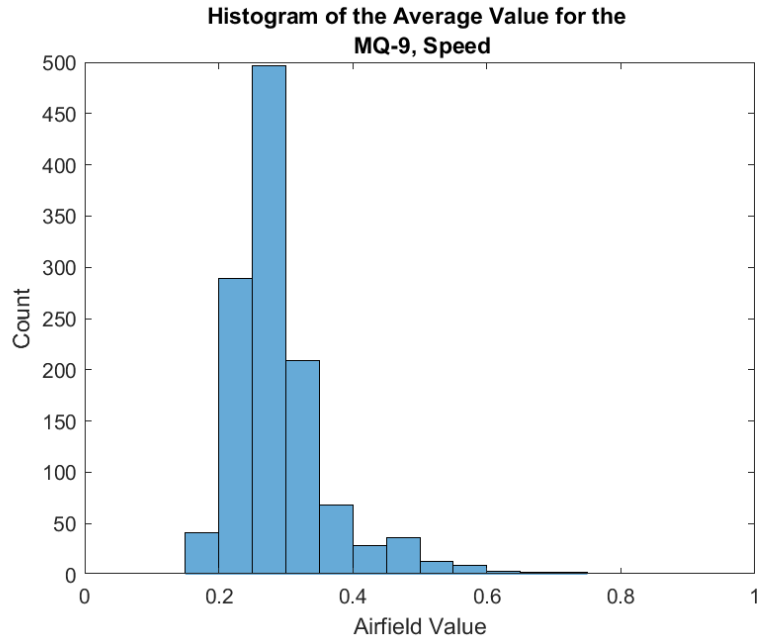


Figure 62. Histogram for the MALE ISR System, Speed

Empty Weight.

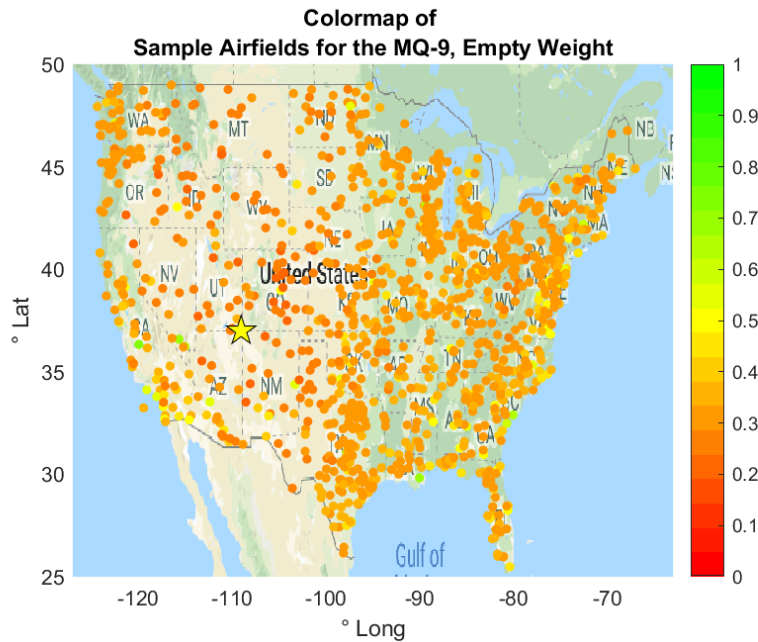


Figure 63. Colormap for the MALE ISR System, Empty Weight

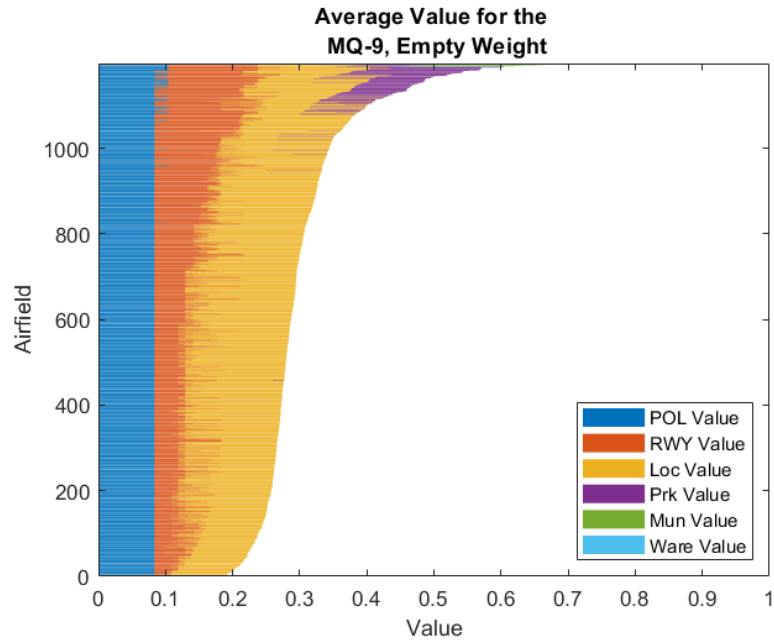


Figure 64. Tornado Chart for the MALE ISR System, Empty Weight

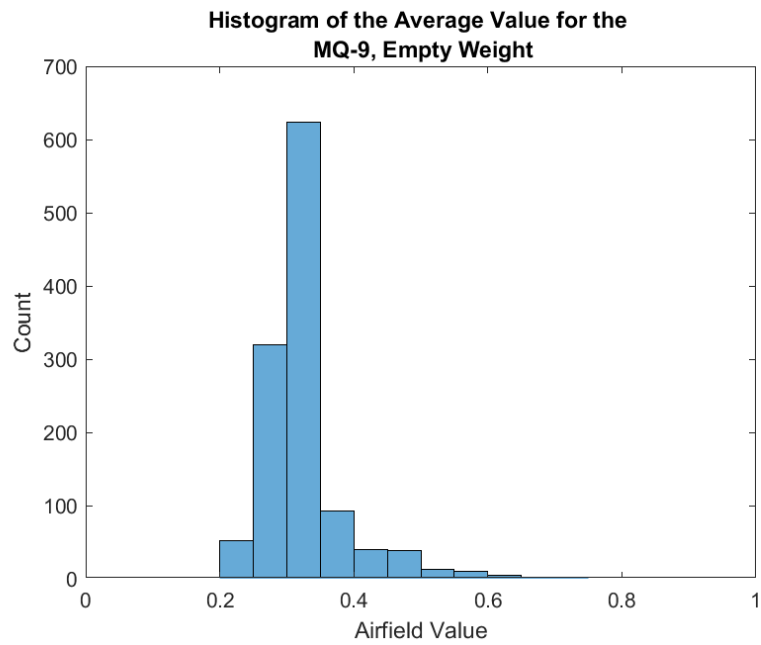


Figure 65. Histogram for the MALE ISR System, Empty Weight

Fuel Weight.

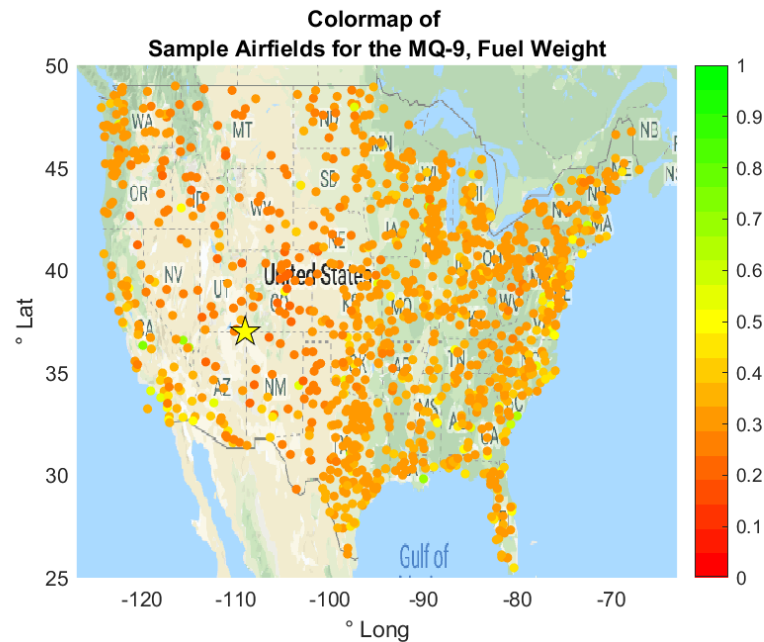


Figure 66. Colormap for the MALE ISR System, Fuel Weight

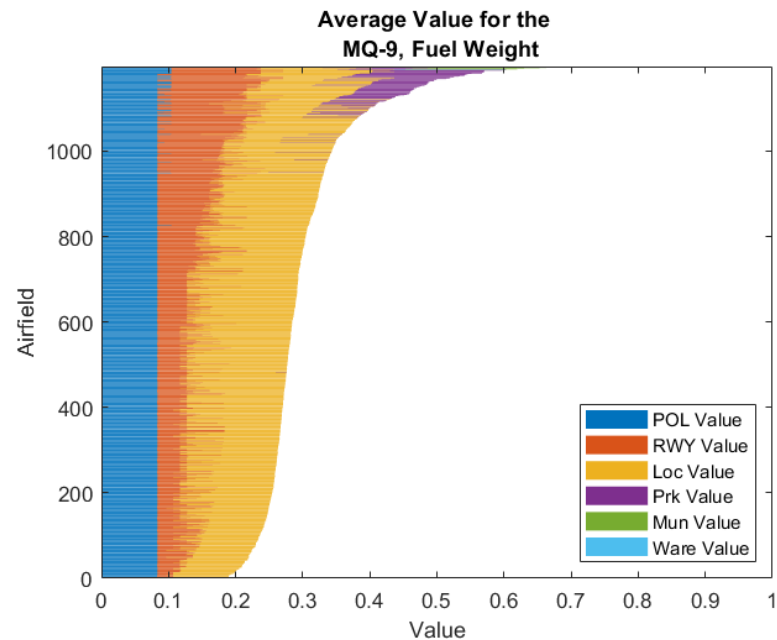


Figure 67. Tornado Chart for the MALE ISR System, Fuel Weight

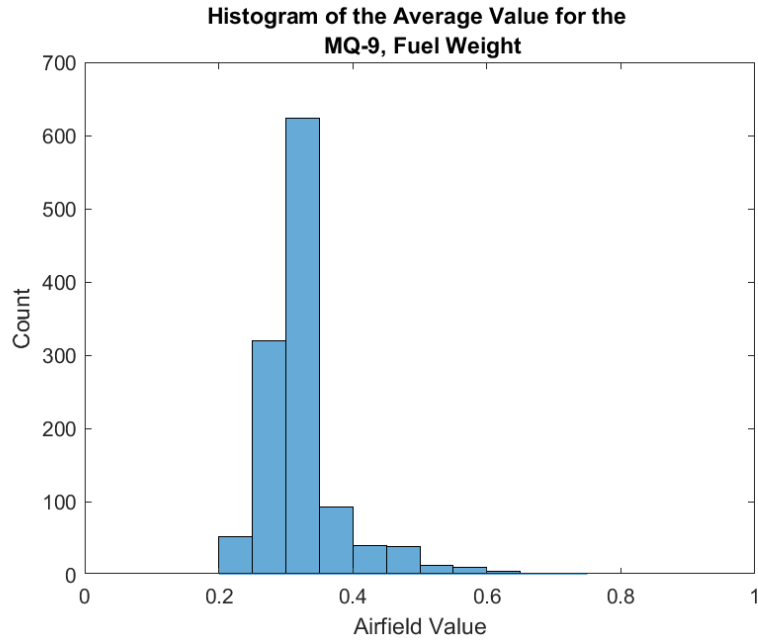


Figure 68. Histogram for the MALE ISR System, Fuel Weight

Payload Weight.

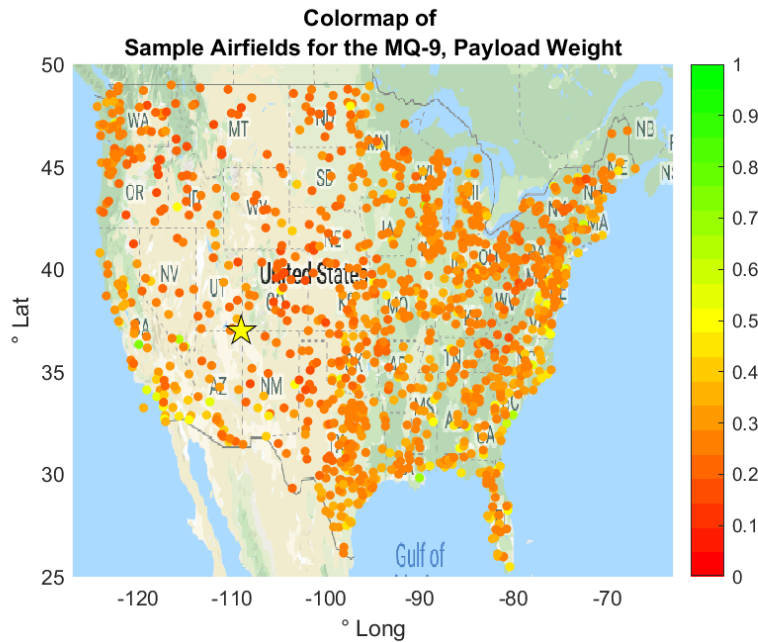


Figure 69. Colormap for the MALE ISR System, Payload Weight

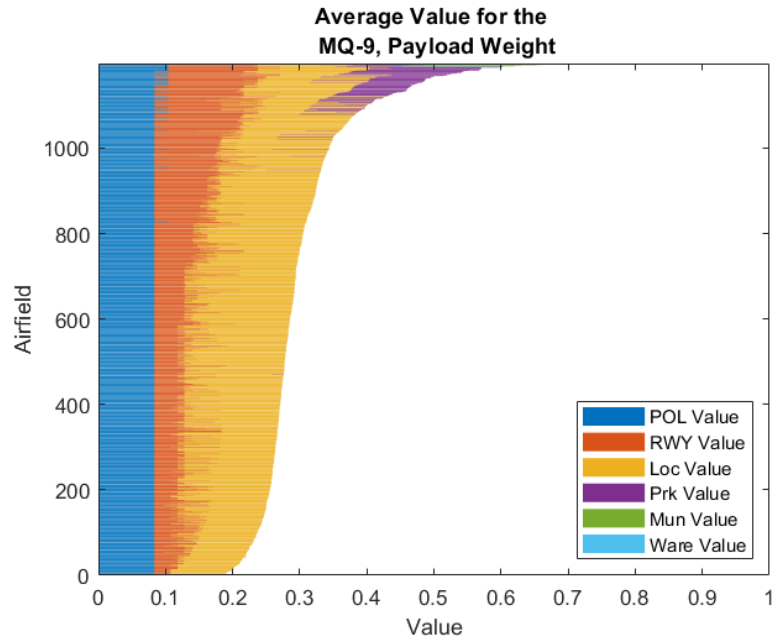


Figure 70. Tornado Chart for the MALE ISR System, Payload Weight

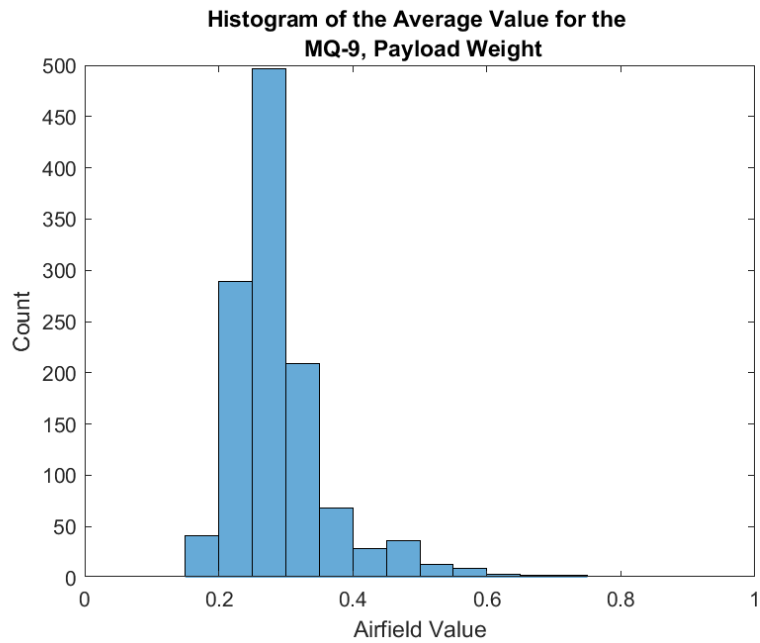


Figure 71. Histogram for the MALE ISR System, Payload Weight

Light Attack Propeller Conceptual System

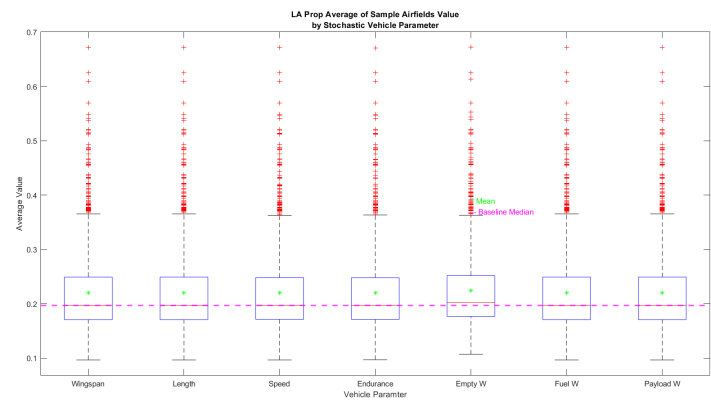


Figure 72. Boxplots for LA Propeller System MC Results

Wingspan.

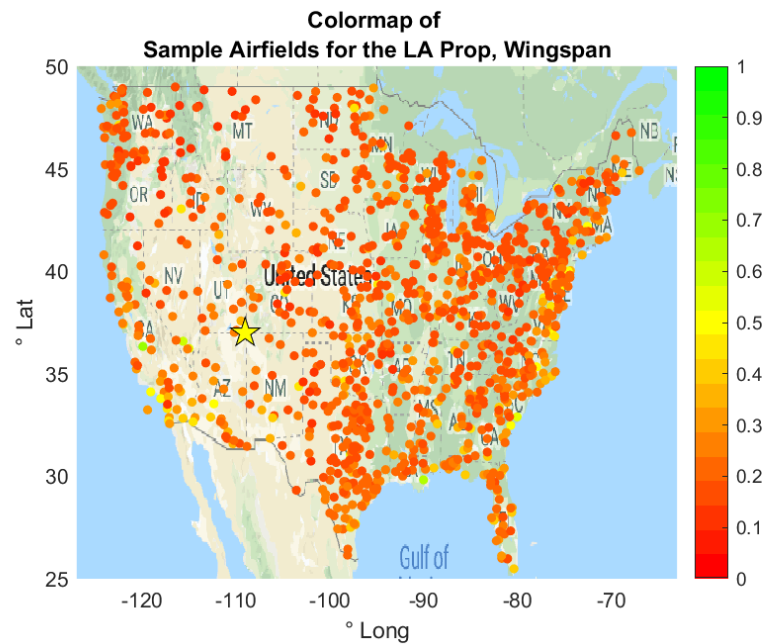


Figure 73. Colormap for the LA Propeller System, Wingspan

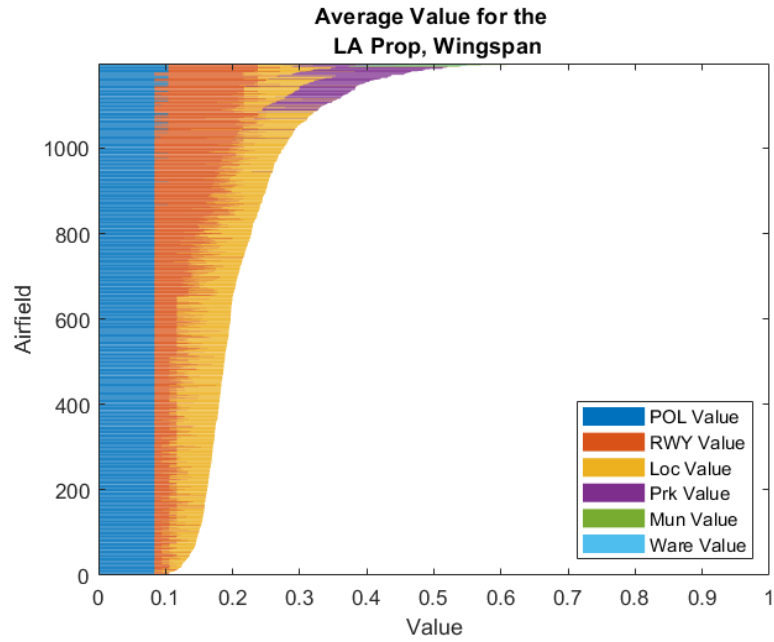


Figure 74. Tornado Chart for the LA Propeller System, Wingspan

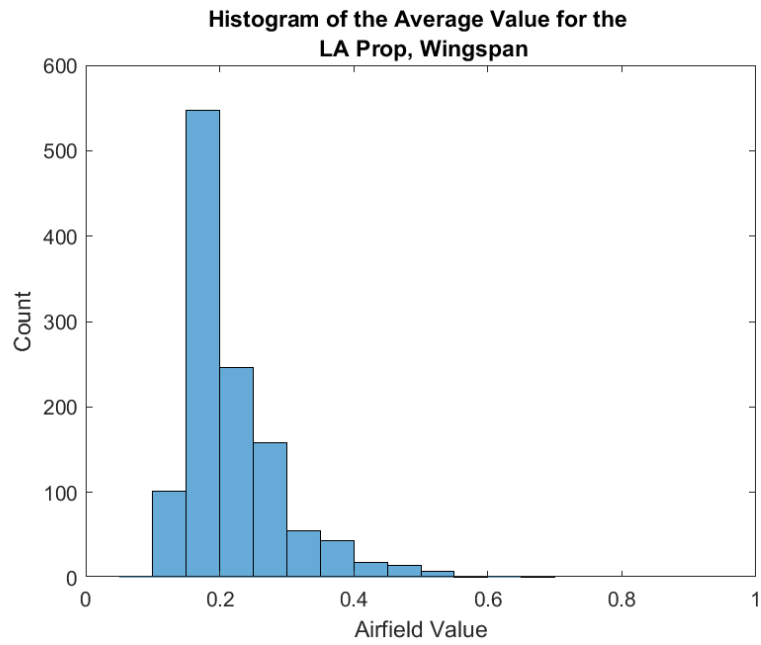


Figure 75. Histogram for the LA Propeller System, Wingspan

Length.

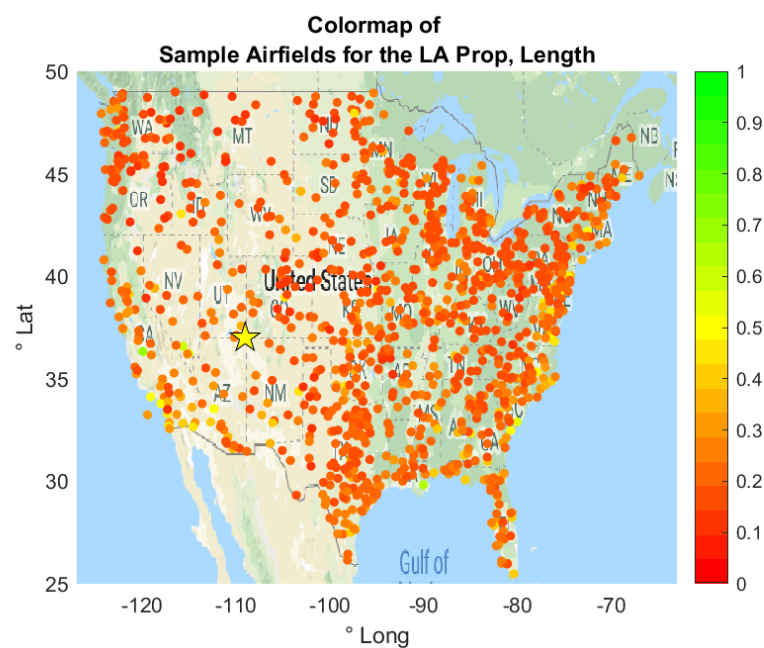


Figure 76. Colormap for the LA Propeller System, Length

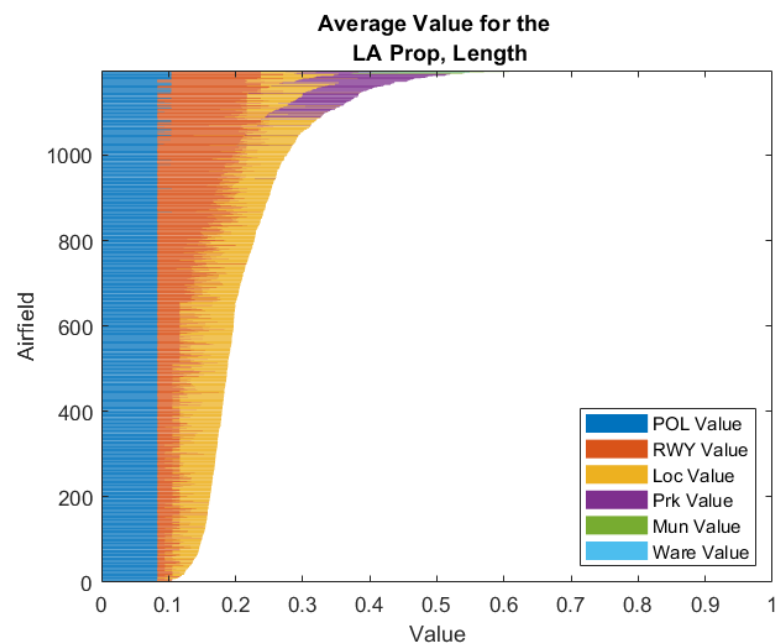


Figure 77. Tornado Chart for the LA Propeller System, Length

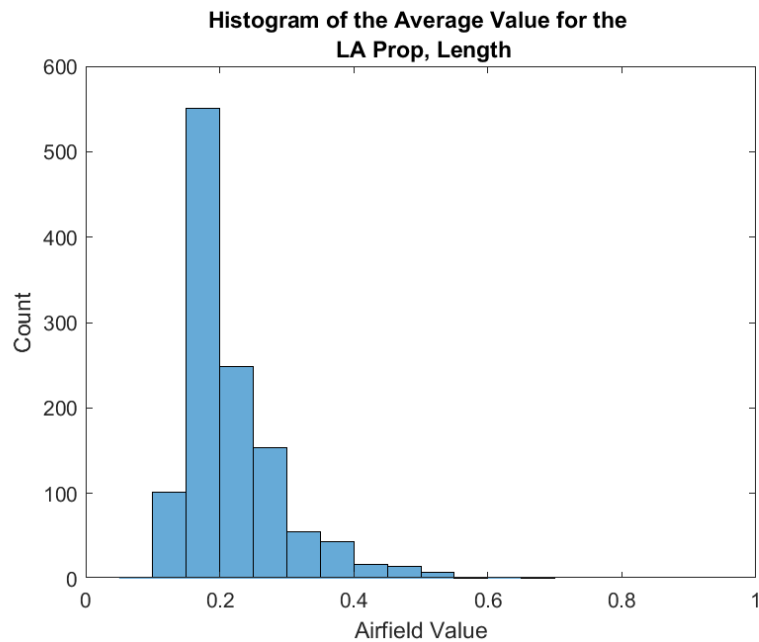


Figure 78. Histogram for the LA Propeller System, Length

Endurance.

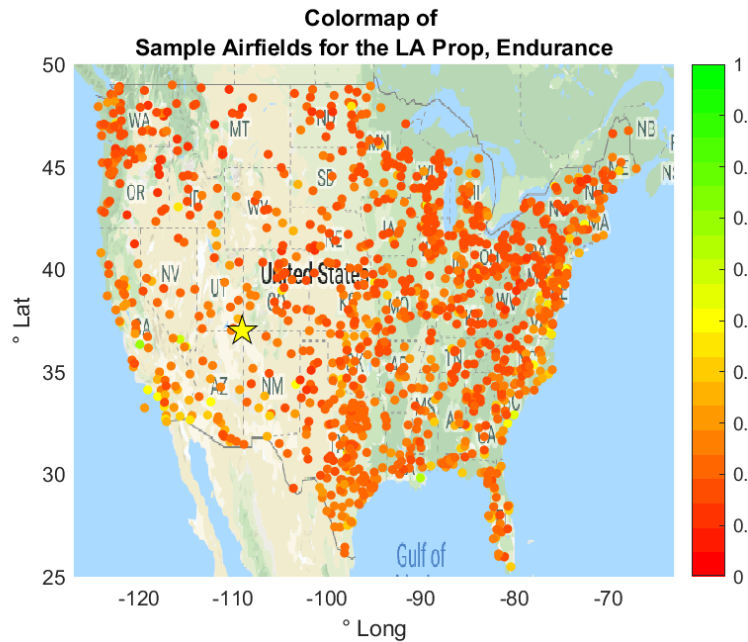


Figure 79. Colormap for the LA Propeller System, Endurance

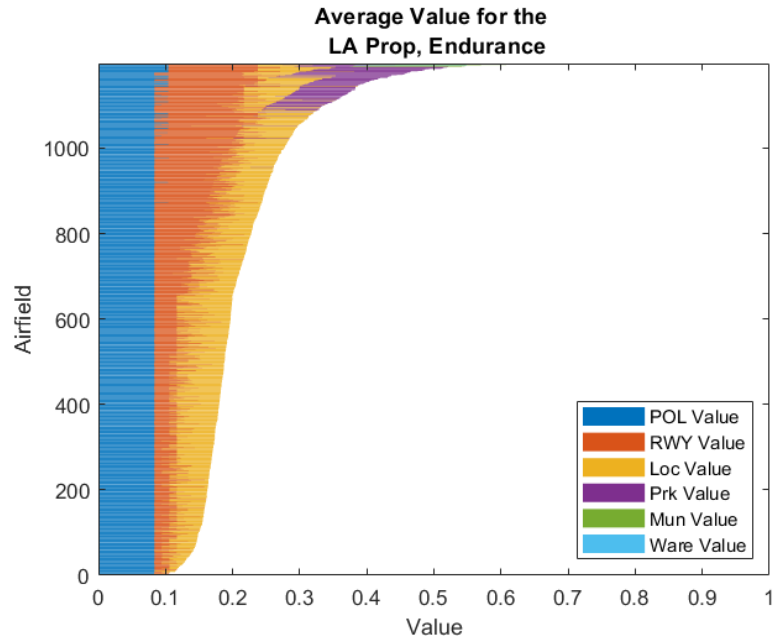


Figure 80. Tornado Chart for the LA Propeller System, Endurance

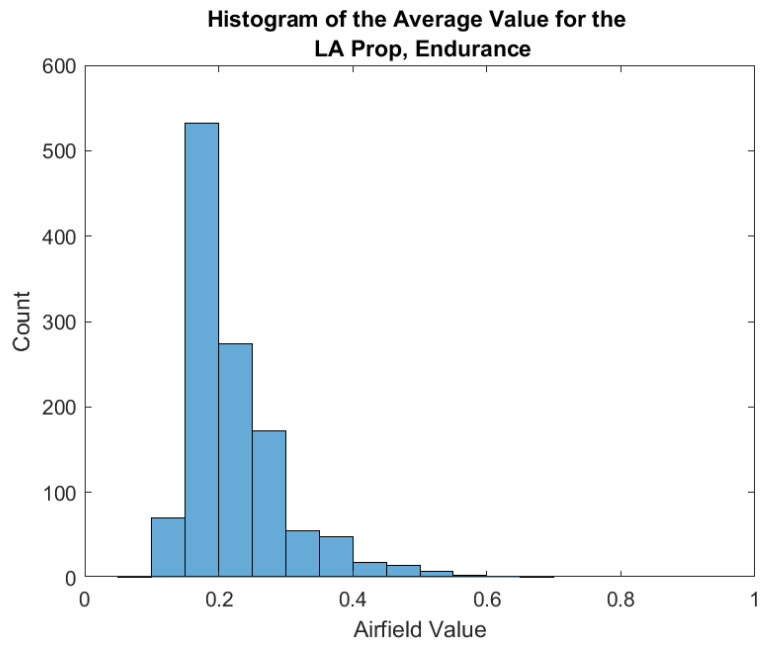


Figure 81. Histogram for the LA Propeller System, Endurance

Speed.

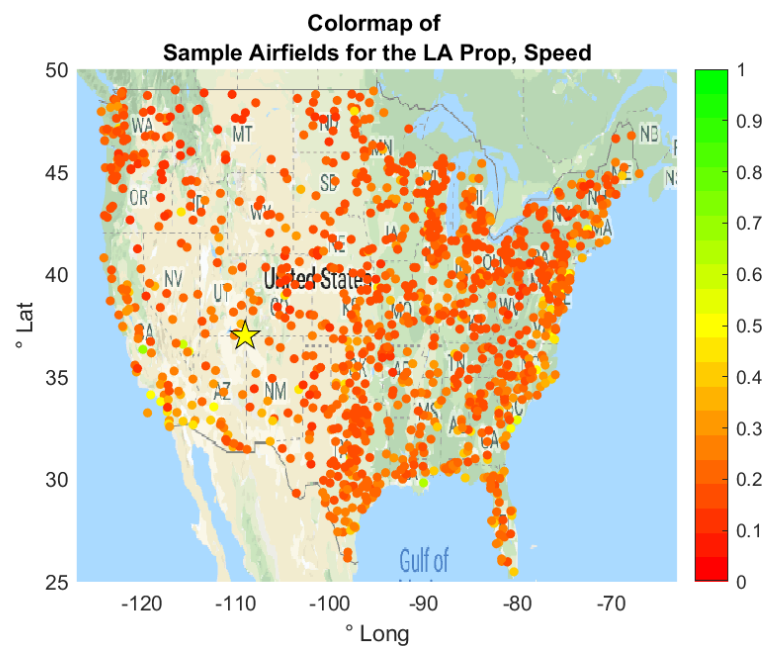


Figure 82. Colormap for the LA Propeller System, Speed

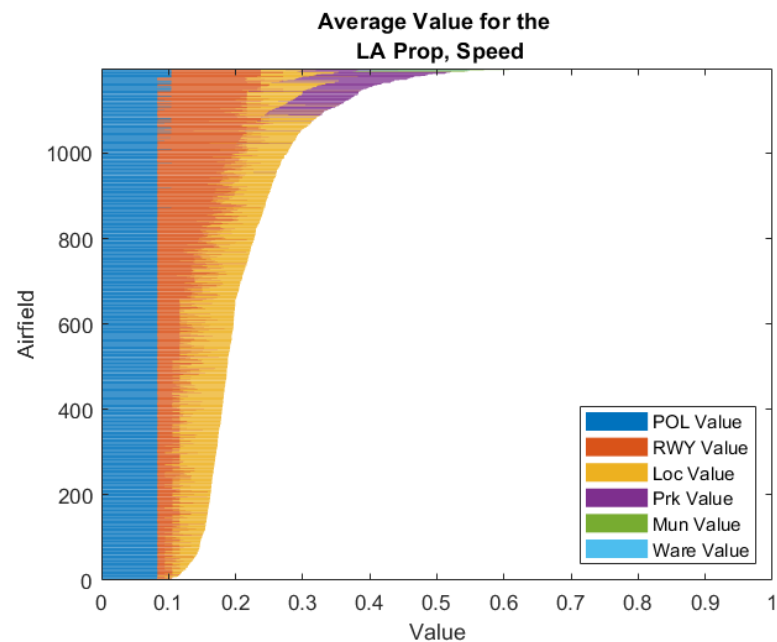


Figure 83. Tornado Chart for the LA Propeller System, Speed

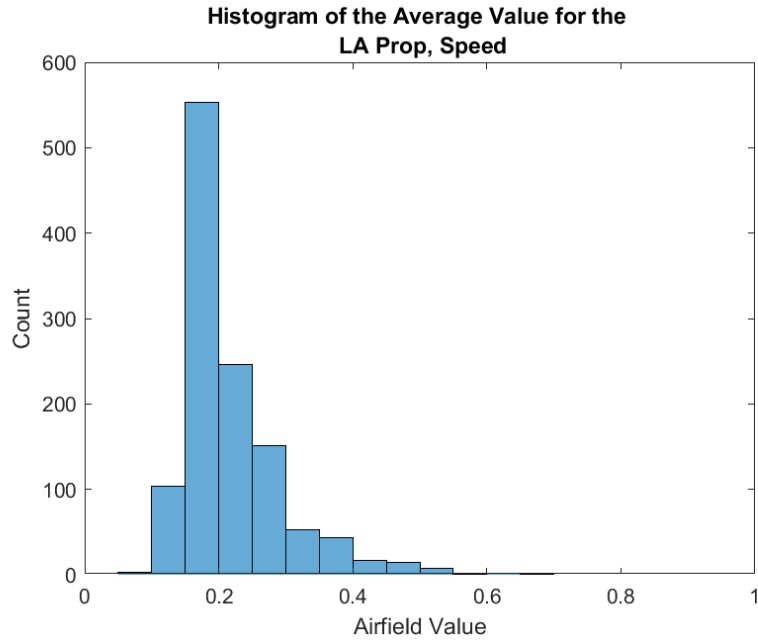


Figure 84. Histogram for the LA Propeller System, Speed

Empty Weight.

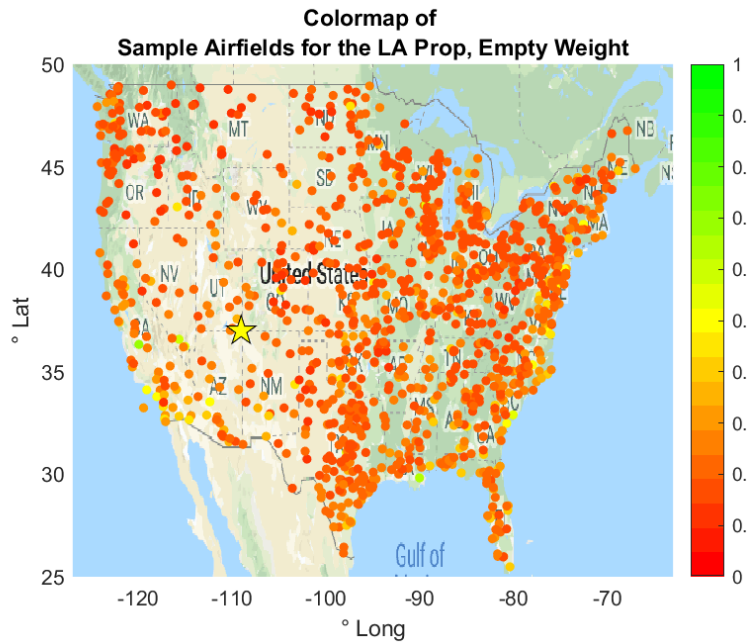


Figure 85. Colormap for the LA Propeller System, Empty Weight

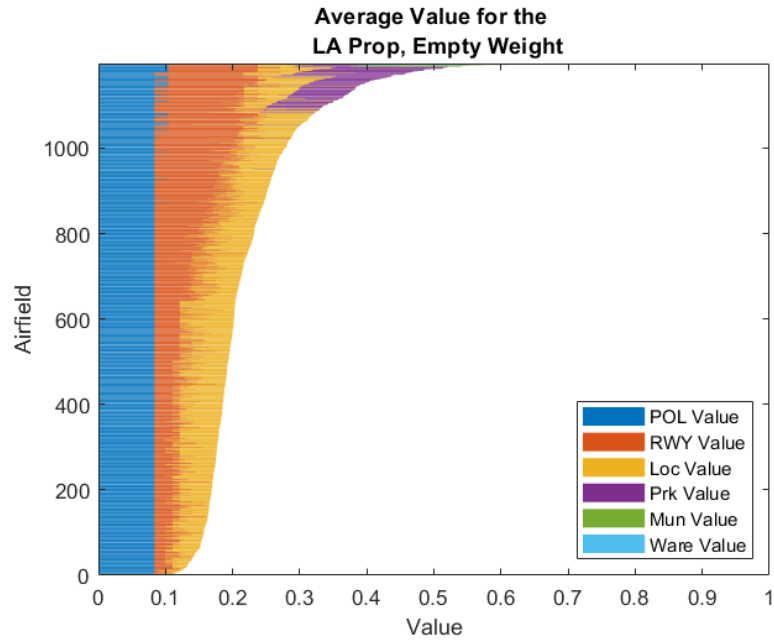


Figure 86. Tornado Chart for the LA Propeller System, Empty Weight

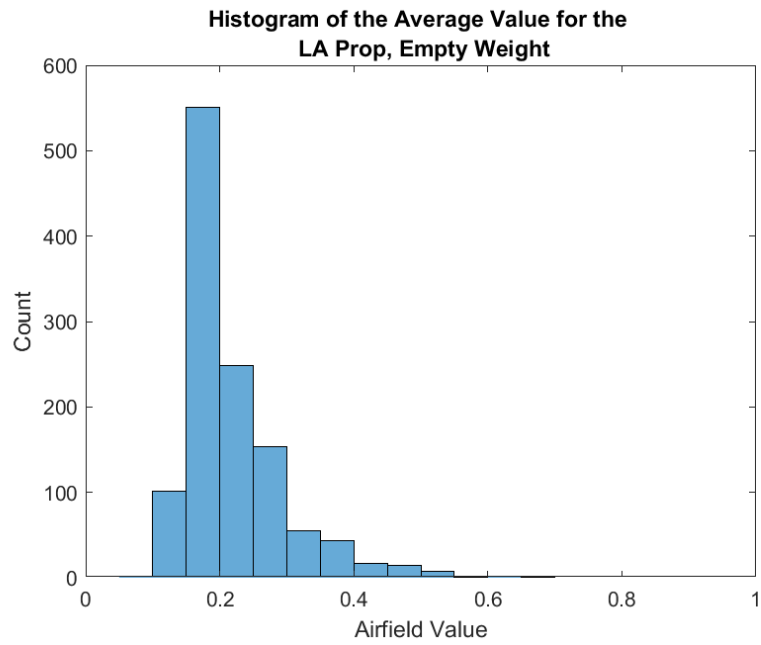


Figure 87. Histogram for the LA Propeller System, Empty Weight

Fuel Weight.

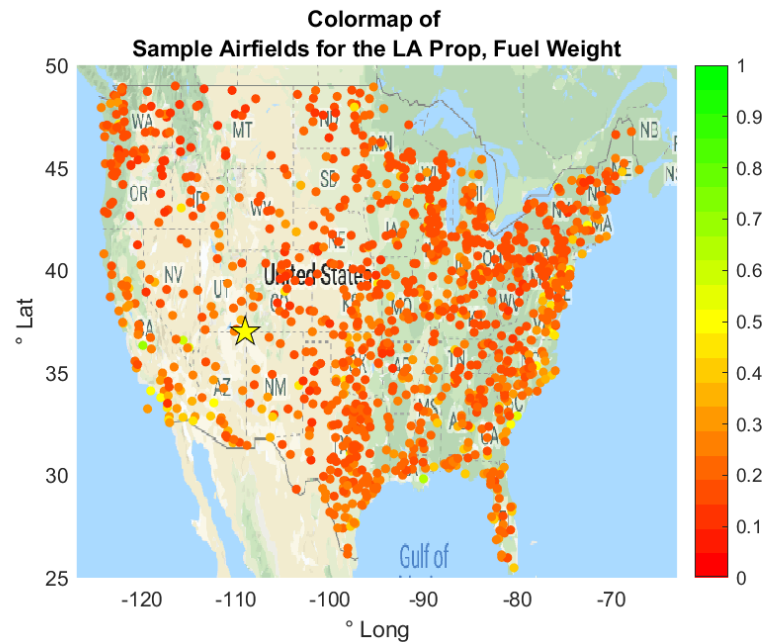


Figure 88. Colormap for the LA Propeller System, Fuel Weight

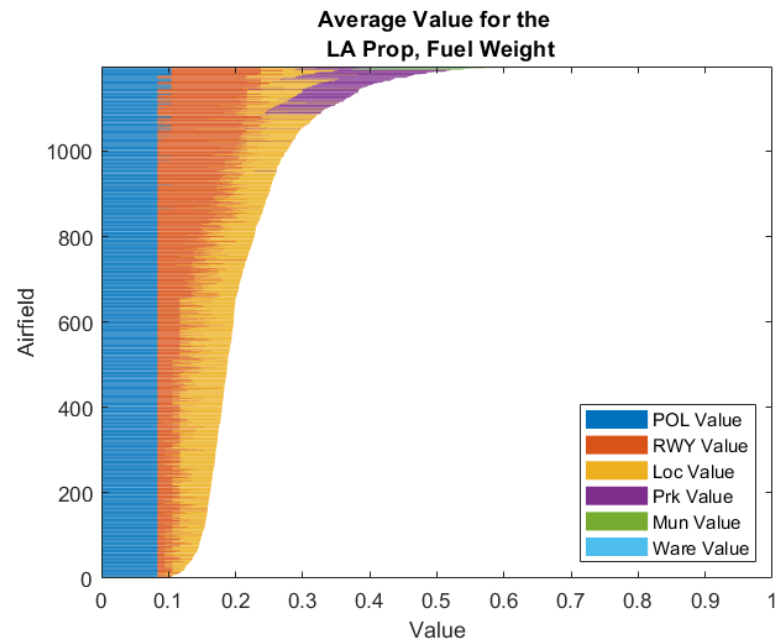


Figure 89. Tornado Chart for the LA Propeller System, Fuel Weight

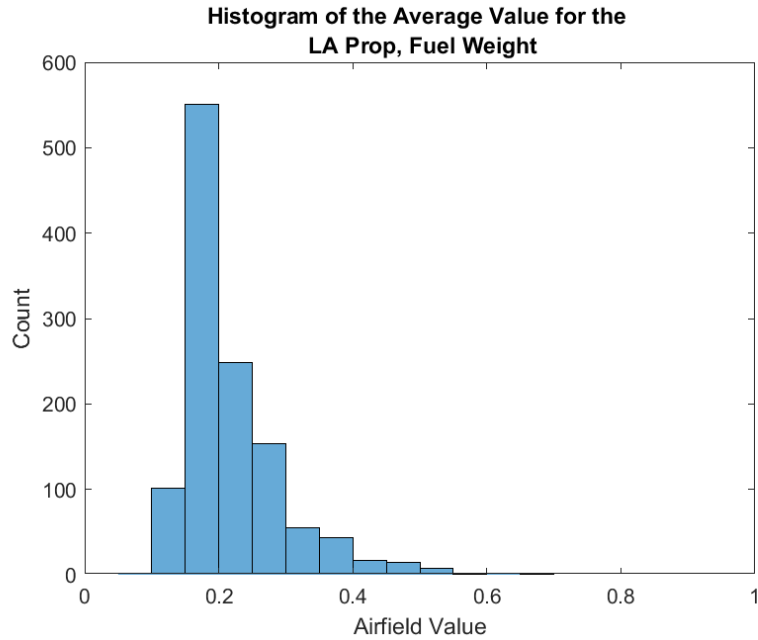


Figure 90. Histogram for the LA Propeller System, Fuel Weight

Payload Weight.

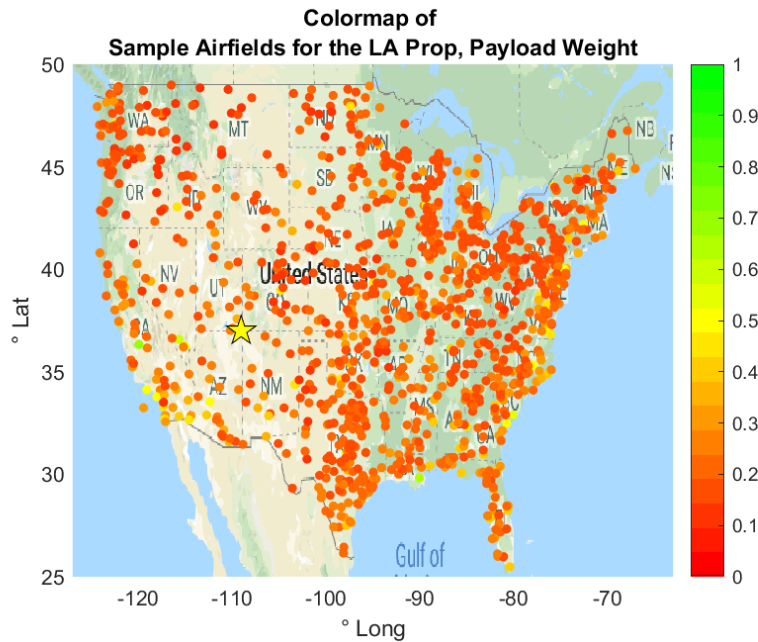


Figure 91. Colormap for the LA Propeller System, Payload Weight

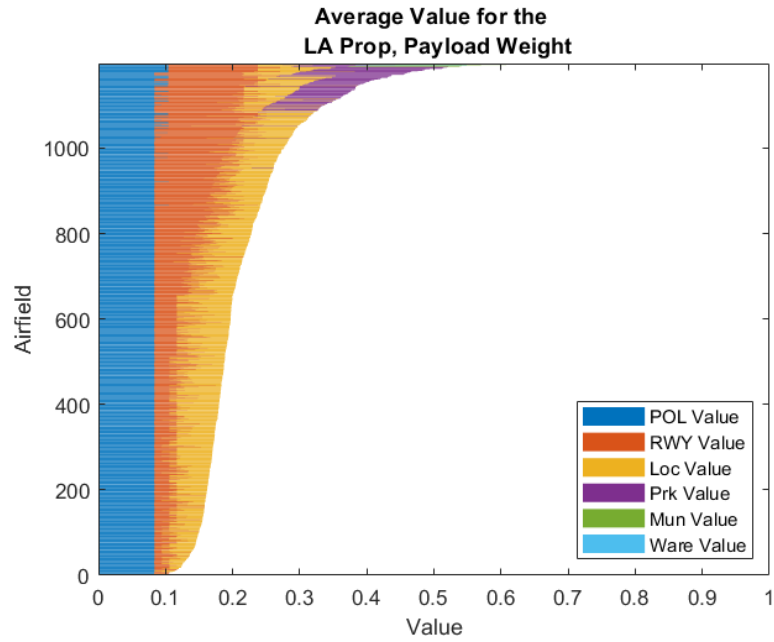


Figure 92. Tornado Chart for the LA Propeller System, Payload Weight

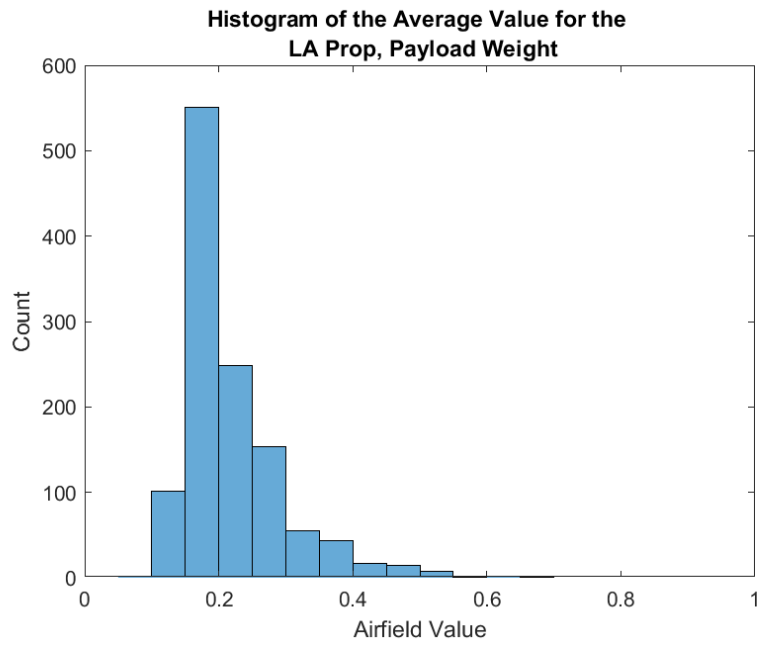


Figure 93. Histogram for the LA Propeller System, Payload Weight

Light Attack Jet Conceptual System

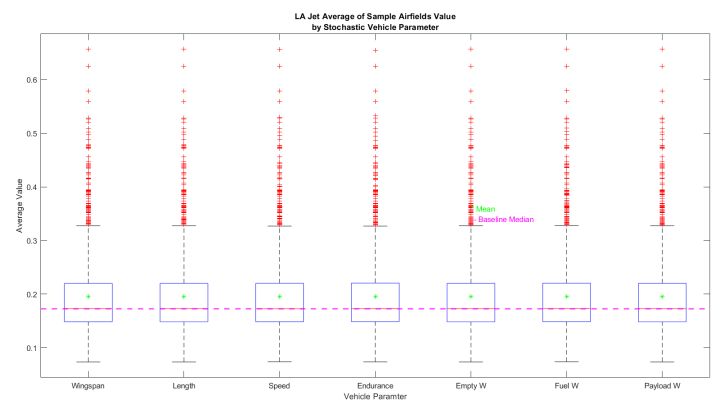


Figure 94. Boxplots for LA Jet System MC Results

Wingspan.

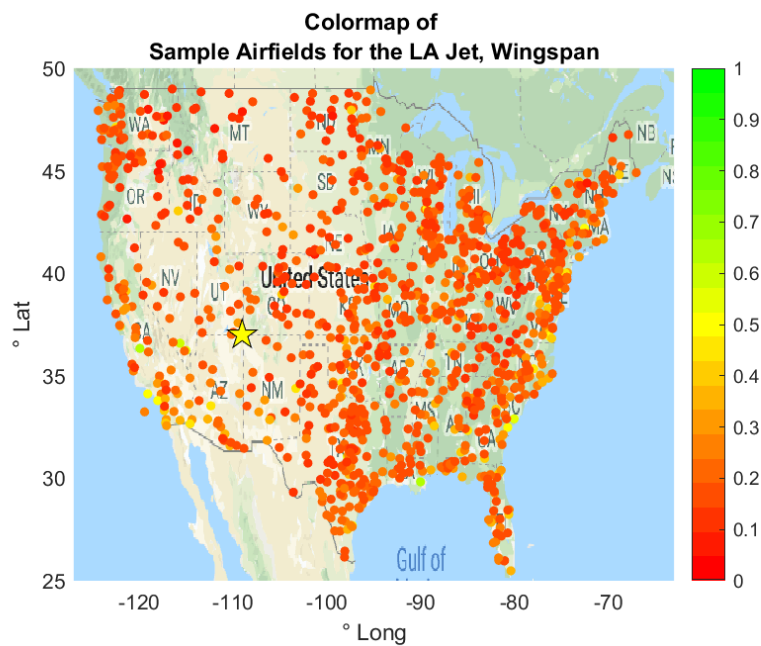


Figure 95. Colormap for the LA Jet System, Wingspan

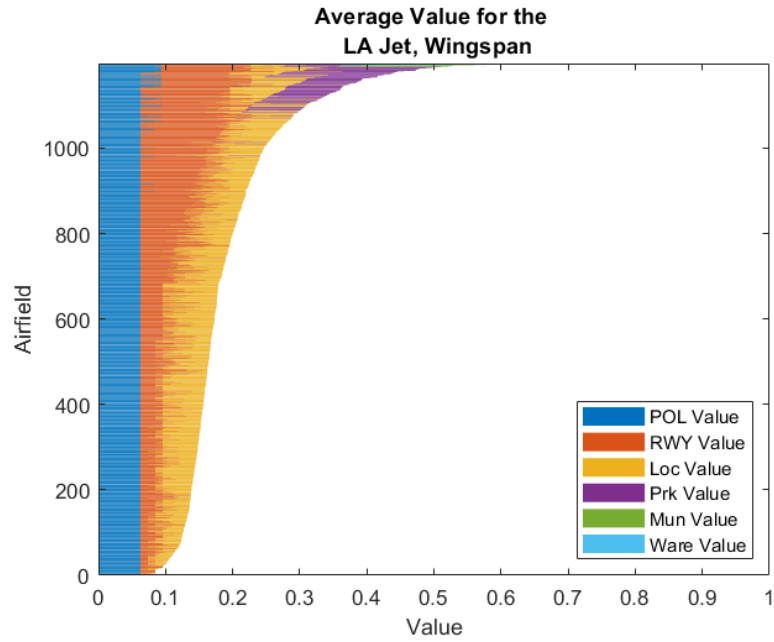


Figure 96. Tornado Chart for the LA Jet System, Wingspan

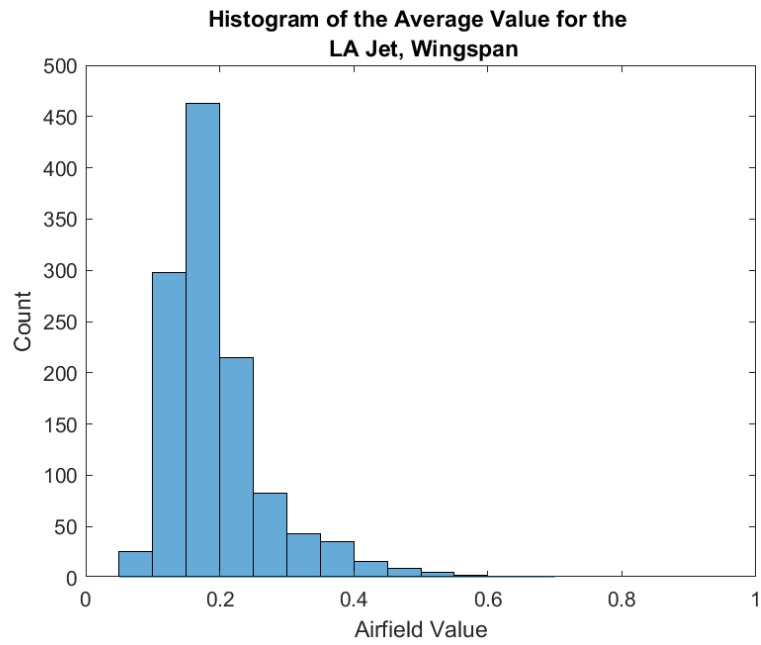


Figure 97. Histogram for the LA Jet System, Wingspan

Length.

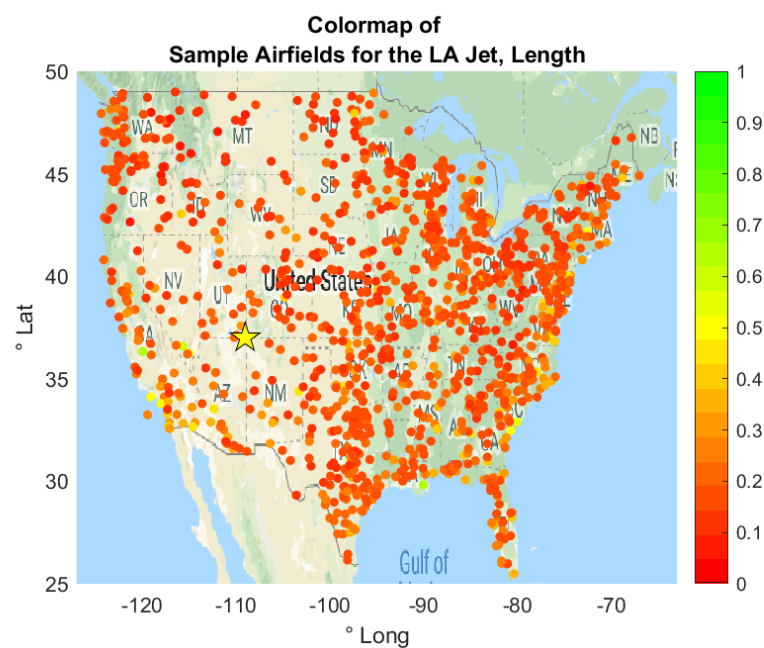


Figure 98. Colormap for the LA Jet System, Length

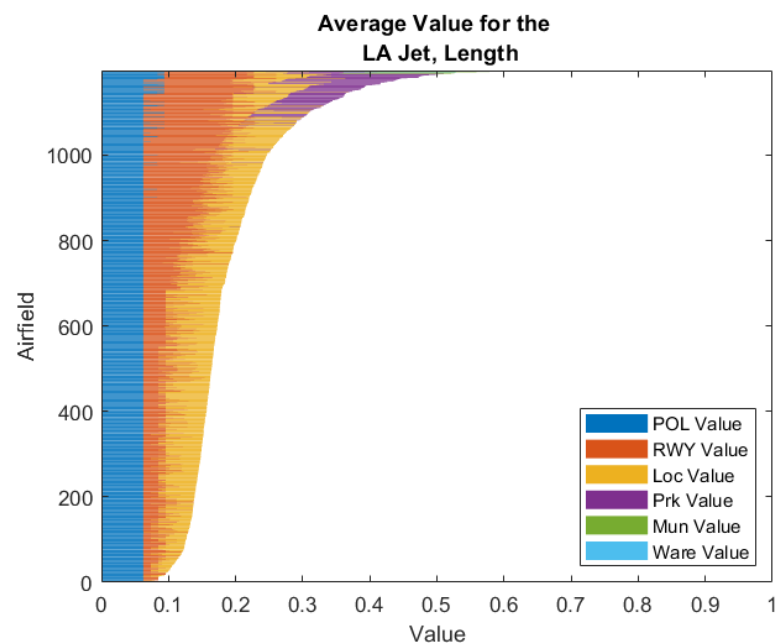


Figure 99. Tornado Chart for the LA Jet System, Length

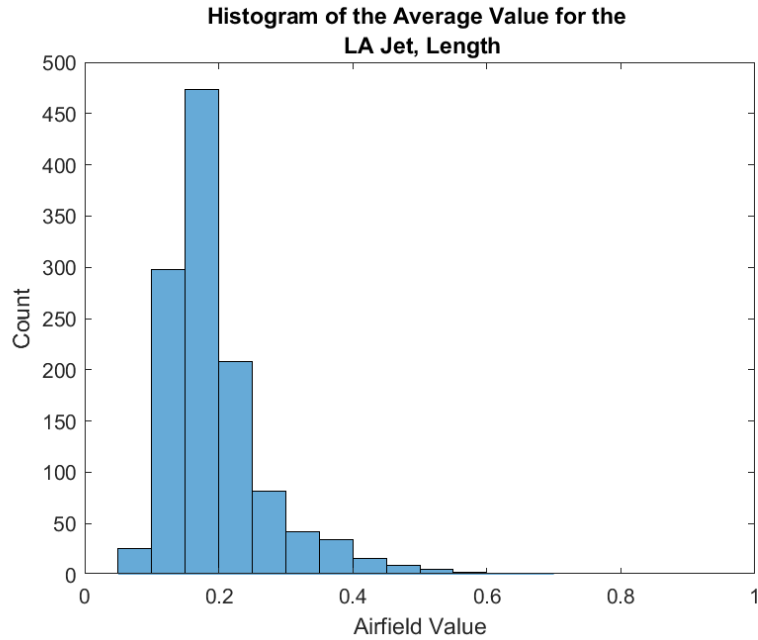


Figure 100. Histogram for the LA Jet System, Length

Endurance.

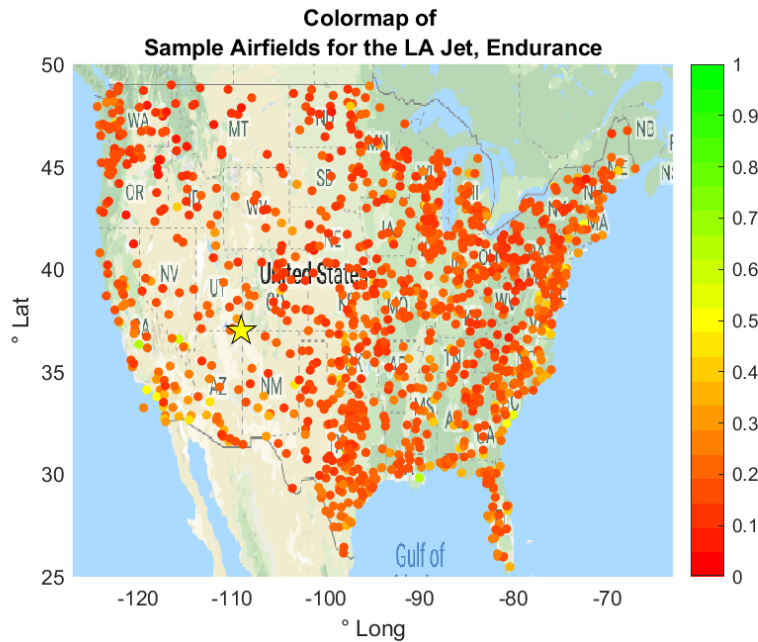


Figure 101. Colormap for the LA Jet System, Endurance

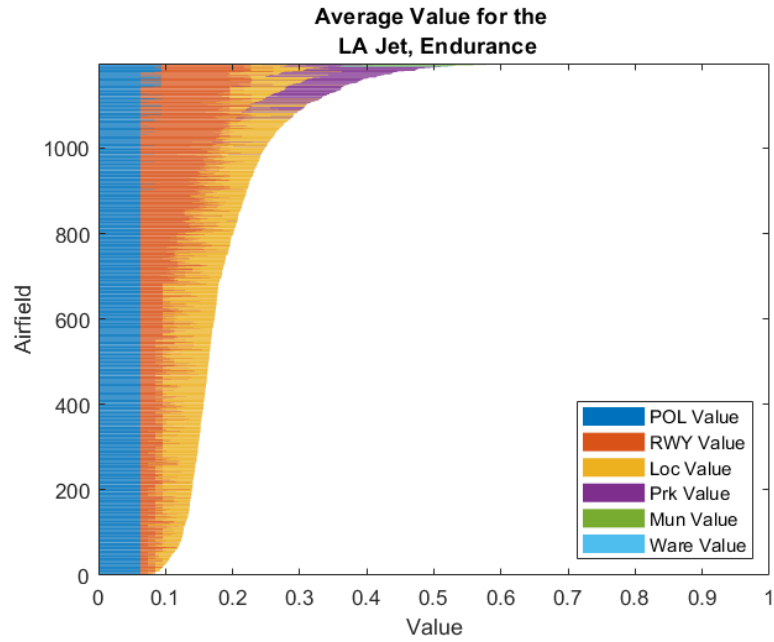


Figure 102. Tornado Chart for the LA Jet System, Endurance

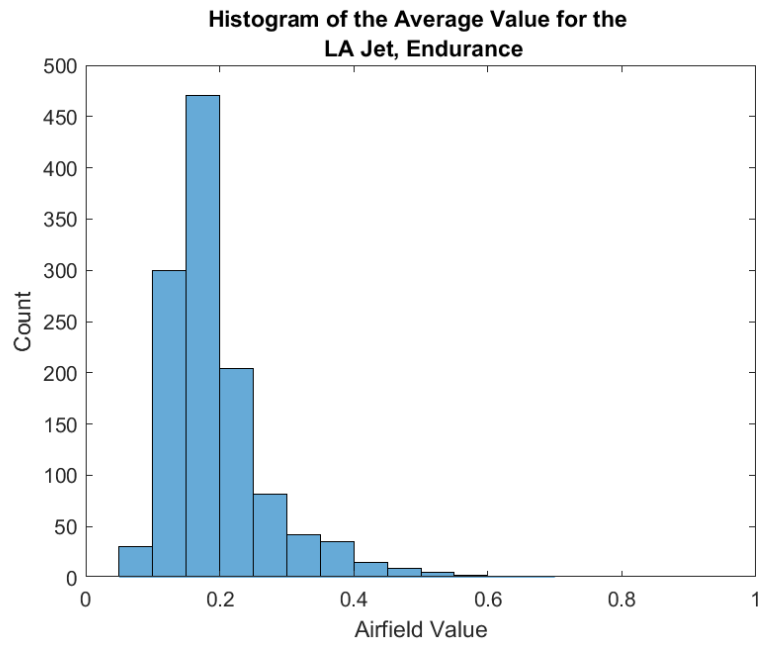


Figure 103. Histogram for the LA Jet System, Endurance

Speed.

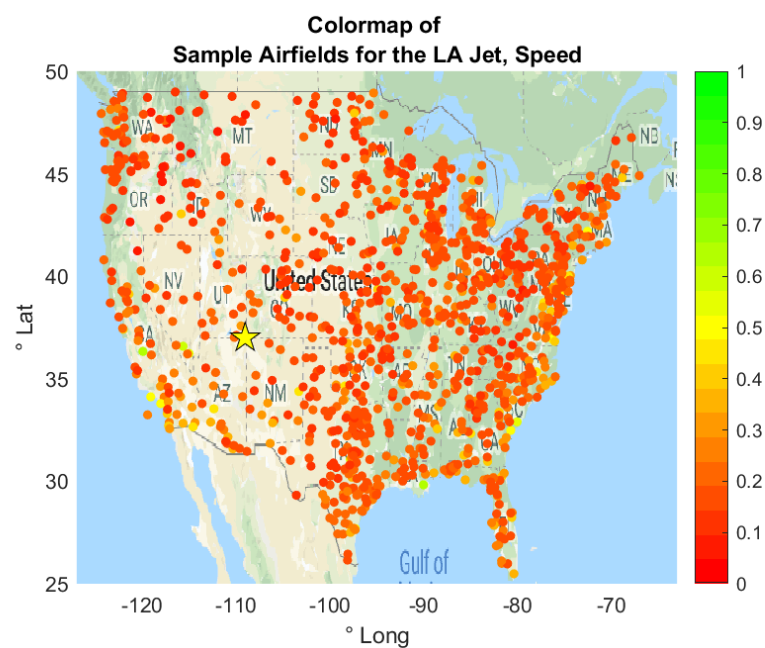


Figure 104. Colormap for the LA Jet System, Speed

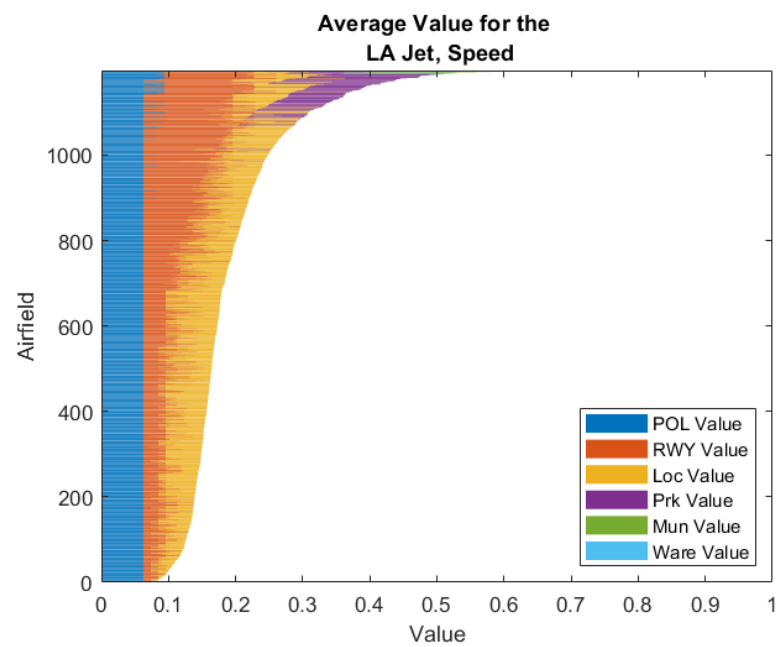


Figure 105. Tornado Chart for the LA Jet System, Speed

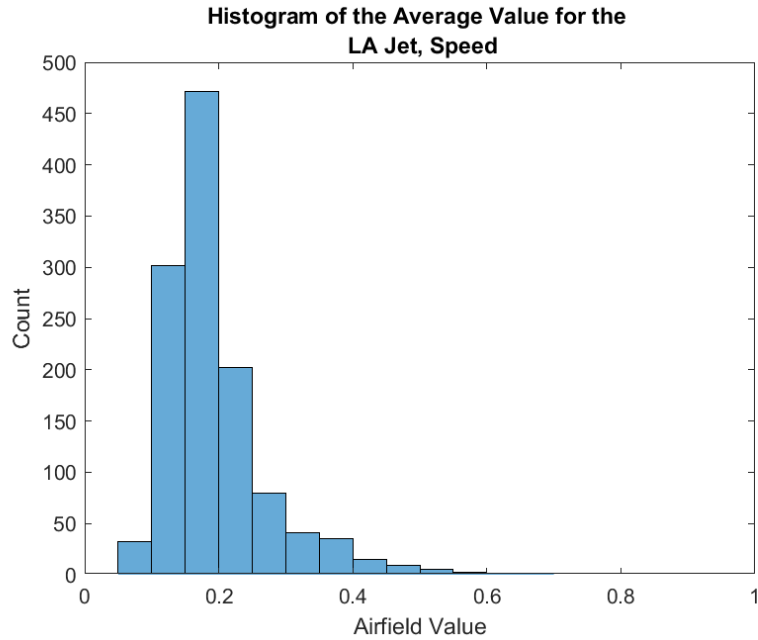


Figure 106. Histogram for the LA Jet System, Speed

Empty Weight.

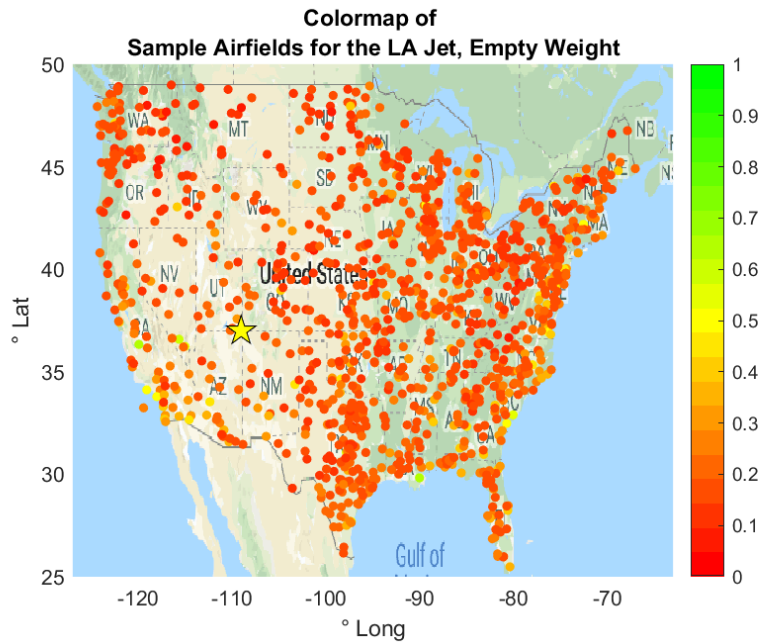


Figure 107. Colormap for the LA Jet System, Empty Weight

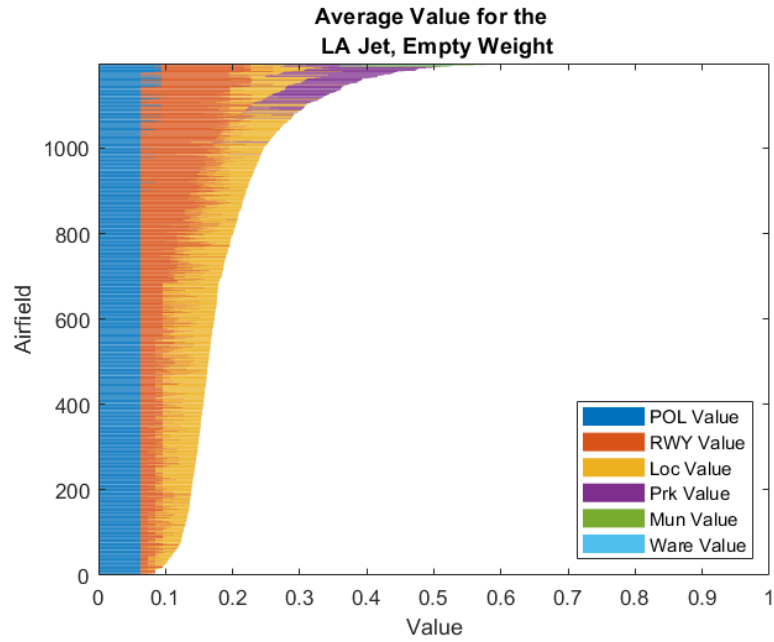


Figure 108. Tornado Chart for the LA Jet System, Empty Weight

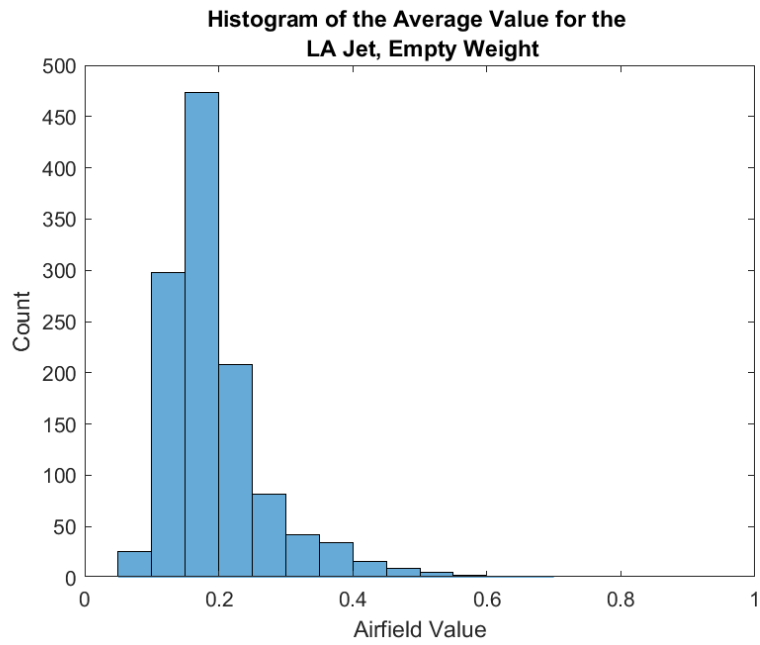


Figure 109. Histogram for the LA Jet System, Empty Weight

Fuel Weight.

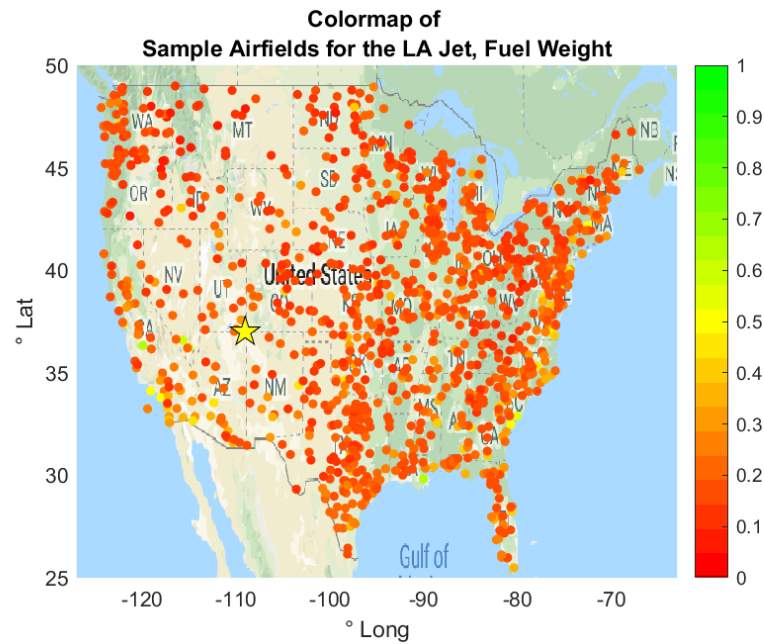


Figure 110. Colormap for the LA Jet System, Fuel Weight

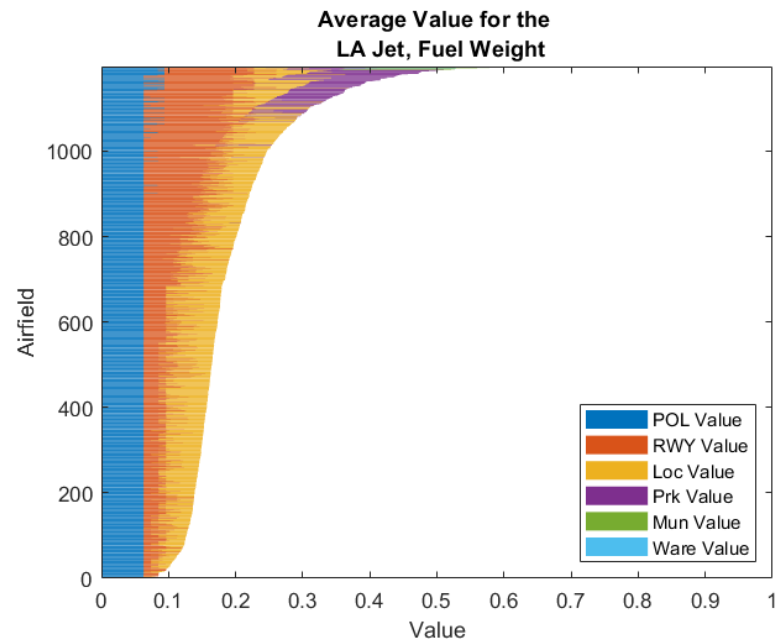


Figure 111. Tornado Chart for the LA Jet System, Fuel Weight

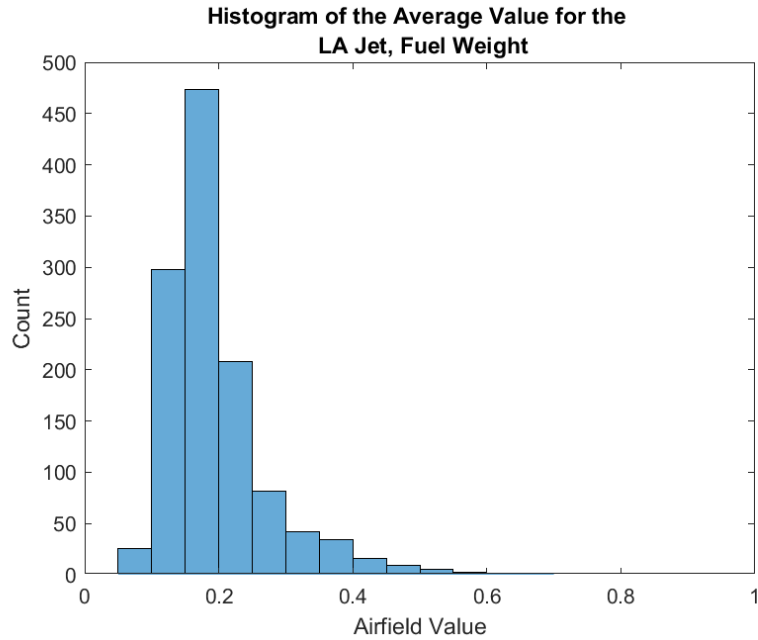


Figure 112. Histogram for the LA Jet System, Fuel Weight

Payload Weight.

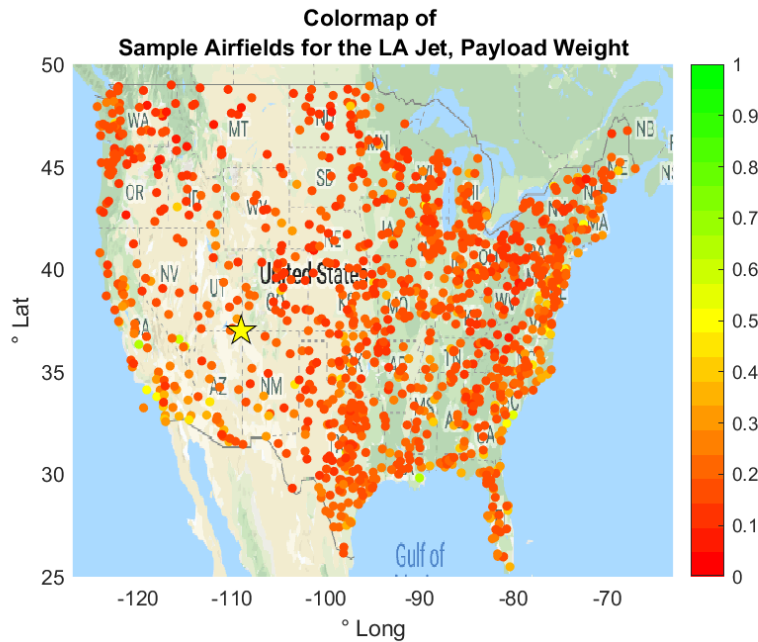


Figure 113. Colormap for the LA Jet System, Payload Weight

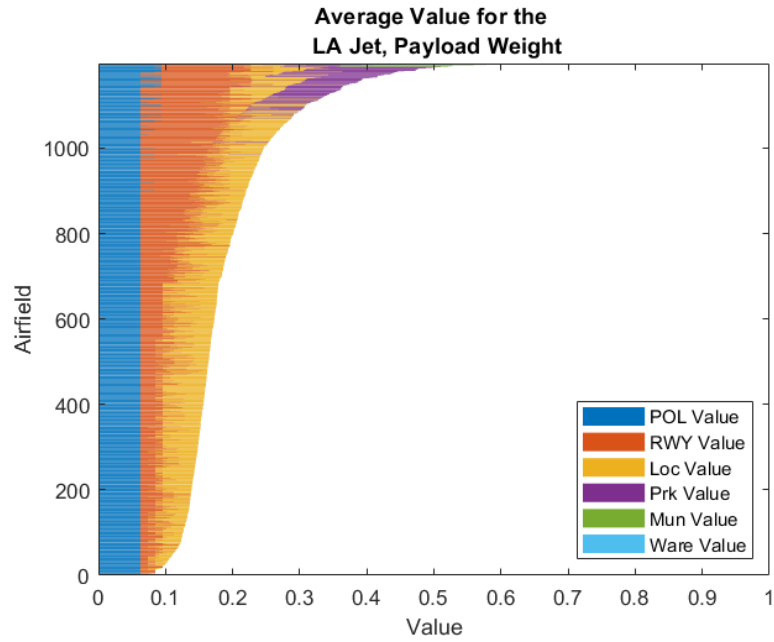


Figure 114. Tornado Chart for the LA Jet System, Payload Weight

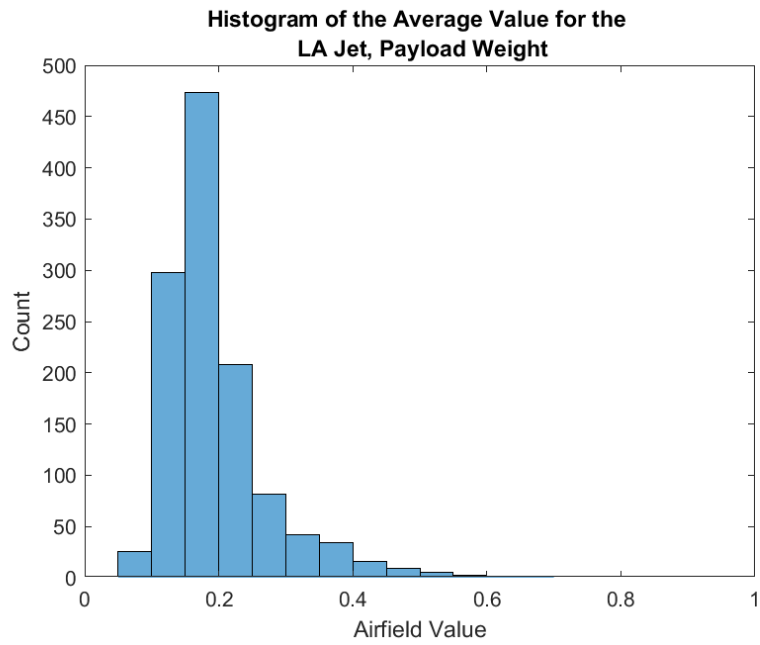


Figure 115. Histogram for the LA Jet System, Payload Weight

LCAAT Conceptual System

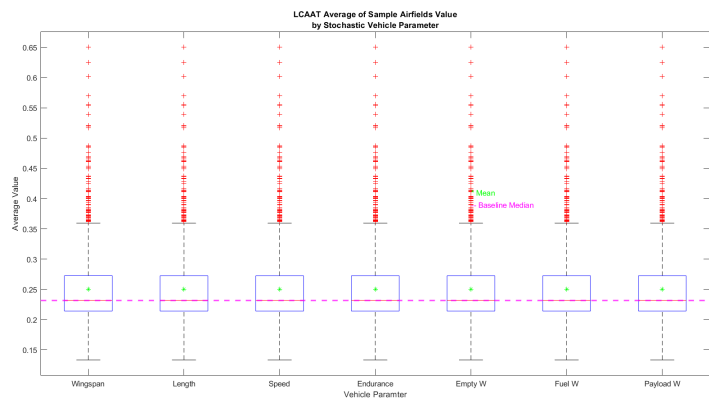


Figure 116. Boxplots for LCAAT System MC Results

Wingspan.

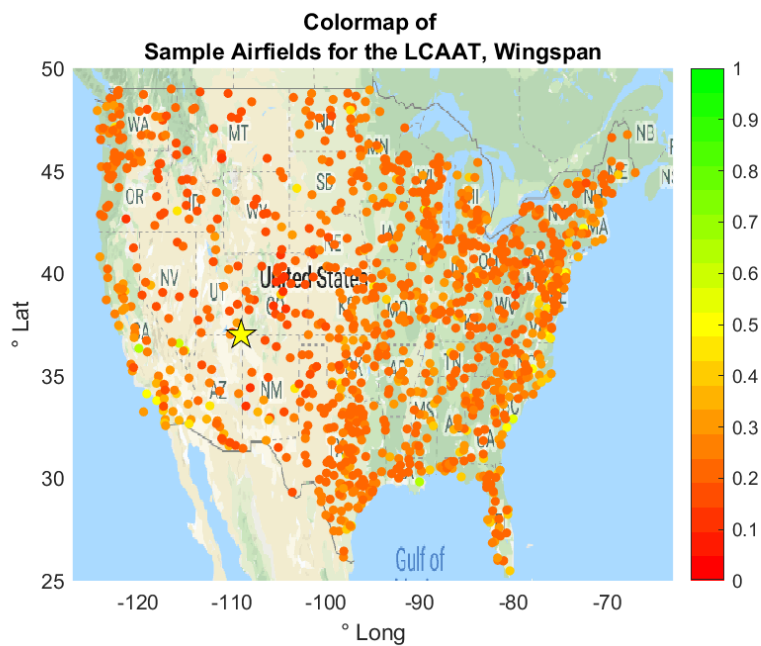


Figure 117. Colormap for the LCAAT System, Wingspan

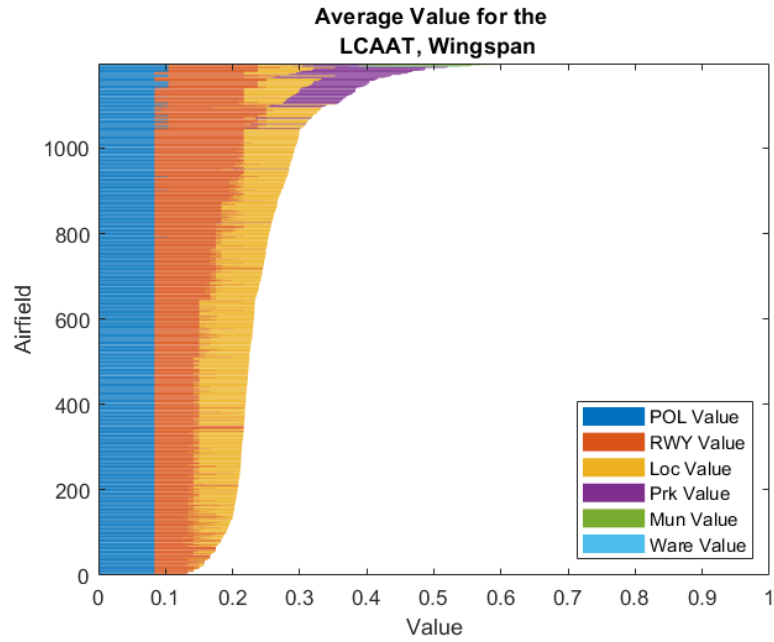


Figure 118. Tornado Chart for the LCAAT System, Wingspan

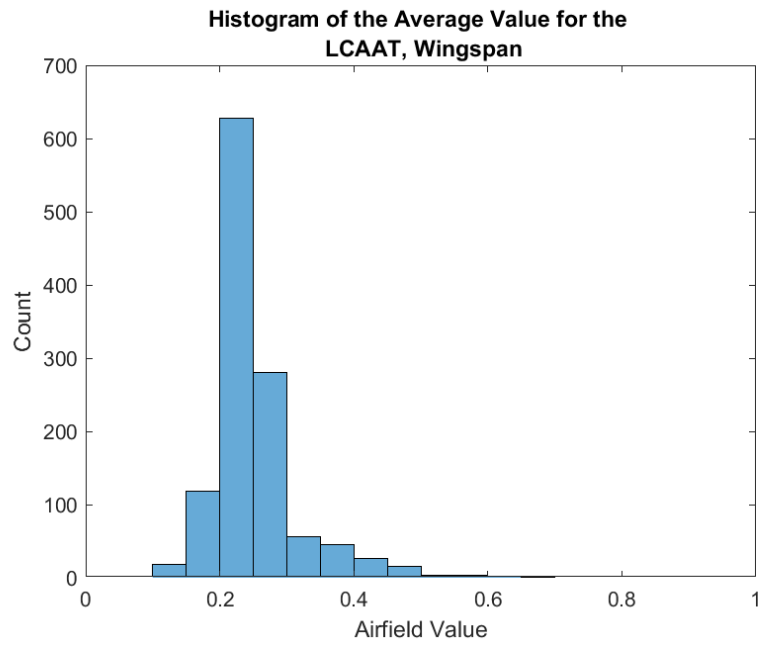


Figure 119. Histogram for the LCAAT System, Wingspan

Length.

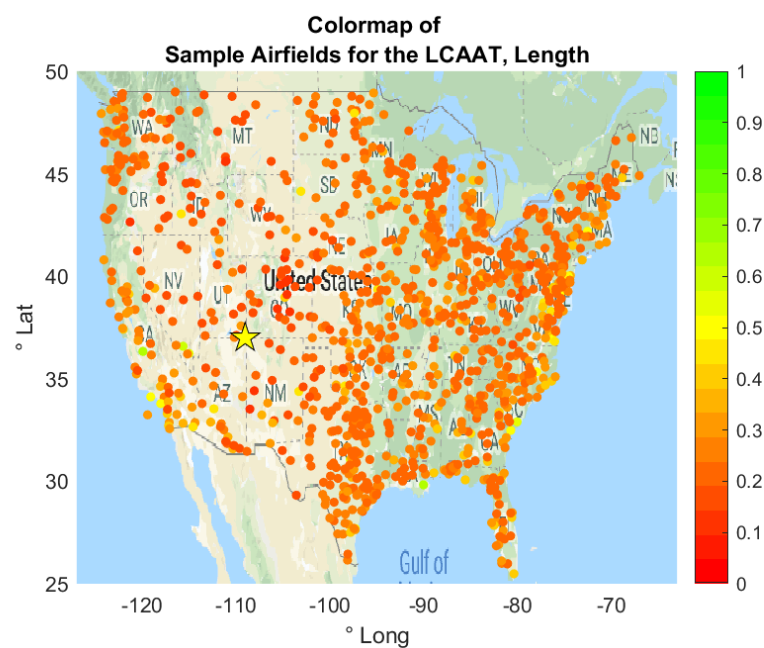


Figure 120. Colormap for the LCAAT System, Length

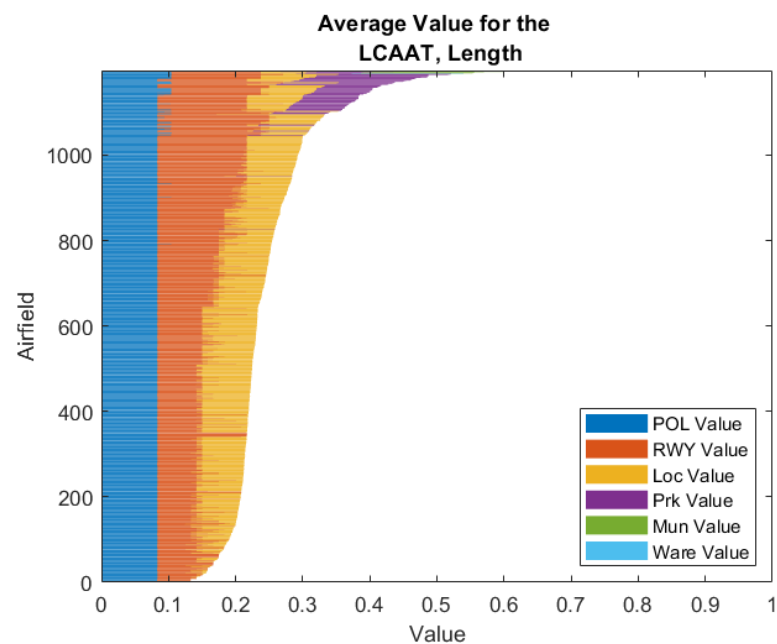


Figure 121. Tornado Chart for the LCAAT System, Length

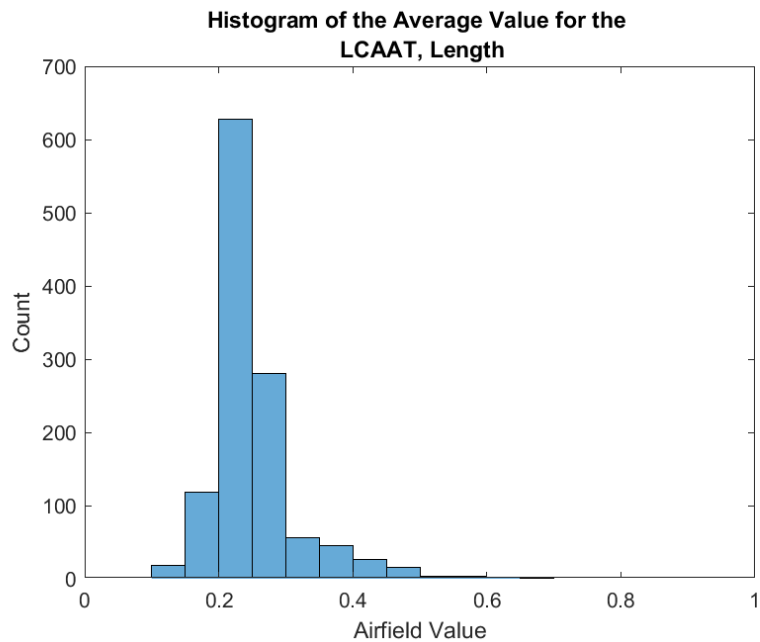


Figure 122. Histogram for the LCAAT System, Length

Endurance.

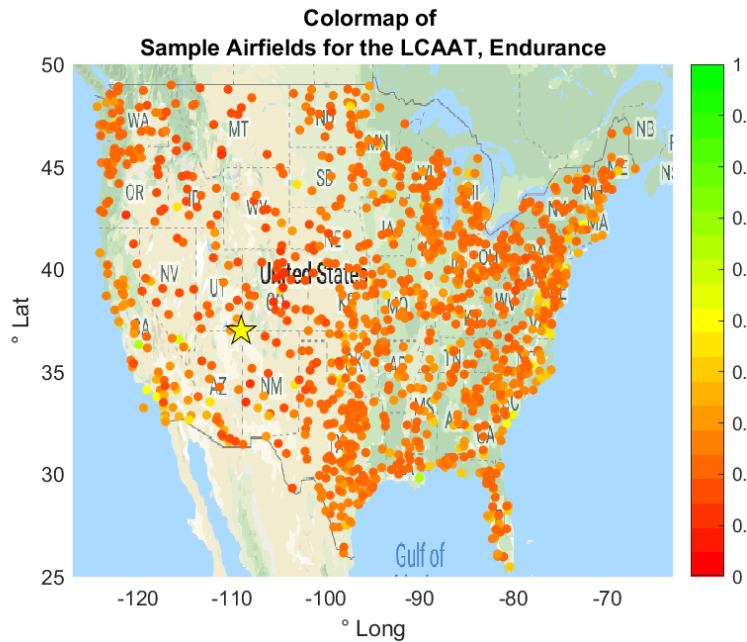


Figure 123. Colormap for the LCAAT System, Endurance

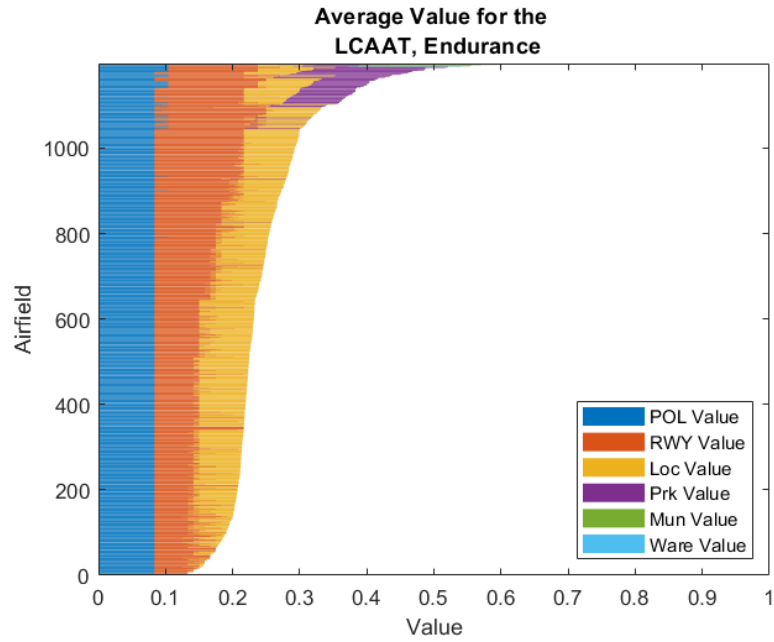


Figure 124. Tornado Chart for the LCAAT System, Endurance

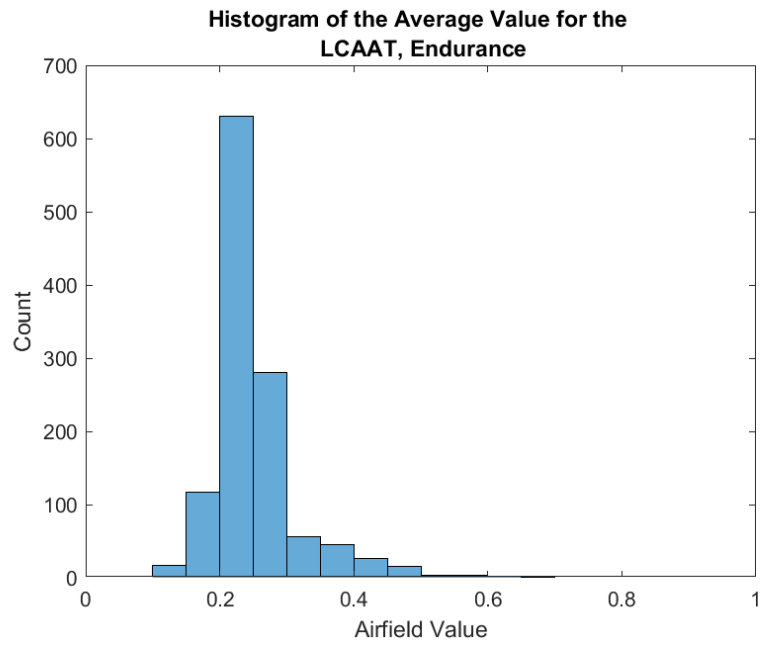


Figure 125. Histogram for the LCAAT System, Endurance

Speed.

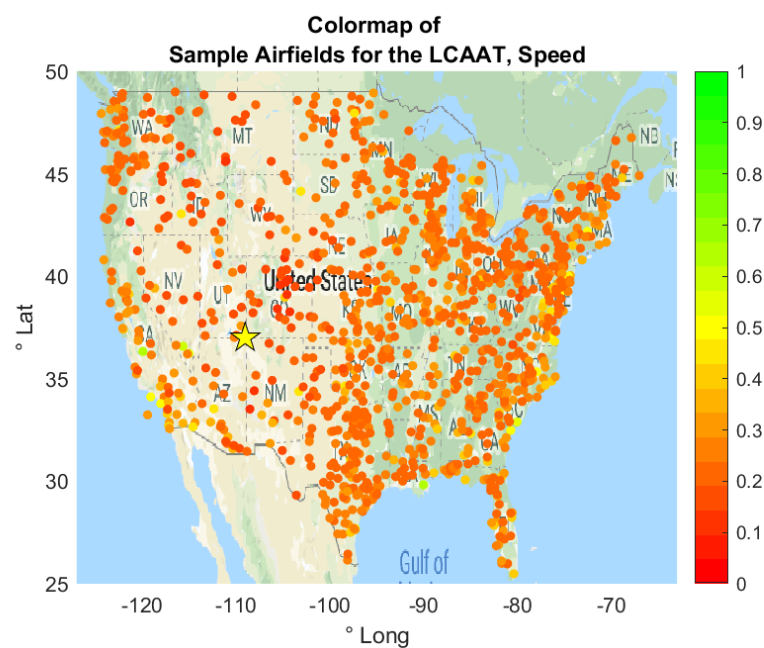


Figure 126. Colormap for the LCAAT System, Speed

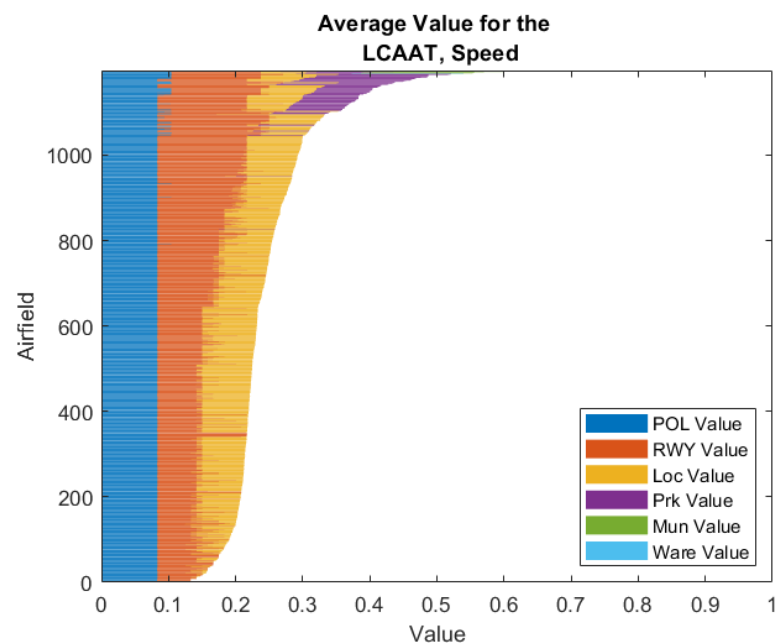


Figure 127. Tornado Chart for the LCAAT System, Speed

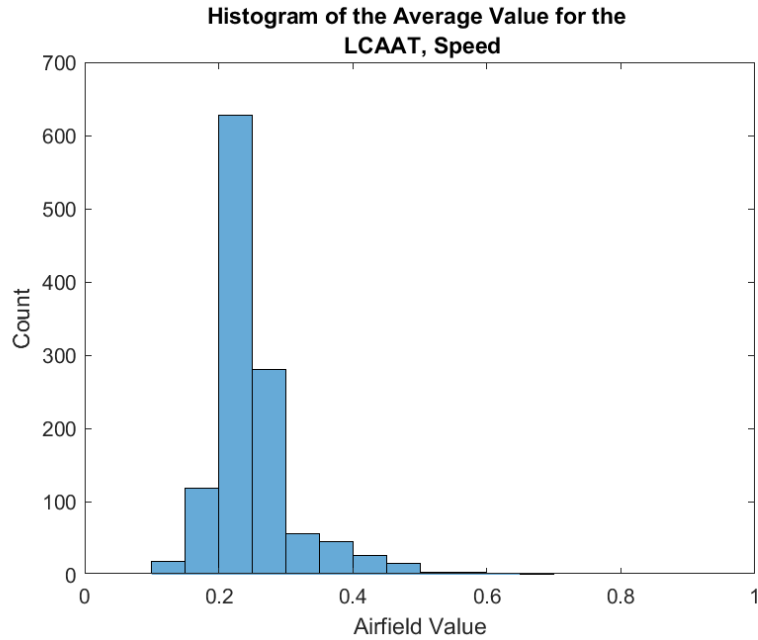


Figure 128. Histogram for the LCAAT System, Speed

Empty Weight.

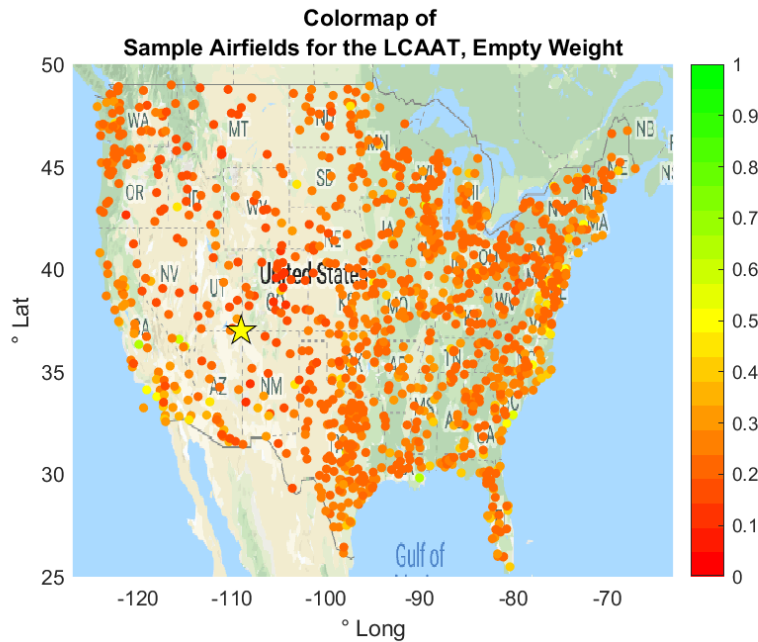


Figure 129. Colormap for the LCAAT System, Empty Weight

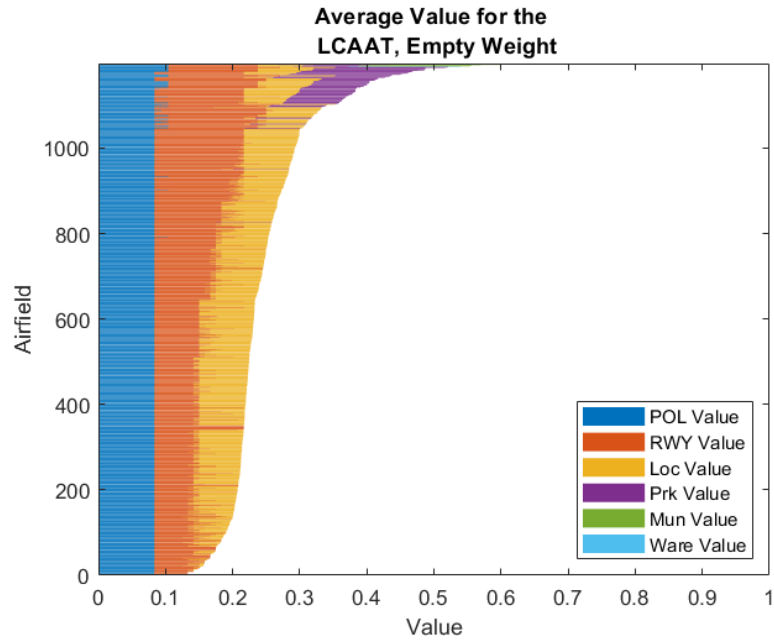


Figure 130. Tornado Chart for the LCAAT System, Empty Weight

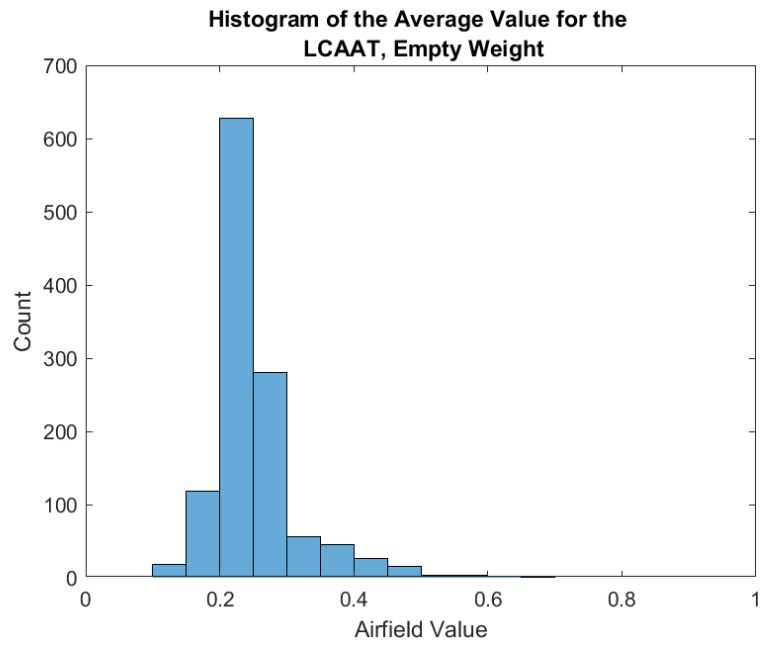


Figure 131. Histogram for the LCAAT System, Empty Weight

Fuel Weight.

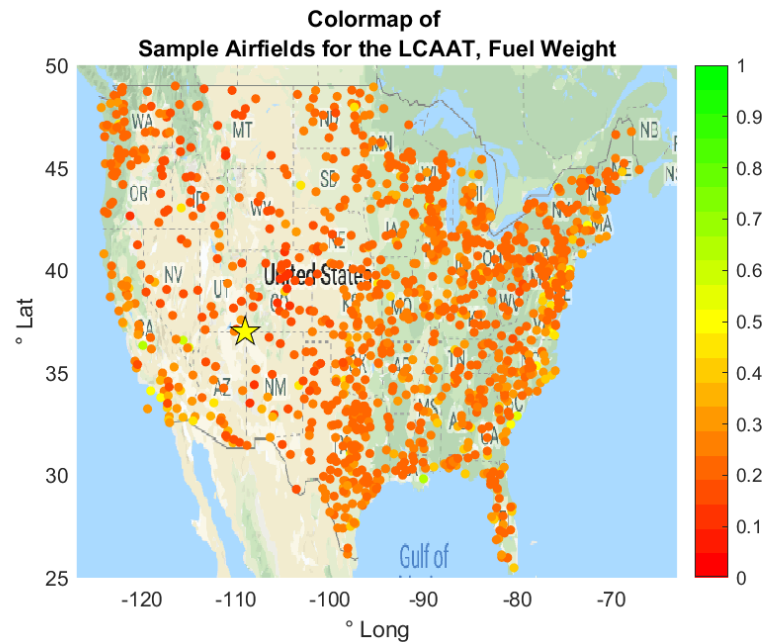


Figure 132. Colormap for the LCAAT System, Fuel Weight

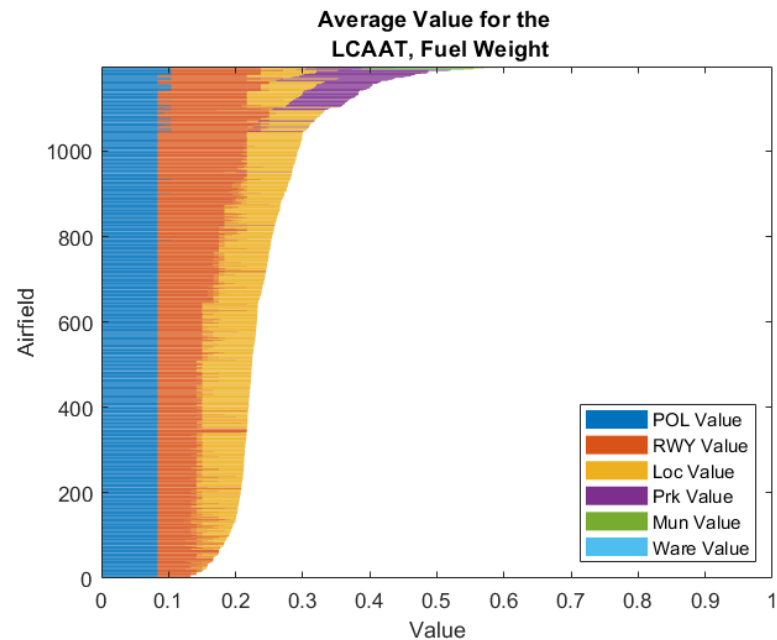


Figure 133. Tornado Chart for the LCAAT System, Fuel Weight

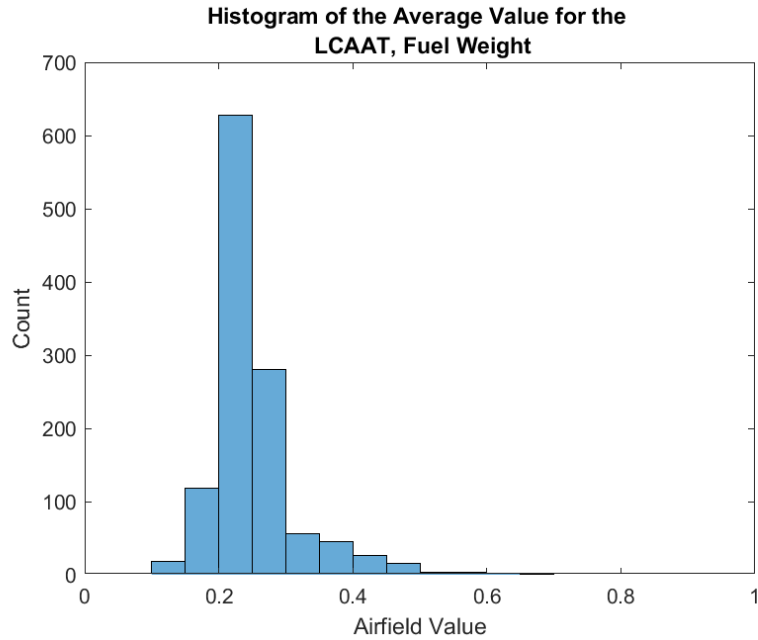


Figure 134. Histogram for the LCAAT System, Fuel Weight

Payload Weight.

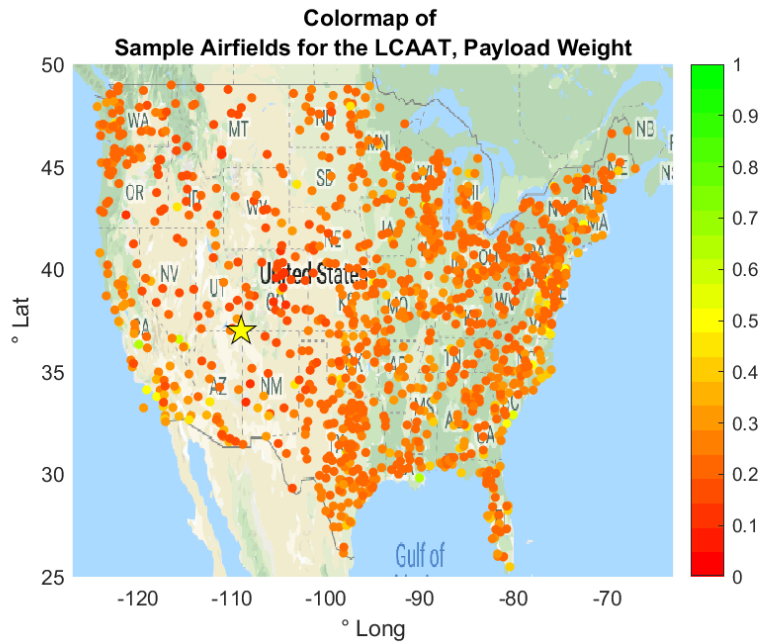


Figure 135. Colormap for the LCAAT System, Payload Weight

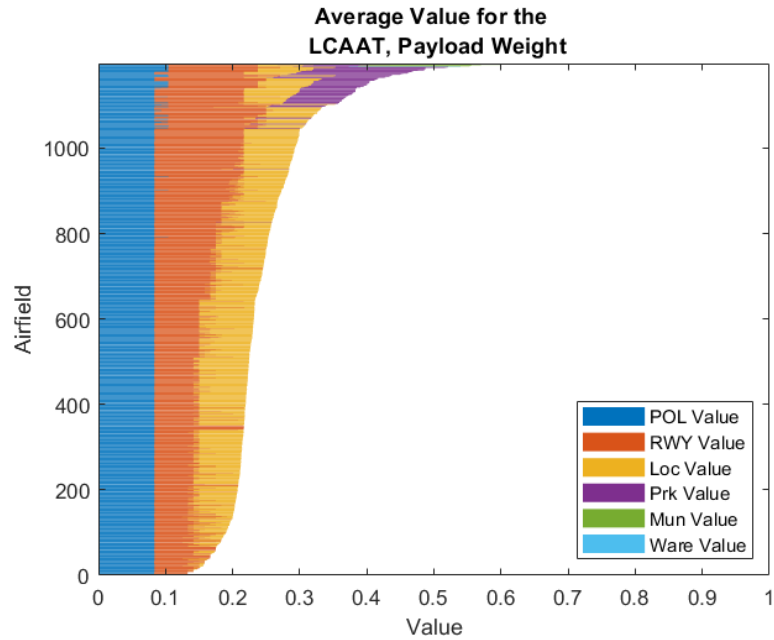


Figure 136. Tornado Chart for the LCAAT System, Payload Weight

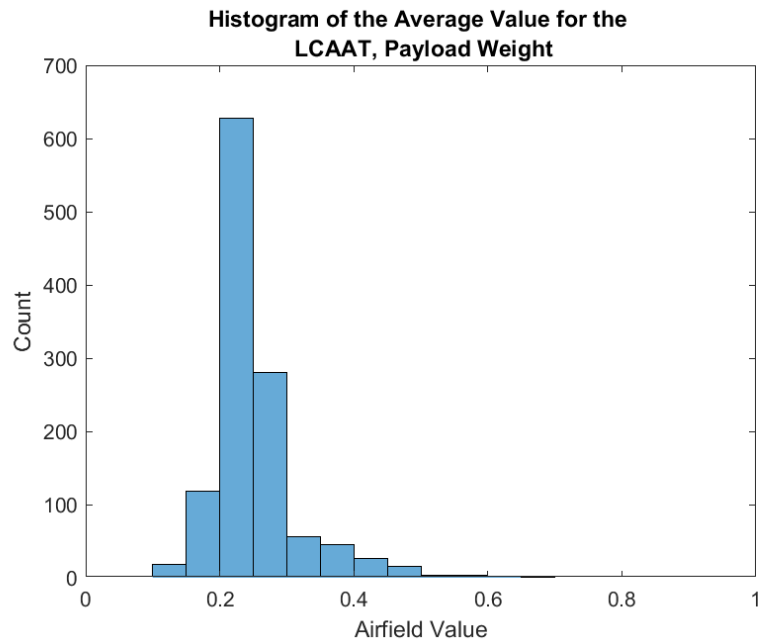


Figure 137. Histogram for the LCAAT System, Payload Weight

Bibliography

- Baker, Judd W. 2014. *OPTIMIZING C-17 PACIFIC BASING (MS thesis)*.
- Blanchard, B.S., & Fabrycky, W. J. 1998. *Systems Engineering and Analysis*. 3rd ed. edn. Prentice Hall.
- Box, George, E.P., Hunter, William, G., & Hunter, J. Stuart. 1978. *Statistics For Experimenter*. New York: John Wiley & Sons.
- CAPE. 2015. *Cost Assessment and Program Evaluation, Department of Defense Instruction 5000.73: cost analysis guidance and procedures*.
- Cessna Textron Aviation. 2019. *Cessna Skyhawk Specification*.
- Dammeier, David, Toliver, Meka, & Smith, Logan. 2016. Overcoming a power projection problem. *CE Online*.
- Department of Defense. 2008. *U.S. Central Command*.
- Department of Defense. 2017. *DoD Lab Day*.
- Department of Defense. 2018. *Manual for the Operation of the Joint Capabilities Integration and Development System*. Tech. rept. J-8 Joint Staff, Washington D.C.
- Department of the Air Force. 2006a. *C-5M Super Galaxy Fact Sheet*. Tech. rept. ACC Fact Sheets.
- Department of the Air Force. 2006b. *Planning And Design of Expeditionary Airbases (Air Force Pamphlet 10-219)*. Tech. rept. HQ AFCESA/CEX, Washington D.C.
- Department of the Air Force. 2009a. *Airfield Planning and Design Criteria for Unmanned Aircraft Systems (UAS), ETL 09-1*. Tech. rept. AFCESA/CEO, Tyndall AFB.
- Department of the Air Force. 2009b. *BQM-167A Fact Sheet*. Tech. rept. ACC Fact Sheets.
- Department of the Air Force. 2013a. *Capability Requirements Development (AFPD 10-6)*. Tech. rept. AF/A3/5, Washington D.C.
- Department of the Air Force. 2013b. *Operational Capability Requirements and Developments (AFI 10-601)*. Tech. rept. AF/A3/5, Washington D.C.
- Department of the Air Force. 2015. *MQ-9 Reaper Fact Sheet*. Tech. rept. ACC Fact Sheets.

- Department of the Air Force. 2017. *Propulsion Life Cycle Management For Aerial Vehicles (AFMAN 20-116)*. Tech. rept. SAF/AQD, Washington D.C.
- Department of the Air Force. 2018. *Base Support and Expeditionary (BASE&E) Site Planning (AFI 10-404)*. Tech. rept. Washington D.C.
- Directorate of Operational Capability Requirements. 2018. *Requirements Development Guidebook*. Tech. rept. AF/A5RP, Washington D.C.
- DoD NDS. 2018. *Summary of the 2018 National Defense Strategy*.
- Friedenthal, Sanford, Izumi, Lisa, Hill, Flint, & Street, Rosehaven. 2007. Object-Oriented Systems Engineering Method (OOSEM) applied to Joint Force Projection (JFP), a Lockheed Martin Integrating Concept (LMIC). *INCOSE International Symposium*, **17**(1), 1471–1491.
- Friedenthal, Sanford, Moore, Alan, & Steiner, Rick. 2009a. OMG Systems Modeling Language (OMG SysML) Tutorial.
- Friedenthal, Sanford A, Moore, Alan, & Steiner, Rick. 2009b. *A Practical Guide to SysML, The Systems Modeling Language*. First edn. Burlington, MA: Morgan Kaufman and Object Modeling Group.
- INCOSE. 2015. *Systems Engineering Handbook A GUIDE FOR SYSTEM LIFE CYCLE PROCESSES AND ACTIVITIES*. 4th edn. Wiley.
- Joint Chiefs of Staff. 2018. *Charter of the Joint Requirements Oversight council (JROC) and Implementation of the Joint Capabilities Integration and Development System (JCIDS)*. Tech. rept. CJCSI 5123.01H, Washington D.C.
- Keeney, Ralph L. 2008. Applying Value-Focused Thinking. *Military Operations Research Journal*, **13**(2), 7–18.
- Lostumbo, Michael J., McNerney, Michael J., Peltz, Eric, Eaton, Derek, Frelinger, David R., Greenfield, Victoria A., Halliday, John, Mills, Patrick, Nardulli, Bruce R., Pettyjohn, Stacie L., Sollinger, Jerry M., & Worman, Stephen M. 2013. *Overseas Basing of US Military Forces: An Assessment of Relative Costs and Strategic Benefits*. Tech. rept. RAND.
- Miravite, Alexander, Charles Schlegel Major, Jr F, & Major, Usaf. 2006. *GLOBAL EN ROUTE BASING INFRASTRUCTURE LOCATION MODEL (MS thesis)*.
- Mouton, Christopher, A., & Grissom, Adam, R. 2018. Preparing for "Post-ISIL" Access Challenges Robust Basing to Support Operations Against Nonstate Adversaries. *RAND Corporation, Research Report*.

- Narayanan, Anu, Bednarz, Sean, Ausink, John A, Baron, Joshua, Decicco, Anthony, Guffey, Robert A, Hart, George E, Matsumura, John, Nixon, Michael, Stelzner, Chuck, Taylor, William W, & Vesely, Joseph V. 2016. *A Modeling Framework for Optimizing F-35A Strategic Basing Decisions to Meet Training Requirements*. Tech. rept. RAND.
- National Geospatial-Intelligence Agency. 2019. *Aeronautical Charts and Publications*.
- ODASD(SE). 2018. *Department of Defense Digital Engineering Strategy*.
- Office of Aerospace Studies. 2014. *Capabilities-Based Assessment (CBA) Handbook*. Tech. rept. AFMC/OAS/A5, Kirtland AFB.
- Owen, Robert C. 2015. *Basing strategies for Air Refueling Forces in Antiaccess/Area-Denial Environments*. Air university Press.
- Sierra Nevada Corporation, & Embraer. 2019. *A-29 Specifications*. Tech. rept. Built for the Mission.
- Textron Aviation Defense LLC. 2019. *Scorpion Specs*. Tech. rept.
- The PERDUCO Group Inc. 2018. *Exploratory Tools Study*.
- U.S. Department of Transportation. 2005. *Runway Length Requirements for Airport Design, AC 150/5325-4B*. Tech. rept. Federal Aviation Administration, Washington.
- Vick, Alan J, & Heim, Jacob L. 2013. *Assessing U.S. Air Force Basing Options in East Asia*. Tech. rept. RAND.
- Way, Chris. 2018. Military Operations Research Society 86th Symposium 27th Working Group. In: *A Value Based Approach to Determining Basing Options for Contingency Planning*.
- Weisz, Brad. 2012. *The Logistical Impact of Seabasing*.
- Welsh, Mark A. 2016. Global Vigilance, Global Reach, Global Power for America. *Air University*.
- Wheeler, Tom. 2016. *MBSE Workshop*.
- Wilson, Heather, Goldfein, David, L., & Wright, Kaleth, O. 2017 (8). *Letter to the Total Force*.

REPORT DOCUMENTATION PAGE					Form Approved OMB No. 0704-0188	
The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.						
1. REPORT DATE (DD-MM-YYYY)		2. REPORT TYPE		3. DATES COVERED (From — To)		
21-03-2019		Master's Thesis		Sept 2017 — Mar 2019		
4. TITLE AND SUBTITLE Methodology for Including Base Infrastructure in Conceptual System Analysis				5a. CONTRACT NUMBER		
				5b. GRANT NUMBER		
				5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Kelly, Patrick, J, 1st LT, USAF				5d. PROJECT NUMBER		
				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 Hobson Way WPAFB OH 45433-7765				8. PERFORMING ORGANIZATION REPORT NUMBER AFIT-ENV-MS-19-M-182		
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Program Development & Integration Directorate 2240 B Street WPAFB OH 45433-7765 DSN 904-4505, COMM 937-674-4505 Email: Walid.Basraoui1@us.af.mil				10. SPONSOR/MONITOR'S ACRONYM(S) AFLCMC/XZ		
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION / AVAILABILITY STATEMENT DISTRIBUTION STATEMENT A: APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.						
13. SUPPLEMENTARY NOTES This work is declared a work of the U.S. Government and is not subject to copyright protection in the United States.						
14. ABSTRACT The 2018 National Defense Strategy defines a transition to agile basing, where the logistics footprint of new conceptual systems can be distributed across a set of airfields, instead of one main operating base. Currently, there is no capability to assess early concepts using airfield data. This research develops a methodology and a tool that assesses system concepts using world-wide civil and military airfield infrastructure, such as runway parameters, parking, munitions, fuel and warehouse storage, and distance to areas of interest. Specifically, the focus of the thesis is on concepts for the Intelligence, Surveillance, and Reconnaissance (ISR) Strike mission. Four concepts were assessed, a Medium-Altitude Long Endurance (MALE) ISR vehicle similar to a MQ-9 Reaper, a light attack aircraft, a light attack jet, and a low-cost attritable aircraft similar to a BQM-167A aerial drone. The tool incorporates Value Focused Thinking, with the value model conditioned by selected design parameters. The system that values a set of airfields the highest would be advantageous in an adaptive basing environment. The MALE ISR platform resulted in a statistically significant difference (nearly 10%) in median value determined by the Wilcoxon signed rank test, then the other systems.						
15. SUBJECT TERMS Model Based Systems Engineering, Agile Basing, Base Infrastructure, Conceptual Design, Object-Oriented Systems Engineer Method						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT	b. ABSTRACT	c. THIS PAGE			Dr. John M. Colombi, AFIT/ENV	
U	U	U	U	165	19b. TELEPHONE NUMBER (include area code) (937) 255-3355, x3347; john.colombi@afit.edu	