



**The Effects of Aircraft Use and Available Repair
Spares on Aircraft Sortie Generation: A
Long-Duration Logistical Wargaming Simulation
Tool**

THESIS

Nathaniel M. Choo
AFIT-ENS-MS-20-D-069

**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-ENS-MS-20-D-069

The Effects of Aircraft Use and Available Repair Spares on Aircraft Sortie
Generation: A Long-Duration Logistical Wargaming Simulation Tool

THESIS

Presented to the Faculty
Department of Operational Sciences
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 Operations Research

Nathaniel M. Choo, B.S.E.

December 24, 2020

DISTRIBUTION STATEMENT A
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

AFIT-ENS-MS-20-D-069

The Effects of Aircraft Use and Available Repair Spares on Aircraft Sortie
Generation: A Long-Duration Logistical Wargaming Simulation Tool

THESIS

Nathaniel M. Choo, B.S.E.

Committee Membership:

Darryl Ahner, Ph.D
Chair

Lance Champagne, Ph.D
Reader

Abstract

A long-duration logistical wargame simulation tool that can provide quick insights into the daily aircraft availability and the daily number of missions accomplished for a variety of operational scenarios is developed. This simulation tool is designed to be a stepwise wargaming support tool for adjudication within long-duration logistical wargames and provides the user many capabilities including, but not limited to, the ability to have multiple bases and types of aircraft. Additionally, the user has the ability to control types of part failures, control parts availability, control maintenance capabilities, and control number of mission scheduled. Finally, the user can account for the possibility of attrition along with the effects of numerous major events present in real-life scenarios. Validation of the tool is achieved through application of a space covering design along with regression modeling and shows that the tool is well-behaved, functions as expected, and can quickly provide meaningful insights into operational scenarios. A utilization rate method is explored that informs the allowable inputs that result in stable long term behavior within the model. An analysis of a variety of operational scenarios demonstrates the effectiveness and usefulness of this tool. Future developments are proposed that can expand the functionality and usefulness of this simulation tool.

*I dedicate this to my parents and family. I am forever grateful for your continuous
love and support.*

Acknowledgements

I am sincerely thankful of Dr. Darryl Ahner for his mentorship and guidance throughout this process; he is an excellent academic advisor and a wonderful mentor. I would like to express my gratitude to Dr. Lance Champagne for reading my thesis and providing his expert recommendations. I want to acknowledge and thank all of the individuals who made this opportunity possible.

Nathaniel M. Choo

Table of Contents

	Page
Abstract	iv
Acknowledgements	vi
List of Figures	ix
List of Tables	xv
I. Introduction	1
1.1 Problem Background	1
1.2 Research Objectives	1
1.3 Document Overview	3
II. Background and Literature Review	4
2.1 Overview	4
2.2 Simulation	6
2.2.1 Part Failures	8
2.2.2 Maintenance	9
2.3 Chapter Summary	10
III. Methodology	12
3.1 Overview	12
3.2 Model Development	12
3.2.1 Simulation Process	15
3.2.2 Major Events	16
3.2.3 Maintenance	17
3.2.4 Flying Missions	23
3.3 Determining the Lower Bound of MTBF for Testing Scenarios	25
3.4 ENIGMA Application Description and User Guide	30
3.4.1 Overview	31
3.4.2 Preparing the Simulation	31
3.4.3 Viewing Original Input Data	35
3.4.4 Viewing/Editing Input Data	35
3.4.5 Input Data Requirements	45
3.4.6 Running the Simulation	50
3.4.7 Post-Simulation Run Controls	54

	Page
IV. Results and Analysis	56
4.1 Preamble	56
4.2 Model Checking	56
4.2.1 Model Validation Through a Main-Effects Metamodel	59
4.2.2 Model Validation Through a Response-Surface Metamodel	65
4.3 Checking the Signs of the Main-Effect Models' Parameter Estimates	72
4.4 Analysis of MTBF Inequality	85
4.5 Operational Testing: A Few Examples	88
4.5.1 Scenario 1: Number of Missions	89
4.5.2 Scenario 2: Attrition Rates	92
4.5.3 Scenario 3: Flying Aircraft to Another Base	95
4.5.4 Scenario 4: Mean Time To Repair	98
4.5.5 Scenario 5: Mean Time Before Failure	101
4.5.6 Scenario 6: Damage/Destruction of Base Aircraft	103
4.5.7 Scenario 7: Logistics (Access to New Spares)	106
4.6 Effects of Including Turnaround Time	109
4.6.1 Expectations of Turnaround Time	110
4.6.2 Scenario 1	113
4.6.3 Scenario 2	115
4.6.4 Scenario 3	116
4.6.5 Scenario 4	117
4.6.6 Scenario 5	119
4.6.7 Scenario 6	120
4.6.8 Scenario 7	121
4.6.9 Summary	122
4.7 Run-time Testing	122
4.7.1 Run-Time Regression Model	123
V. Conclusions	136
5.1 Future Work	137
Appendix A. Additional Tables	139
Bibliography	155

List of Figures

Figure	Page
1. Overview of ENIGMA	13
2. Time-Step	15
3. Overview of Maintenance Process	18
4. Flying Missions Process	24
5. Open the Load Files Dropdown Menu	32
6. Choose Which Type of File to Upload	33
7. Upload Selected File	33
8. Clear All Uploaded Files	34
9. Clear Specific File	35
10. Select the Uploaded File to View	36
11. Example of Viewing Uploaded File	36
12. Select Input Data for Edit Table	37
13. Edit Directly Into the Data Table	38
14. Save Edits	38
15. Add New Rows	39
16. Result of Adding Row to Blank Data Table	40
17. Adding Row to Data Table with Only Column Names Popup Window	40
18. Missions Requiring Multiple Aircraft (Prior to Separation)	42
19. Result of Separating Missions (Result of Separation)	43
20. Example of Invalid names	44
21. Making Invalid Names Valid Example	45

Figure	Page
22.	Input Number of Days and Number of Replications 51
23.	Selecting Step-wise 52
24.	Example - Step-wise First Iteration (First[5 Days]) 53
25.	Example - Step-wise Second Iteration (First[5 Days] + Second[7 Days]) 53
26.	Example Displaying Output 54
27.	Exporting Output As a File 55
28.	Exporting File 55
29.	Residuals by Predicted: Average Proportion of Aircraft that are Mission Capable (Main Effects Model) 61
30.	Distribution of Residuals: Average Proportion of Aircraft that are Mission Capable (Main Effects Model) 62
31.	Residuals by Predicted: Average Proportion of Aircraft that are Mission Capable (Main Effects Model) 64
32.	Distribution of Residuals: Average Proportion of Missions Accomplished (Main Effects Model) 64
33.	Residuals Response Surface(Average Proportion of Aircraft that are Mission Capable) 67
34.	Residuals by Predicted: Average Proportion of Aircraft that are Mission Capable 67
35.	Residuals Response Surface (Average Proportion of Missions Flown) 68
36.	Residuals by Predicted: Average Proportion of Missions Flown (Response Surface) 70
37.	Distribution of Average Proportion of Missions Flown (Response Surface Metamodel) 70
38.	Average Proportion of Aircraft That are Mission Capable: Baseline Scenario 73

Figure	Page
39. Average Proportion of Missions Accomplished: Baseline Scenario	74
40. Scenario 1 - Quantity of Missions: Average Proportion of Aircraft that are Mission Capable	75
41. Scenario 1 - Quantity of Missions: Average Proportion of Missions Accomplished	75
42. Scenario 2 - Attrition Rate: Average Proportion of Aircraft that are Mission Capable	76
43. Scenario 2 - Attrition Rate: Average Proportion of Missions Accomplished	76
44. Scenario 3 - Reinforcements: Average Proportion of Aircraft that are Mission Capable	77
45. Scenario 3 - Reinforcements: Average Proportion of Missions Accomplished	78
46. Scenario 4 - Repair Rate: Average Proportion of Aircraft that are Mission Capable	79
47. Scenario 4 - Reinforcements: Average Proportion of Missions Accomplished	79
48. Scenario 5 - Failure Rate: Average Proportion of Aircraft that are Mission Capable	80
49. Scenario 5 - Failure Rate: Average Proportion of Missions Accomplished	80
50. Scenario 6 - Damage/Destroy Aircraft: Average Proportion of Aircraft that are Mission Capable	81
51. Scenario 6 - Damage/Destroy Aircraft: Average Proportion of Missions Accomplished	82
52. Scenario 7 - Effect of Spares: Average Proportion of Aircraft that are Mission Capable	83
53. Scenario 7 - Effect of Spares: Average Proportion of Missions Accomplished	83

Figure	Page
54. Plotting $E(F) = E(R)$ to relate MTBF to Average Aircraft Availability	86
55. Testing Varying Levels of MTBF	88
56. Scenario 1 Excursions: Aircraft Availability	91
57. Scenario 1 Excursions: Sorties Flown	92
58. Scenario 2 Excursions: Aircraft Availability	94
59. Scenario 2 Excursions: Sorties Flown	94
60. Scenario 3 Excursions: Aircraft Availability	97
61. Scenario 3 Excursions: Sorties Flown	97
62. Scenario 4 Excursions: Aircraft Availability	100
63. Scenario 4 Excursions: Sorties Flown	100
64. Scenario 5 Excursions: Aircraft Availability	102
65. Scenario 5 Excursions: Sorties Flown	103
66. Scenario 6 Excursions: Aircraft Availability	105
67. Scenario 6 Excursions: Sorties Flown	106
68. Scenario 7 Excursions: Aircraft Availability	108
69. Scenario 7 Excursions: Sorties Flown	108
70. Aircraft Availability: Turnaround Time No Effect	112
71. Number of Missions Flown: Turnaround Time No Effect	112
72. Aircraft Availability: Turnaround Time with Effect	113
73. Number of Missions Flown: Turnaround Time with Effect	113
74. Operational Scenario 1 With Turnaround Time: Aircraft Availability	114
75. Operational Scenario 1 With Turnaround Time: Number of Sorties Flown	114

Figure		Page
76.	Operational Scenario 2 With Turnaround Time: Aircraft Availability	115
77.	Operational Scenario 2 With Turnaround Time: Number of Sorties Flown	115
78.	Operational Scenario 3 With Turnaround Time: Aircraft Availability	116
79.	Operational Scenario 3 With Turnaround Time: Number of Sorties Flown	116
80.	Operational Scenario 4 With Turnaround Time: Aircraft Availability	118
81.	Operational Scenario 4 With Turnaround Time: Number of Sorties Flown	118
82.	Operational Scenario 5 With Turnaround Time: Aircraft Availability	119
83.	Operational Scenario 5 With Turnaround Time: Number of Sorties Flown	119
84.	Operational Scenario 6 With Turnaround Time: Aircraft Availability	120
85.	Operational Scenario 6 With Turnaround Time: Number of Sorties Flown	120
86.	Operational Scenario 7 With Turnaround Time: Aircraft Availability	121
87.	Operational Scenario 7 With Turnaround Time: Number of Sorties Flown	122
88.	Summary of Fit: Run Time	124
89.	Parameter Estimates: Run Time	124
90.	Effects Summary: Run Time	125
91.	Distribution of Residuals	126
92.	Residuals: Run Time	126

Figure		Page
93.	Summary of Fit: $\sqrt{RunTime}$	128
94.	Parameter Estimates: $\sqrt{RunTime}$	128
95.	Effects Summary: $\sqrt{RunTime}$	128
96.	Distribution of Residuals: $\sqrt{RunTime}$	129
97.	Residuals by Predicted: $\sqrt{RunTime}$	129
98.	Distribution: $\frac{Time}{NumberofDays*NumberofRuns}$	131
99.	Distribution (Separate Missions Prior): $\frac{Time}{NumberofDays*NumberofRuns}$	132
100.	Distribution (Did Not Separate Missions Prior): $\frac{Time}{NumberofDays*NumberofRuns}$	133
101.	Comparing Distributions (Separate or Not to Separate): $\frac{Time}{NumberofDays*NumberofRuns}$	134

List of Tables

Table		Page
1.	Features Available in this Phase of ENIGMA	14
2	Possible Select Column(s) Inputs	41
3	Aircraft States Data Table Headers	46
4	Spares Data Table Headers.....	47
5	Repair/Failure Rates Data Table Headers	48
6	Missions Data Table Headers	48
7	Major Events Data Table Headers	49
8	Major Event Options.....	50
9.	Parameter Estimates Main-Effects Metamodel (Average Proportion of Aircraft that are Mission Capable).....	60
10.	Summary of Fit Main-Effects Metamodel (Average Proportion of Aircraft that are Mission Capable).....	61
11.	Effects Summary Main-Effects Metamodel (Average Proportion of Aircraft that are Mission Capable).....	61
12.	Durbin-Watson Statistic of Average Proportion of Aircraft that are Mission Capable (Main Effects Model).....	61
13.	Parameter Estimates Main-Effects Metamodel (Average Proportion of Missions Flown).....	63
14.	Summary of Fit Main-Effects Metamodel (Average Proportion of Missions Flown).....	63
15.	Effects Summary Main-Effects Metamodel (Average Proportion of Missions Flown).....	64
16.	Durbin-Watson Statistic of Average Proportion of Missions Accomplished (Main Effects Model)	64
17.	Parameter Estimates Response Surface (Average Proportion of Aircraft that are Mission Capable).....	66

Table		Page
18.	Summary of Fit Response Surface (Average Proportion of Aircraft that are Mission Capable)	66
19.	Durbin-Watson Statistic of Average Proportion of Aircraft that are Mission Capable (Response Surface)	66
20.	Parameter Estimates Response Surface(Average Proportion of Missions Flown)	69
21.	Summary of Fit Response Surface (Average Proportion of Missions Flown)	69
22.	Durbin-Watson Statistic of Average Proportion of Missions Accomplished (Response Surface)	69
23	Ranges of Inputs for Testing	71
24.	Baseline Scenario for Checking Main-Effects Parameter Estimates	72
25.	Scenarios to Compare to Baseline	73
26.	Coefficient Analysis: Summary of the Comparison of the Scenarios to the Baseline	84
27	Baseline Properties Scenario 1	90
28	Scenario 1 Excursion	90
29	Baseline Properties Scenario 2	93
30	Scenario 2 Excursions	93
31	Baseline Properties Scenario 3	95
32	Scenario 3 Excursions	96
33	Baseline Properties Scenario 4	98
34	Scenario 4 Excursions	99
35	Baseline Properties Scenario 5	101
36	Scenario 5 Excursions	102
37	Baseline Properties Scenario 6	104

Table		Page
38	Scenario 6 Excursions	104
39	Baseline Properties Scenario 7	107
40	Scenario 7 Excursions	107
41	Turnaround Times Simulation Inputs (No effect)	110
42	Turnaround Times Simulation Inputs (Effect)	111
43.	Durbin-Watson Statistical Test Results: $\sqrt{RunTime}$	130
44	Types of Major Events	140
45	Experimental Design: Simulation Behavior	144
46	Experimental Design Run Time	146
47	Experimental Design Run Time (Separate Missions Prior to Running Simulation)	149
48	Experimental Design Run Time (Does Not Separate Missions Prior to Running Simulation)	152

The Effects of Aircraft Use and Available Repair Spares on Aircraft Sortie
Generation: A Long-Duration Logistical Wargaming Simulation Tool

I. Introduction

1.1 Problem Background

In conducting operations, Air force planners must balance the conduct of missions against the impact on near-term aircraft availability. Since equipment becomes damaged over time with usage, a trade-off exists between current usage and future availability. Additionally, operational scenarios may require decision makers to balance the availability of mission aircraft with their operational impact by changing the number and the type of missions flown. In order to explore these trade-offs, a tool that helps users observe the trade-offs between the future daily aircraft availability and the current aircraft usage would be beneficial. Such a tool would incorporate additional realism into planning processes that do not have planning tools that capture such trade-offs. A tool such as this must not only be traceable and defensible, but must also function quickly to inform real-time operational impacts.

1.2 Research Objectives

The objective of this thesis is to create a simulation tool that can project an estimate of the daily aircraft availability and the daily number of missions accomplished based on a set of inputs that define an operational scenario. This tool needs to be easy to use and able to return a result in a short period of time in order to be practical. To reduce the computation time of the simulation, real-world processes

will need to be simplified to reduce the complexity and number of calculations that must be done. The abstraction to a simpler model has added benefits of traceability and defendability, as well as increased versatility. Generalization also may allow for robust use over a wide variety of locations as it will not be bound by assumptions about specific real-world locations.

Once developed, the model will be validated to behave properly. Additionally, the tool will also be used to demonstrate operational scenarios to provide insights into the effects of different parameters of the system. For example, an operational scenario can explore the effect of increasing the number of on-site spares available for maintenance on the daily aircraft availability and the daily number of missions flown. The operational scenarios that will be explored in this paper include:

1. Increasing the quantity of missions over a short period of time on the daily aircraft availability and the daily number of missions flown.
2. Increasing the attrition rate of missions on the daily aircraft availability and on the daily number of missions flown.
3. Flying aircraft between bases to reinforce an operational environment experiencing a high attrition rate on the daily aircraft availability and the daily number of missions flown.
4. Changing the repair rate of damaged aircraft on the daily aircraft availability and the daily number of missions flown.
5. Changing the rate of part failures of aircraft on the daily aircraft availability and the daily number of missions flown.
6. Damaging and destroying a variety of number of aircraft on a specific period on the daily aircraft availability and the daily number of missions flown.

7. Changing the number of on-site spares available for repairing aircraft during a time period when new spares are not able to be acquired on daily aircraft availability and daily missions flown.

Once the scenarios have been explored, the run time of the simulation tool will be investigated.

1.3 Document Overview

The remainder of this document is as follows. Chapter 2 provides an overview of other research and approaches to modeling the average aircraft availability and sortie generation processes. Chapter 3 describes the approach to the development of the simulation tool and the method of how to use the tool. Chapter 4 develops the results of the analysis that was done on the simulation tool and provides insights. Chapter 5 summarizes the conclusion and discusses future work that can be done on the simulation tool to continue to expand its features and functionality.

II. Background and Literature Review

This chapter presents a review of relevant literature and previous research and methods that have been used to investigate sortie generation and mission capable rates of aircraft squadrons.

2.1 Overview

The aircraft and the equipment that is required to complete missions must be of mission capable status in order for the Air Force to successfully conduct its missions. In this paper, an aircraft is considered to be mission capable if it is functionally able to fly and complete its missions. The Air Force has three different classification levels of mission capable status: fully mission capable, partially mission capable, and non-mission capable; aircraft in either fully mission capable or partially mission capable status is considered to be mission capable, since it is still able to complete the mission that it is assigned[1]. When aircraft are mission capable, they are able to fly sorties. The definition of a sortie that will be used by this paper adopts Mackenzie, Miller, Hill, and Chambal's definition of a sortie, which is one mission flown by an individual aircraft[2].

Due to the importance of flying and completing the Air Force's missions, there have been many methodologies and approaches employed to study the real-world systems and processes impacting both the sortie generation rates and the mission capable rates of the Air Force's aircraft. For example, Faas utilized discrete-event simulation to model the effects of the Autonomic Logistics System, which is a tool that can autonomously handle certain logistical tasks, including sending notifications that a returning aircraft will not be able to fly its next missions and automatically ordering parts needed for maintenance, on the sortie generation process of a fighter

squadron[3]. Similarly, Aykiri developed a discrete-event simulation tool to model the sortie generation process of a specific Turkish air base in order to support decision-making in the Turkish Air Force[4].

Agent based modeling is another approach that has been employed to study sortie generation rates. Agent based modeling differs from top-down approaches, such as discrete-event simulation that may not adequately capture the unknown effects of a system, by modeling individual agents interacting with other agents and resources to observe the properties of the system of interest that may not be captured with other methods[5].

Due to the complexity of the process of generating sorties, it can be difficult to generate a single model to consistently and accurately reflect the true sortie generation rates of different real-world systems. Despite the complexity of sortie generation, its fundamental processes and behaviors can be observed with a simple model[6]. Using the appropriate approach, assumptions, and simplifications, Dietz and Jenkins managed to find an analytical method that can accurately estimate the mean performance of sortie generation processes modeled as a queuing network with concurrent repair activities[6]. Though the proposed model may not include all of the variables necessary to be able to replace simulation analysis, Dietz and Jenkins demonstrate how simplified models, such as queuing models, can still provide useful insights into sortie generation. Previous work suggests that it may be beneficial to produce a simple, a flexible, and an expedient tool that can quickly approximate the aircraft availability across Air Force bases while including the variables that may be neglected in non-simulation based models to support decision making processes for situations when there is not enough time to utilize computationally expensive simulations, but that still require a significant level of detail.

2.2 Simulation

Simulation is an effective tool because it can provide meaningful insights into systems that may be too complicated for the current analytical approaches to solve[7]. Simulations can be used to compare different scenarios or policies and can even be used to find optimal solutions to problems using a process known as simulation optimization[8]. Since the process of sortie generation is a complicated process to study and to create analytical models for, simulation methods can be an effective way to investigate the impact of different changes to the process. There have been numerous studies that have used simulation to study the effects of different scenarios on sortie generation rates. In simulation, it is important to focus on the purpose of the simulation in order to make the appropriate simplifications to the model so that an adequate answer to the question at hand is realized.

There are many studies that have used simulation to model the sortie generation process in the Air Force. Balaban, et al, used Crystal Ball, a simulation software, to develop a mission capable rate model specifically for the C-5 in order to investigate the potential benefits of upgrading different systems in the C-5[1]. Crystal Ball is a Monte Carlo simulation software that is run as an add-in to Microsoft Excel to run Excel models[9]. The simulation that Balaban, et al, developed assumes that multiple C-5 parts can fail upon return from a mission with a specified duration. Most components were modeled to fail according to an exponential distribution with a specified rate of failure; other non-time dependent components were modeled to fail according to a binomial distribution[1]. Distinguishing the rate of failure of each of the parts separately allows the model to capture part failures more accurately.

O’Neal [10] demonstrates the importance of determining failure rates of a part as either time dependent or non-time dependent since the rate of failure of some parts are more correlated with the number of hours flown, while other parts are more

correlated with the number of missions flown; O’Neal demonstrates that incorporating this distinction can significantly reduce forecasting error of spare part demand[10]. Similarly, Balaban, et al, model was shown to provide realistic mission capable rates for the C-5, which was the focus of their model[1].

Agent-based modeling has also been used to study the sortie generation process. MacKenzie, Miller, Hill, and Chambal used NetLogo, an agent-based modeling environment, to examine the effects of different maintenance personnel on the sortie generation rate of a single fleet of aircraft[2]. Agent-based modeling allowed them to model the effects of individual maintenance personnel with a variety of skill levels and Air Force Specialty Codes (AFSC) interacting with one another and the system. The individual agents in the simulation attempted to simultaneously provide the appropriate maintenance and provide adequate training to other agents to model the trade-off between the dedication to training and the dedication to performing maintenance on aircraft. This approach of agent-based modeling allowed the researchers to observe dynamic processes and relationships in the maintenance aspect of sortie generation[2].

Simulation tools have also been developed in attempt to obtain quick insights into the state of a fleet at any given point in time. Harris developed the Sortie Generation Rate Model that can be used to quickly test different scenarios effects on the sortie generation rate to quickly compare planning options and to add realism to the planning processes of operations[11]. The Sortie Generation Model was developed as a discrete-event simulation in Arena 5.0 and utilizes triangular distributions to estimate event times. Since the model was intended to be used quickly, there were far fewer inputs required than in other simulations modeling similar systems. This tool was validated by comparing the sortie generation rates to previous studies that used other simulation models, specifically LCOM and Flyer[11]. Despite the many

assumptions required to build the Sortie Generation Rate model, it showed that even simple simulation tools may be beneficial in planning operations where time to perform analysis is limited.

2.2.1 Part Failures

In order to appropriately model the mission capable status of aircraft, both the aircraft usage and the aircraft maintenance must be simultaneously modeled in the simulation[12]. Many of the simulations that are used to study the sortie generation process incorporate both the aircraft usage and the maintenance of the sortie generation process for this reason. Modeling an appropriate rate of arrivals of aircraft requiring maintenance is important in simulations of sortie generation because it allows the maintenance aspect of sortie generation to be incorporated into the model.

Aircraft failures are important events that can be used to obtain an appropriate arrival rate of aircraft needing maintenance. Due to the complexity of aircraft, there are many factors that affect the rate at which part failures occur. Some of these factors include the environment where the part is used, the frequency and duration that the part is used, and the load on the part during each usage. Despite the many factors that affect the rates of failures in aircraft parts, the part failure rates can be based solely upon the overall duration of time the aircraft is used[12]. Additionally, the inter-arrival times of failures can be modeled with an exponential distribution in certain circumstances[13]. Thus, for simplification of the model, the inter-arrival times of aircraft failures can be represented with an exponential distribution of a known failure rate. Additionally, exponential distributions are useful in discrete-time simulations because they are memoryless, meaning that the probability of an event occurring within a certain period of time is independent of the current time. Equation (1) defines this memoryless property.

$$P(T > t + s | T > t) = P(T > s) \quad (1)$$

Besides part failures, there are also many other reasons why an aircraft can be in a non-mission capable state and requiring maintenance. Some of these reasons include: isochronal inspections, which are scheduled maintenance activities performed approximately every 400 days; home station checks, which is a scheduled maintenance activity performed approximately every 90 days; refurbishments, which includes minor routine maintenance that is not as a result of part failure; and other non-corrective maintenance[1]. Although there are many reasons why an aircraft can be in maintenance, the primary reasons why an aircraft is in maintenance is a result of part failures; thus, flight failures may represent the only source of required maintenance when modeling aircraft availability through a sortie generation process[14].

2.2.2 Maintenance

The maintenance aspect of sortie generation is difficult to replicate accurately in models due to its complexity. Maintenance capabilities are also difficult to simulate because of the uncertainty in the effects of supply chain disruptions, which can result from the actions of an enemy or simply the absence of spare parts[15]. Despite its complexity, maintenance operations are important to incorporate into sortie generation models because of their ability to heavily impact the number of mission capable aircraft available for operations. There have been many approaches and simulations to study maintenance systems. Alrabghi and Tiwari demonstrated that discrete event simulation is an effective method for modeling and obtaining insights into complex maintenance processes[16]. The quantity of spare parts available is one of the aspects that can affect the effectiveness of the maintenance process. Spares are especially important to include in simulating maintenance processes because if a spare part is

not available to be used for a repair, it will result in additional time needed to fix the damaged part[1]. Changsung states that maintenance capability can be improved by increasing the number of spare parts available to maintenance teams; however, having large number of spares is not always feasible due to the cost of maintaining and storing spare parts[12]. Agent based modeling has also been employed as another approach to study the maintenance system's effect on sortie generation. MacKenzie, et al, demonstrated that the number of personnel of different Air Force Specialty Codes (AFSC) and different training levels significantly influence the effectiveness of a maintenance system supporting sortie generation[2]. They did this by modeling individual maintenance personnel, each with a different training and knowledge base, making decisions and interacting with other personnel to represent the maintenance process[2]. Since the quantities of AFSC personnel impact the effectiveness of the maintenance process, the Logistics Composite Model (LCOM) can be used to generate models that relate the quantity of different AFSC personnel to the rate of repair in maintenance. Likewise, LCOM is a simulation that has been validated for study the effects of personnel capability on various Air Force systems[17]. It can be used to obtain insights into the rate of repair for certain aircraft for varying levels of AFSC personnel.

2.3 Chapter Summary

The purpose of this chapter was to provide a summary of some of the previous research that has been done to study sortie generation. Various types of simulation methods were highlighted, including discrete-event simulation and agent-based modeling, to study the sortie generation process. The chapter then discussed two important aspects of sortie generation that are important to be included into simulations attempting to model it: part failures and maintenance. Subsequent chapters

will detail the research of this thesis.

III. Methodology

3.1 Overview

The purpose of this chapter is to discuss the simulation tool that was developed to provide predictions into operational aircraft availability and mission accomplishments, verification and validation of model adequacy, and the approach to demonstrate the capabilities of the simulation tool. There are two parts of the simulation tool: the graphical user interface and the simulation model. Both of these aspects of the tool are discussed in this chapter. Section 3.2 discusses the development of the simulation model and the key assumptions that were made to simplify the model. Section 3.3 discusses the methodology used to determine an appropriate input ranges used to validate the behavior of the model. Section 3.4 discusses how to use the tool's graphical user interface.

3.2 Model Development

The simulation tool that is developed is a discrete-time simulation called the Expected Number of In-Game Mission-Capable Aircraft (ENIGMA). A discrete time simulation process is used because the purpose of the tool is to compute the aircraft availability at the beginning of each day, and a discrete time simulation provides the proper framework to obtain that information. Additionally, a discrete time simulation approach allows the simulation tool to run in a stepwise fashion, which will allow decision-making to be incorporated into the simulation. The purpose of its development was to produce a tool that could be used to predict the operational aircraft availability of specific types of aircraft and mission accomplishments across different bases for adjudication in long-duration wargaming. The most recent version of this simulation tool was developed and coded in MATLAB 2019a. Similarly, the graphical

user interface was also developed and coded in MATLAB 2019a. This application is also compiled in MATLAB's application compiler and can be run as a standalone application when the appropriate version of MATLAB RunTime is installed on the device that is attempting to use this tool. The simulation model and the graphical user interface were developed separately. The simulation model was created first and verified to function as expected. The graphical user interface was created after the simulation model was created to allow users to run simulations without the burden of working directly with the MATLAB functions.

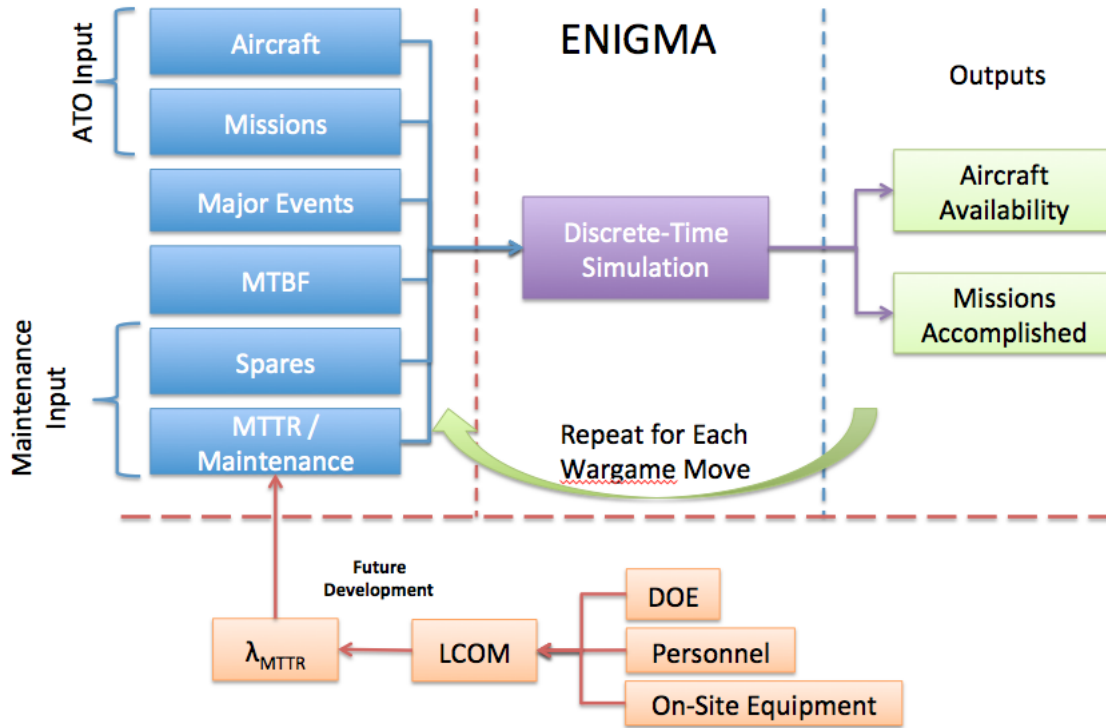


Figure 1: Overview of ENIGMA

A visual overview of ENIGMA is shown in Figure 1. ENIGMA uses inputs describing scheduled missions, any major events that may occur, failure rates, and repair rates to run a discrete time simulation to output the predicted daily aircraft availability and the daily quantity of missions accomplished throughout the duration of

the simulation. This simulation tool simplifies the modeling of aircraft availability by representing the aircraft availability as a queuing-like system with a varying failure rate and varying repair rate. In the current version of ENIGMA, the repair rate is a direct input. However, future versions of ENIGMA will include an option to determine a repair rate from models describing the relationship between the repair rate and the quantity of maintenance personnel. Although this feature has not been implemented in this phase of ENIGMA, the relationship between repair rates and maintenance personnel will be described by Air Force Specialty Codes (AFSC) and will be developed from outputs of experimental designs run on LCOM.

Capability	Current Capabilities of ENIGMA
Stepwise Option	✓
Speed of Simulation	Quick
Number of Aircrafts	Any
Number of Types of Aircrafts	Any
Number of Bases	Any
Number of Types of Failures	Any
Simultaneous Repairs	✓
Flexible Missions Input	✓
Spares	✓
Able to Fly to Different Bases	✓
Able to Conduct Major Events	✓
Attrition	✓

Table 1: Features Available in this Phase of ENIGMA

ENIGMA simulates the daily operational aircraft availability of specific types of aircraft at bases by tracking the status of individual aircraft throughout the simulation. ENIGMA does not have any predefined bases nor predefined aircraft already coded into the model; the user is able to define any type of aircraft and any base name that they wish to include in the model as long as the names satisfy the naming requirements of variables in MATLAB. This flexibility of ENIGMA allows the user to use arbitrary names for aircraft types, part failure types, and bases. User-controlled features that are included in this version of ENIGMA are shown in Table 1.

3.2.1 Simulation Process

The simulation requires a couple of sets of inputs from the user in order to run. These inputs are tables that contain the necessary information describing the scenario. This necessary information includes maintenance information, mission information, aircraft information, and major events information. The required information will be discussed in more depth later in this paper. Once all of the necessary information is uploaded into the simulation tool, the information is converted and stored as the appropriate data types. Once the necessary information is prepared, the simulation is run. The simulation is a discrete time simulation with a period length of one day and the beginning of each period represents the very beginning of each day. The time-step process of this simulation is shown in Figure 2.

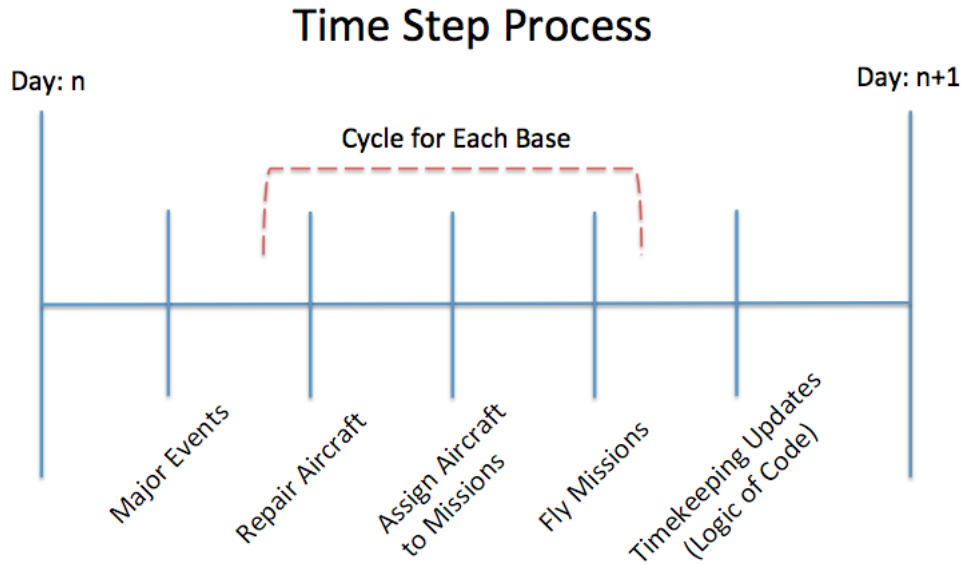


Figure 2: Time-Step

At the beginning of each time-step, all major events that have been scheduled to occur on this day will occur before any missions are flown and before any maintenance is performed. The following steps then occur at each base separately in the following order. First the base maintenance attempts to repair broken aircraft. Second, the

scheduled missions that may result in part failures and attrition are flown. Third, the maintenance system is updated to reflect the proper state of the maintenance system at each base.

Many of the nuances that allow the logic of the simulation to function properly are excluded from the description in this paper. The specific time that events occur during a period, or day, is assumed to be irrelevant for future periods. For example, if an object enters an arbitrary State 1 during period n , where a State is a set of values defining the characteristics of an object, it is treated as though it has been in State 1 for one full period during all of period $n+1$ regardless of when the object entered State 1 during period n . This assumption is important because the simulation is utilizing discrete-time steps.

3.2.2 Major Events

Major events are one of the features of ENIGMA that may be useful in examining many scenarios because they allow for changes to the system during the simulation that do not have to result from aircraft flying missions or from maintenance repairing aircraft. For example, it may be interesting to study the impact of a sudden loss of aircraft and maintenance personnel on sortie generation. There is a set number of predefined major events that can occur in the simulation because each major event must be coded into the simulation tool separately. Each major event available in the simulation tool is represented by an identification code, which is used to input the major event into the simulation. Table 44 in Appendix A shows the current major events and their required inputs that are available in the current version of ENIGMA.

Major events are implemented before any other process in the iteration cycle of the simulation. Thus, they occur immediately before each period's maintenance and mission operations of each base. This ordering is done in order to prevent issues with

aircraft traveling to different bases when returning from missions, because the order that bases execute their missions are not predetermined. Multiple major events may occur in a single period; however, the order that these events occur in a single period are also not predetermined, which means that the user should avoid assigning major events that require a specific order of execution in the same period since the major events may execute in an undesired order. If the order that the events occur is not of concern to the user, then having multiple major events in a single day will not result in any issue.

3.2.3 Maintenance

The maintenance process is included in the simulation because it allows damaged aircraft to be repaired and return to mission capable status. An overview of the simulated maintenance process at each base is shown in Figure 3. When an aircraft is damaged, the first step is to determine the type of part failure the aircraft had. If there is a spare part available that is required to make the repair of the type of failure, then the aircraft awaits repair; otherwise, the aircraft must first wait until the necessary part becomes available before it is ready to be repaired. Once an aircraft is repaired, it returns to mission capable status and can fly missions.

Part Failures

Each simulated base is assumed to have a maintenance system that can be used to repair damaged aircraft. The process of each of the maintenance systems at each of the bases are assumed to be the same. Although there are many reasons why an aircraft can be in maintenance, this model assumes that an aircraft is in maintenance only as a result of a part failure. ENIGMA does not predetermine any type of part failures for any aircraft type; thus, the types of failures that can occur are determined entirely by the user. The user must define the types of failures for each type of aircraft

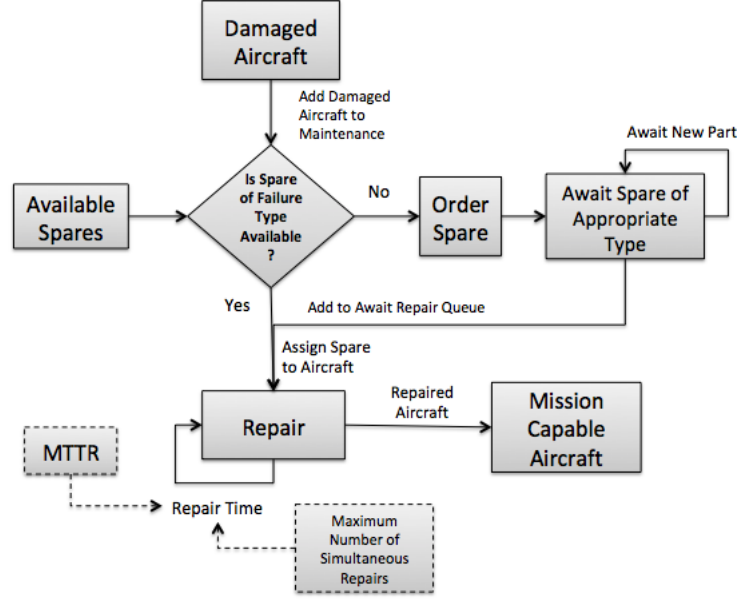


Figure 3: Overview of Maintenance Process

that will be in the simulation. For each of these types of failures, the user must also define additional information that determines how often failures occur and what the proportion of failure types of each type of aircraft is at each base. The proportion of each type of failure for a specific type of aircraft at a specific base are determined by user-specified weights.

Specifying failure rates by base accounts for varying operating conditions at each base. This provides the user needed flexibility to adjust failure rates of aircraft parts to their expected value at each of the bases. For simplicity of the model, an aircraft is assumed to only have a maximum of a single part failure at any given time. Additionally, all aircraft fail according to an exponential distribution with a mean of the user assigned Mean-Time Between Failure (MTBF) for that type of aircraft.

Once an aircraft returns from its mission, attrition is adjudicated based on the probability of loss specified by that mission. If the aircraft is no longer usable due to attrition, then the aircraft is assigned to a base labeled "N/A" indicating that the air-

craft is no longer usable for the remainder of the simulation. If the aircraft is not lost due to attrition, then the aircraft will have a part failure according to an exponential distribution with a mean defined by the MTBF assigned to that aircraft type. Since aircraft are able to return to different bases after completing a mission, ENIGMA uses the MTBF of the aircraft type assigned to the base that the aircraft flies from to determine failures. In contrast, the base that the aircraft returns to determines the type of failure that occurs because the aircraft will be added to the maintenance system of the return base if a failure occurs. Since all failures are assumed to be time-dependent and assumed to fail according to an exponential distribution in this model, failures can be determined entirely by the duration of the mission that was flown by taking advantage of the exponential distribution's memoryless property. If an aircraft has flown a mission of duration t and fails with a MTBF of μ , then the probability that an aircraft has a part failure is shown in Equation (2).

$$P_{PartFailure}(t) = 1 - e^{-\frac{t}{\mu}} \quad (2)$$

Whenever a part failure occurs in an aircraft, it is sent to maintenance upon return from its mission. An aircraft can also be sent to maintenance as a result of a major event, depending on the type of major event that occurs. If an aircraft is determined to have a part failure, the type of failure is determined by the weights corresponding to each type of failure defined by the user. The weights of each type of failure for an aircraft type can vary across bases, which may be beneficial if different types of failures are more prominent in different operating environments.

Repair Capability

The repair capabilities of a base are determined by many factors including the availability of spare parts and the availability of qualified maintenance personnel. The rate that aircraft are repaired is dependent on the Mean Time to Repair (MTTR),

which is unique for each type of aircraft at each base. There are two ways that the MTTR values can be determined in upcoming versions of ENIGMA: the first case is for the user to assign an MTTR directly, the second case is to have the MTTR be a function of the quantity of different Air Force specialty codes present at the base. Currently the method of determining the MTTR through a function of AFSC values remains under development and is expected to be implemented in future versions of ENIGMA. The version of ENIGMA discussed in this paper utilize user-specified MTTR.

Spares

Spares are also an important aspect of the maintenance system. At the beginning of the simulation, all spares assigned to each base are assumed to be available and ready for use to repair an aircraft. Each base will have a unique set of spares that is determined by the user. Additionally, each type of part will require the user to define the number of days it takes to replace a spare of that specific part type. Each type of failure is assumed to require a spare; however, ENIGMA is programmed so that failures that do not require spares are still able to be modeled by setting the number of days to replace a spare to zero.

When an aircraft has a part failure and is sent to maintenance, the type of failure is identified, and if a spare is available, the aircraft is assigned the spare for repair. Then the spare will be replaced in the number of days specified for another spare to become available again. If there are no spares available when an aircraft arrives, a spare of that part type will arrive in the number of days specified to replace that part. Until a spare becomes available, the aircraft will not be able to be repaired. When aircraft are added to maintenance, they are assigned spare parts in the order that they arrive if the spares are available. If spares are not yet available when aircraft arrive, the new arrivals will be given to the aircraft in the order that the aircraft

arrived. This First-In First-Out approach is used to make sure that the aircraft that enter maintenance first have priority in receiving spares.

Each type of aircraft at each base is assumed to have independent maintenance system and resources, meaning the repair of one type of aircraft does not impact the repair capability or process of another type of aircraft because each type of aircraft requires different types of parts and maintenance personnel specializations. This model assumes that parts from one type of aircraft cannot be used as substitutes for missing parts in another type of aircraft. Aircraft are repaired in the order that they are assigned a spare part. This First-In First-Out approach is used based on the assumption that aircraft that have been waiting to be repaired and able to be repaired the longest receive priority in maintenance.

Since the timing of missions and maintenance between time-steps are not modeled, aircraft that are repaired in a given period will not be able to fly a mission until the next period. Aircraft are repaired sequentially, such that the cumulative time to repair each aircraft in a given period does not exceed 24 hours. The amount of time that it takes maintenance to repair an aircraft is assumed to follow an exponential distribution due to its memoryless property. The rate of repair for a given aircraft is a function of its MTTR and the number of simultaneous repairs that can occur for this aircraft type. The maximum number of aircraft that can be simultaneously repaired is defined as the minimum between the number of broken aircraft and the maximum number of repairs that maintenance can simultaneously handle, as shown in Equation (3).

$$N = \min(B, M) \tag{3}$$

Where:

N = Number of simultaneous repairs

B = Number of broken aircraft that are ready to be repaired

M = Maximum number of simultaneous repairs that maintenance can handle

This methodology is used to make sure that the rate of repairing aircraft reflects both the number of aircraft that are ready to be repaired and the maintenance capability of simultaneous repairs. Currently, repair rates are not dependent on the type of failure that has occurred. When aircraft are repaired simultaneously, the assumption is made that the time to repair them are independent of one another and have identical MTTR values. Since the repairs are occurring in parallel when there are simultaneous repairs, the time to complete the repairs of a single aircraft is defined as the minimum time of the set of times required to repair an individual aircraft. Let $X_i \sim EXP(\lambda)$, where X_i are independent and identically distributed random variables representing the time it takes to repair individual aircraft, where λ represents the rate of repair. Let Z_1 represent the time that it takes to repair the first aircraft that is repaired of the group of damaged aircraft being repaired in parallel. Then the time it takes to repair an aircraft when there are N simultaneous repairs is shown in Equation (4), where λ is the inverse of the MTTR as shown in Equation (5).

$$Z_1 = \min\{X_1, X_2, \dots, X_N\} \sim EXP(N\lambda) \quad (4)$$

$$\lambda = \frac{1}{MTTR} \quad (5)$$

Thus, the amount of time required to repair an aircraft follows an exponential distribution with a rate as a function of the number of aircraft that can be simultaneously repaired, the number of aircraft awaiting and able to be repaired, and the

MTTR of the aircraft type, as shown in Equation (6). The process of repairing aircraft is programmed sequentially in order to update the rate of repair as the number of broken aircraft changes due to the repair cycle.

$$Z_1 \sim EXP\left(\frac{\min\{B, M\}}{MTTR}\right) \quad (6)$$

3.2.4 Flying Missions

Missions are a critical part of the simulation process because they are the primary source of aircraft failures in this simulation. Missions are flown according to the process shown in Figure 4. The first step of flying sorties is to assign missions to aircraft. Missions are assigned to aircraft according to daily cumulative flying hours. Missions are assigned to the aircraft with the least amount of cumulative flying hours of the period that the missions occur. Once an aircraft is assigned a mission, it flies the mission for the specified duration of time unique to that mission. An assumption is that once an aircraft takes off for its mission, it successfully completes it. Once the aircraft returns to base, probabilities of attrition and part failure are adjudicated as previously discussed. A single aircraft can fly multiple missions in a single day, as long as the aircraft returns to the same base from which it took off. If an aircraft returns to a different base from where it started its mission, then the aircraft will not be able to fly any more missions until the next day.

If an aircraft flies a mission that results in an aircraft flying longer than 24 hours in a single period, then the aircraft will not return to the base until the duration of the missions is completed. Thus, the method of choosing aircraft for missions is an important assumption. Currently, aircraft with the fewest cumulative fly hours that day are chosen first for missions in order to reduce the likelihood that the same aircraft flies all of the missions in a single period.

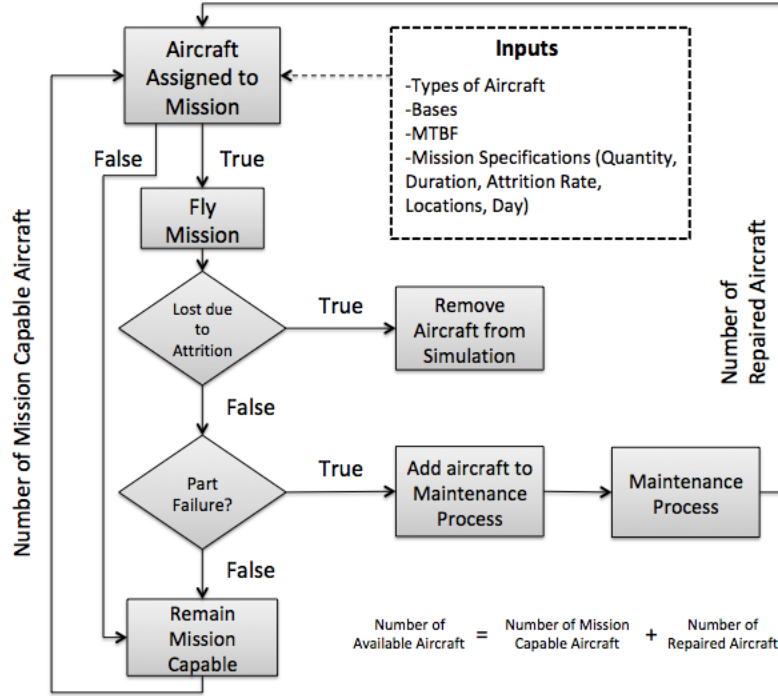


Figure 4: Flying Missions Process

The user must define all of the missions that will occur in the simulation by via a missions table. The required information includes the base that the mission flies from, the type of aircraft required for the mission, the duration of the mission, the quantity of aircraft needed for the mission, and the base that the aircraft will return to once the sortie is completed.

The way that the user inputs the quantity of aircraft required for a mission will impact how the missions are assigned in the simulation. There are two ways that the quantity of aircraft required for a mission can be inputted: as a single number defining the number of aircraft required for this mission or as separate missions each requiring a single aircraft. In either case, each mission is separated into single-aircraft missions. For example, if a mission requires four aircraft, then the simulation will automatically treat this as four separate single-aircraft missions. The difference in how the quantity of missions are inputted will affect how the missions are assigned. In the first method,

where the quantity of aircraft required is inputted as a number greater than one, an aircraft assigned to the mission can only fly it once. For example, if a mission requires five aircraft and there are only three aircraft available, then the simulation will state that three of the mission were flown and two were not flown. In contrast, the second input option, where missions are inputted as separate single-aircraft missions, allows an aircraft to fly multiple of that type of mission. For example, if there are five missions and there are only three available aircraft, three missions will be assigned to the aircraft and then the remaining two missions will be assigned to the returning aircraft, if the returning aircraft remain mission capable. Thus, all five missions can be flown despite not having five mission capable aircraft when the second input option is used.

These options can be extended into creating very flexible missions tables. For example, if a user wants to fly five sorties in one period, they can implement this in many ways: one mission requiring a certain number of aircraft, multiple missions requiring fewer than the number of aircraft but that sum to the number of desired missions, or many single-aircraft missions that sum to the total number of desired missions. Although these options gives the user flexibility in scheduling the missions of the simulation, it requires the user to properly understand the output based on the method they chose to input the missions since the meaning will be slightly different. The simulation tool includes an option to separate missions into single aircraft missions automatically to allow the user to quickly separate missions, if desired.

3.3 Determining the Lower Bound of MTBF for Testing Scenarios

It may be beneficial to approximate the average aircraft availability based on the inputs that are used for the simulation. This is especially true when validating the behavior of the simulation because it may not be useful to validate the behavior of

the simulation with inputs that drive the average aircraft availability to zero. The modeling of the aircraft availability in this simulation can be thought of as a queuing system with aircraft failures arriving at a specific arrival rate and aircraft being fixed at a specific repair rate. Little's Law states that the utilization of a server in a queuing system, which is the average proportion of time that a server is busy in a queuing system, is equal to the ratio of the arrival rate and the service rate of the system when the inter-arrival times and service times both follow exponential distributions, as shown in Equation (7)[18].

$$\rho = \frac{\dot{\lambda}}{\dot{\mu}} \quad (7)$$

Where:

$$\begin{aligned} \rho &= \text{Utilization of a server} \\ \dot{\lambda} &= \text{Arrival rate} \\ \dot{\mu} &= \text{Service rate} \end{aligned}$$

In order to maintain stability in a single server queuing system, meaning that the queue length does not become infinitely long, the utilization of the server must be $\rho < 1$, resulting in the following stability condition shown in Equation (8)[18].

$$\frac{\dot{\lambda}}{\dot{\mu}} < 1 \quad (8)$$

Equation (8) shows that in order for a single server queuing system to remain stable, the arrival rate must always be less than the service rate. Unfortunately, this stability condition cannot be directly used to determine whether or not the average aircraft availability of the simulated system will be stable because the maximum number of aircraft that can fail in a given period is based on both the number of missions and the aircraft availability of that period, which means that the arrival rate is not constant throughout the simulation.

In order to potentially obtain some insight into the stability of the aircraft availability in the system, some assumptions must be made about the simulation. The first assumption is that multiple sorties for a single aircraft in a single period does not occur, meaning an aircraft can only fly a single sortie each period. The second assumption is that spare parts are not required to repair aircraft. The third assumption is that only one aircraft can be repaired at a time. Let F be a random number representing the number of failures that occur in a given period and R be a random number representing the number of repairs that occur in a given period. In order to potentially maintain a stable average aircraft availability, the expected value of the number of failures in a period should not exceed the expected number of repairs in a period, as shown in Equation (9).

$$\frac{E(F)}{E(R)} < 1 \quad (9)$$

Where:

$$\begin{aligned} F &= \text{Number of failures that occur in a period} \\ R &= \text{Number of repairs that occur in a period} \end{aligned}$$

This equation will be used to develop an inequality to determine the appropriate input range for validating the behavior of the model such that the average aircraft availability is not driven towards zero. In order to do this, it is assumed that all the inputs are known except for a single input; in this case, the MTBF will be chosen as the unknown variable. Missions for each day are assumed to be stationary, meaning each period has the same mission requirements. The worst-case input combination of the possible input ranges for the testing scenarios will be used when using this inequality. The worst-case scenario is defined to be the model states such that the average number of mission-capable aircraft should not decrease below a set threshold with the minimum maintenance capabilities and the maximum aircraft usage.

Determining $E(F)$

The first task that needs to be done to develop this inequality is to determine the expected value of the number of failures that occur in a given period. Let $\hat{N}$, which is shown in Equation (10), represent the number of mission capable aircraft that fly sorties in a given period, let D represent the duration of each of those sorties, and let μ represent the MTBF. Note that in the simulation each aircraft is independent of all other aircraft and the probability that an aircraft has a part failure is independent of all other aircraft. Since aircraft failures occur according to an exponential distribution of rate $\frac{1}{\mu}$, which will be represented by $\hat{\mu}$, the probability that an aircraft has a part failure given that it flew for a specified duration, D , is shown in Equation (11).

$$\hat{N} = \min(\text{Number Of Available Aircraft}, \text{Number Of Daily Missions}) \quad (10)$$

$$p = P(\text{Failure Occurs} | D = \text{Duration}) = 1 - e^{-D\hat{\mu}} \quad (11)$$

Since each aircraft fails independently, the number of failures that occur in a given period follows a binomial distribution as shown in Equation (12) and the expected value of the number of failures that occurs is shown in Equation (13).

$$F \sim \text{BIN}(\hat{N}, p) \quad (12)$$

$$E(F) = \hat{N}p = \min(A, M)(1 - e^{-D\hat{\mu}}) \quad (13)$$

Where:

A = Number of mission capable aircraft
 M = Number of daily missions

Determining $E(R)$

The number of aircraft that are repaired is dependent on many factors including the number of aircraft that need to be repaired, the MTTR of an individual aircraft,

the number of aircraft that can be simultaneously repaired, and the duration of time that repairs can occur in the period. In order to determine the number of aircraft that need repairs, the total number of aircraft must be known; let T represent the total number of aircraft. Since the time it takes to repair a single aircraft follows an exponential distribution of rate λ , the number of aircraft repaired in a given period follows an Poisson distribution. Let $R(\dot{t})$ represent the number of repairs within time t and S_k represent the time it takes for the k^{th} event to occur. Let $\{R(\dot{t}), \dot{t} \geq 0\}$ be a $POI(24\lambda)$, then the probability that the number of repairs in a specified time, $\dot{t}$, is equal to k is shown in equation Equation (14).

$$Prob(R(\dot{t}) = k) = (e^{-\lambda\dot{t}}) \frac{((\lambda)\dot{t})^k}{k!} \quad (14)$$

However, since the maximum number of repairs that can occur in a single period is defined by the number of aircraft that need repairs, $T - A$, the probability of obtaining a certain number of repairs must be adjusted according to Equation (15) and Equation (16).

$$Prob(R(\dot{t}) = k) = (e^{-\lambda\dot{t}}) \frac{((\lambda)\dot{t})^k}{k!} \quad \forall k = 1, 2, \dots, (T - A - 1) \quad (15)$$

$$Prob(R(\dot{t}) = (T - A)) = Prob(S_{(T-A)} \leq \dot{t}) = 1 - \sum_{k=0}^{T-A-1} (e^{-\lambda\dot{t}}) \frac{((\lambda)\dot{t})^k}{k!} \quad (16)$$

The expected value of a random variable, X , where the random variable has a finite number of values with probability $\hat{p}$ for each value is defined in Equation (17).

$$E(X) = \sum_{i=1}^j x_i \hat{p}_i \quad (17)$$

From Equation (17), the expected value for the number of repairs can be determined and is expressed in Equation (18).

$$E(R(\dot{t})) = \sum_{k=0}^{T-A-1} [(k)Prob(R(\dot{t}) = k)] + (T - A)Prob(S_{(T-A)} \leq \dot{t}) \quad (18)$$

Substituting Equation (13) and Equation (18) into Equation (8), the lower boundary of the MTBF can be solved for a particular set of inputs and is shown in Equations 19 to 23. For simplicity, the expression of $E(R)$ from Equation (18) will not be substituted into the equation.

$$\frac{\min(A, M)(1 - e^{-D\hat{\mu}})}{E(R)} < 1 \quad (19)$$

$$1 - e^{-D\hat{\mu}} < \frac{E(R)}{\min(A, M)} \quad (20)$$

$$1 - \frac{E(R)}{\min(A, M)} < e^{-D\hat{\mu}} \quad (21)$$

$$\ln \left(1 - \frac{E(R)}{\min(A, M)} \right) < -D\hat{\mu} \quad (22)$$

$$MTBF > \frac{-D}{\ln \left(1 - \frac{E(R)}{\min(A, M)} \right)} \quad (23)$$

Equation (23) is true such that $\min(A, M) > 0$, $T - A > 0$, and $\min(A, M) > E(R)$. If the condition $\min(A, M) > E(R)$ is not satisfied, then there is no MTBF that will be able to maintain the desired level of average aircraft availability. This inequality is used to determine the lower range value for the MTBF input when developing the experiment for validating the behavior of the simulation. Further functionality of this inequality is shown in the *Results and Analysis* section.

3.4 ENIGMA Application Description and User Guide

The purpose of this section is to provide a description and a user guide for the standalone ENIGMA application. This application was created using MATLAB's application compiler.

3.4.1 Overview

The layout of the ENIGMA application is designed to be organized and easy to follow. There are three tabs that present three different dashboards to the user: the Input Settings tab, the Dashboard Plot tab, and the Dashboard Data tab. The Input Settings tab is separated into three clearly labeled panels that are used to prepare and run a simulation. The Dashboard Plot and the Dashboard Data tabs are both used to present the output data in the form of plots and data tables respectively. Some of the features of ENIGMA are not yet enabled to the user because they remain under development.

3.4.2 Preparing the Simulation

The first step to running a simulation in ENIGMA is to properly prepare the input data. There are certain requirements and proper labeling that must be used in order for ENIGMA to properly prepare the data for the simulation. These data requirements will be discussed further in this section.

3.4.2.1 Loading Files

There are five separate data tables that must be prepared to run a simulation in ENIGMA: a missions table, an aircraft table, a major events table, and two maintenance tables. These tables can either be prepared by uploading files or by using the application to create tables. This section will discuss how to upload files. For developing tables in the application, see page 35 for subsection *Viewing/Editing Input Data*.

Uploading Files Process

ENIGMA is able to upload delimited files and spreadsheet files with file extensions `/*.txt`, `/*.dat`, `/*.csv`] and `/*.xls`, `/*.xlsb`, `/*.xslm`, `/*.xlsx`, `/*.xltm`, `/*.xlt`, `/*.ods`] respectively.

To upload a file, select the *Load Files* dropdown menu on the top left of the application as shown in Figure 5. Next, select the type of file that needs to be uploaded, as shown in Figure 6, and select the file of choice to upload as shown in Figure 7. When a file is successfully uploaded, a check mark will appear next to the selected file. Please note that when a file is uploaded into ENIGMA, two data tables are created: one is to maintain the original input data and the second is to be used as the table to generate the input data for the simulation.

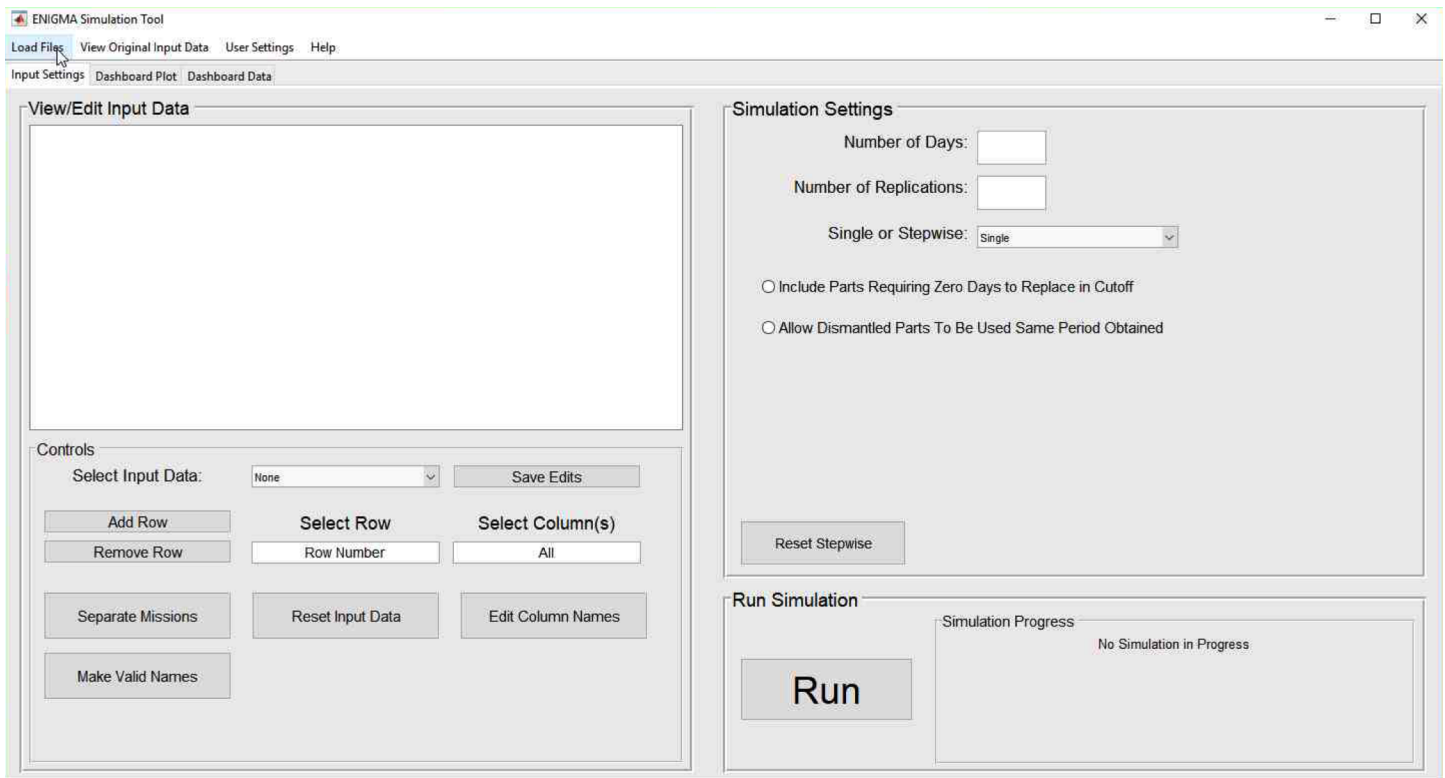


Figure 5: Open the Load Files Dropdown Menu

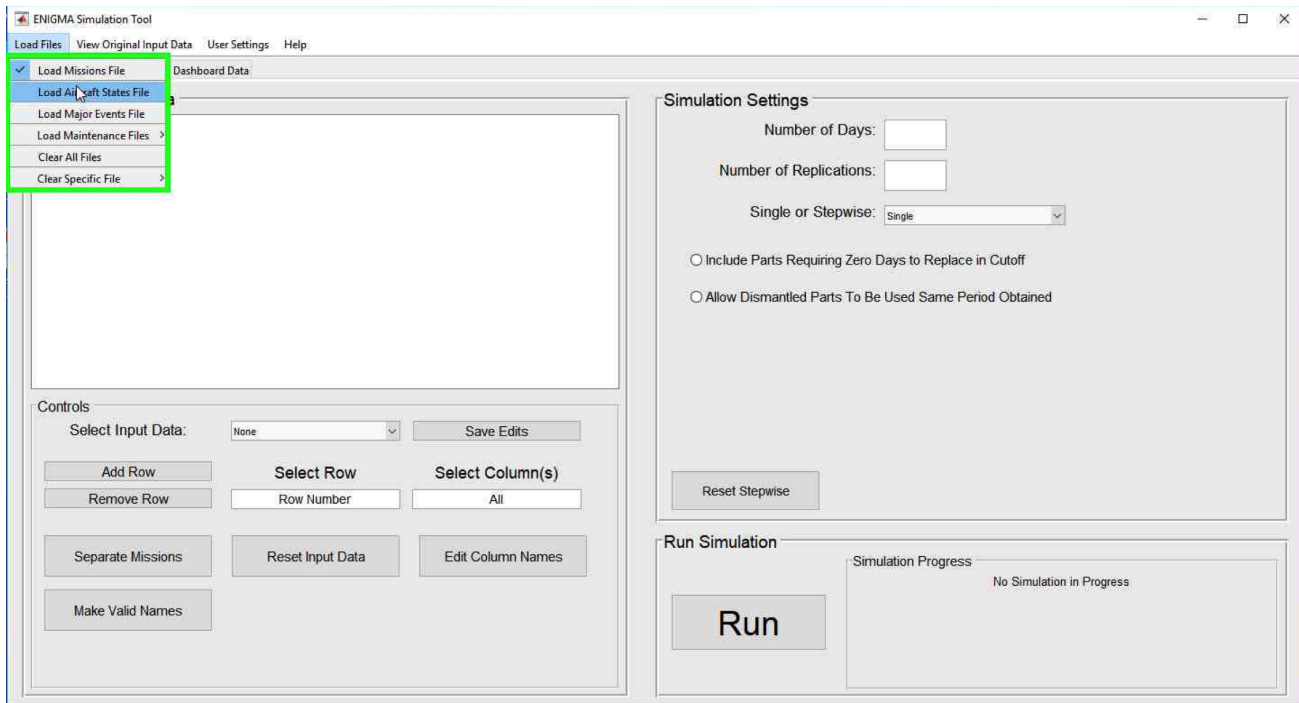


Figure 6: Choose Which Type of File to Upload

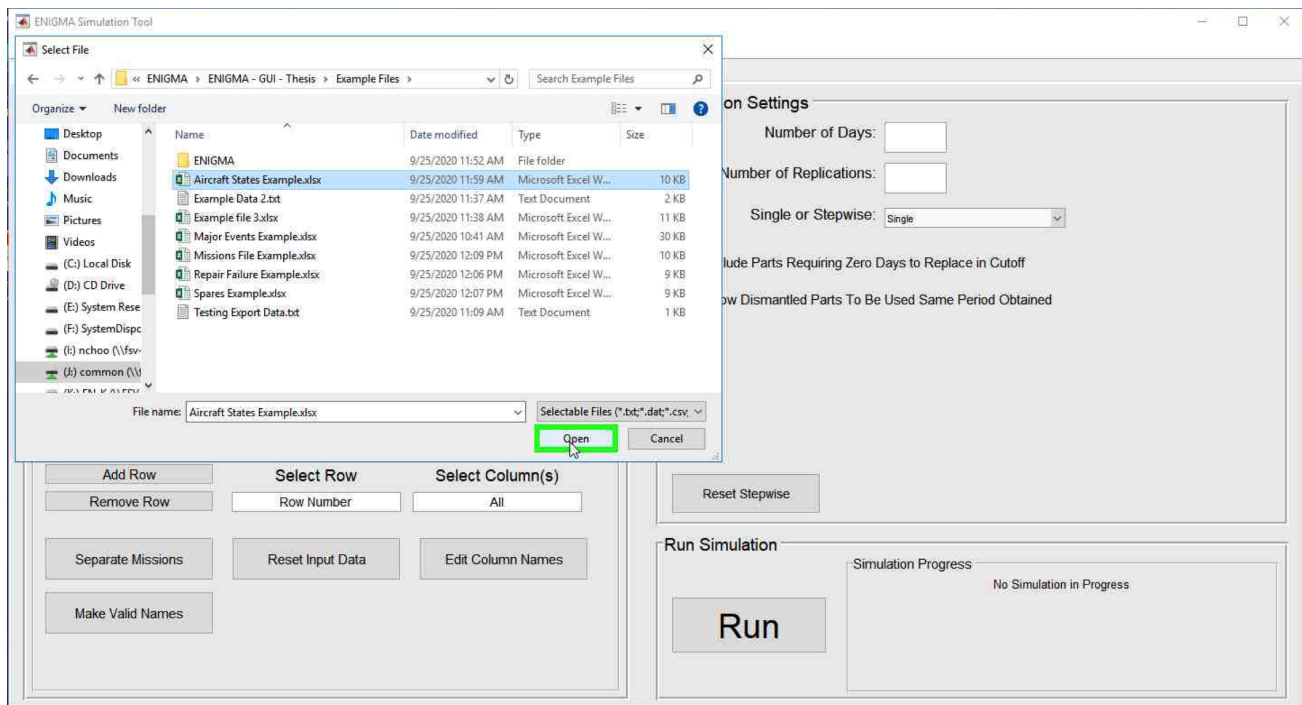


Figure 7: Upload Selected File

Clearing Uploaded Files

Uploaded files can also be erased from the application. All of the uploaded files can be cleared simultaneously using the *Clear All Files* button or a specific file can be erased by clearing a specific file, as shown in Figure 8 and Figure 9, respectively. Please note that the original file will be cleared, but the table that is used for generating the input data for the simulation will not be erased. The table that is used to generate the input data for the simulation can be cleared by uploading another file or by pressing the *Reset Input Data* button after the original input file is cleared, as explained in subsection *Viewing/Editing Input Data* on page 35.

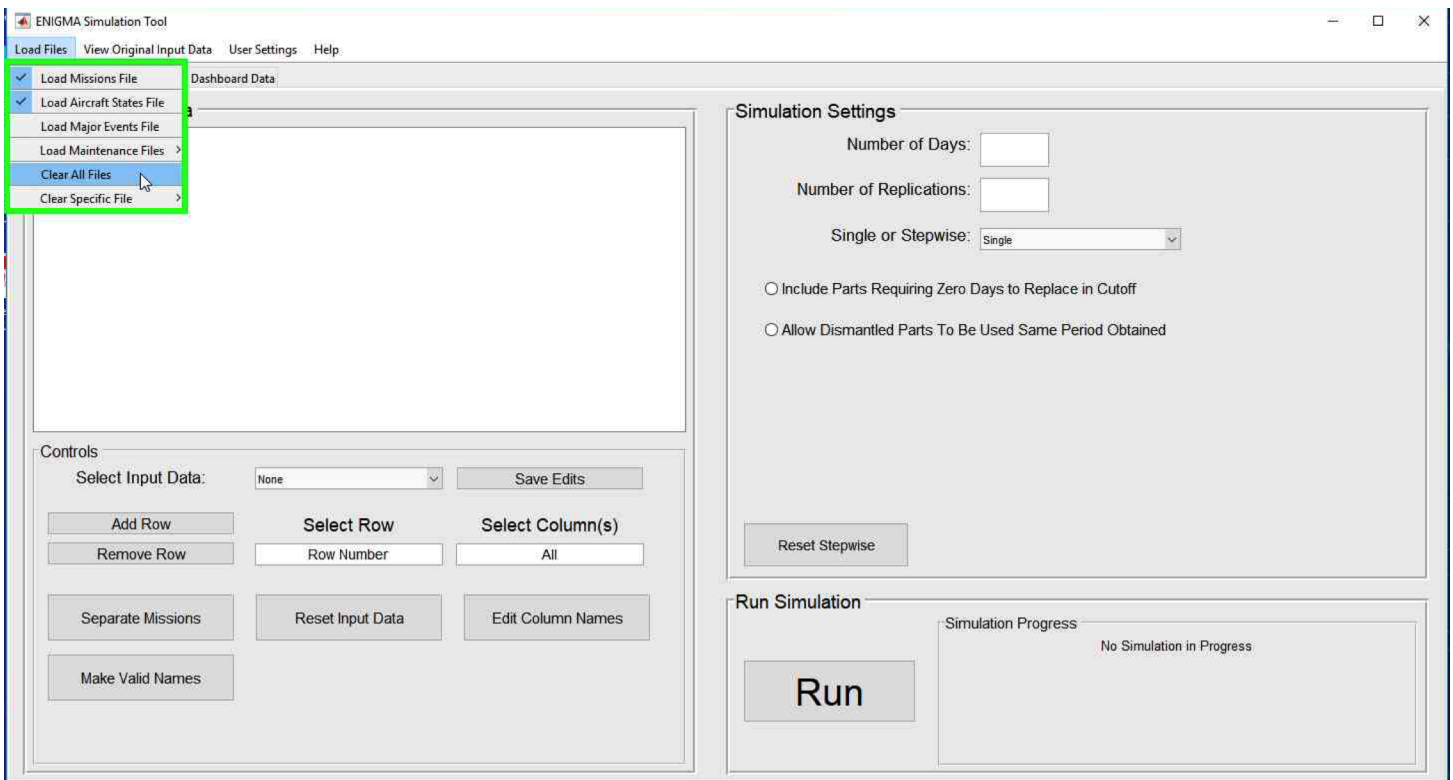


Figure 8: Clear All Uploaded Files

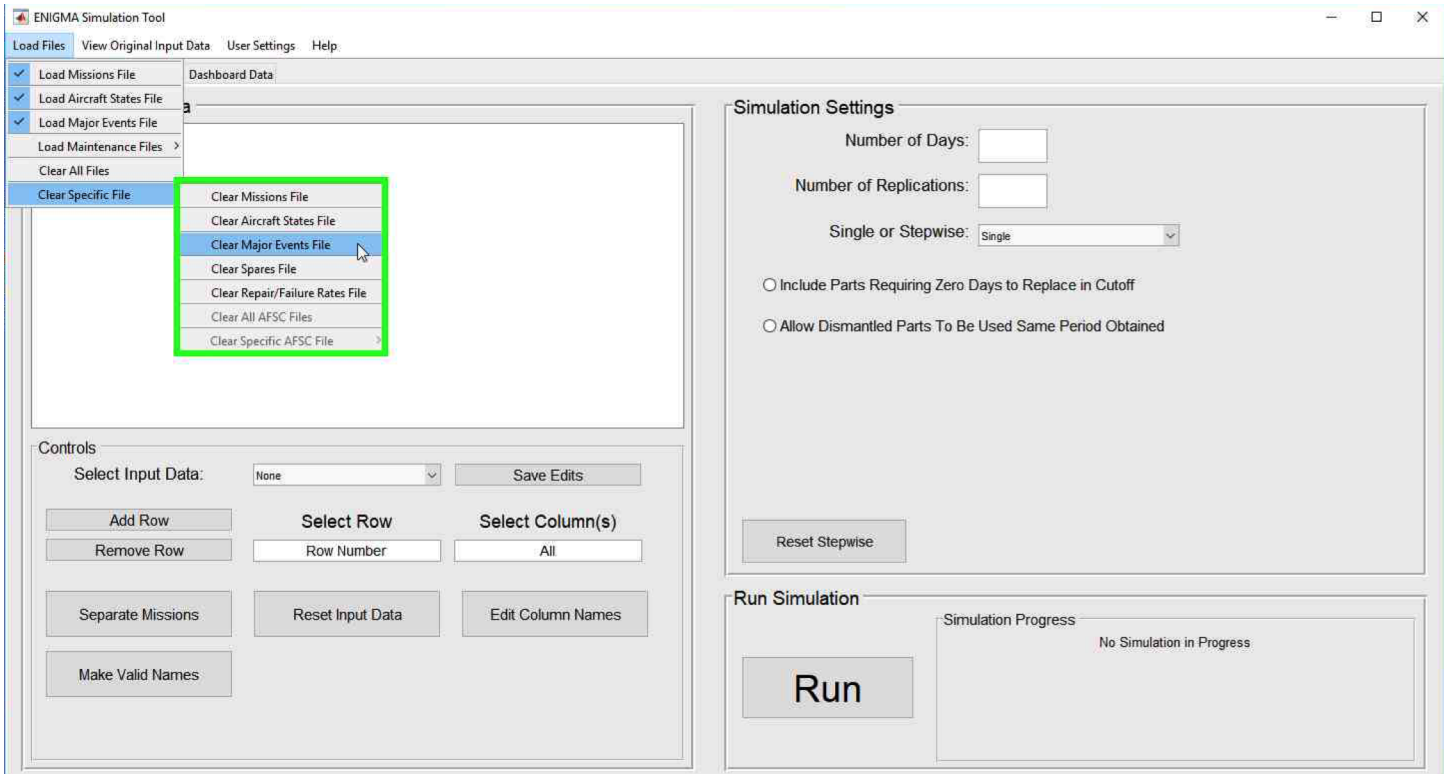


Figure 9: Clear Specific File

3.4.3 Viewing Original Input Data

Pressing the *View Original Input Data* button in the top left corner of the application and by selecting the specified file, as shown in Figure 10, displays the uploaded file. The uploaded data will appear in a new window as shown in Figure 11. If there is no file uploaded, the window will be blank. To exit the window, simply close the window using the close button on the top right corner of the window.

3.4.4 Viewing/Editing Input Data

ENIGMA allows the user to easily edit the data tables that will be used to prepare the input data for the simulation. The *View/Edit Input Data* panel in the *Input Settings* tab of the application allows the user to edit the data tables. Editing a table only edits the table that will be used to create the data for the simulation and will

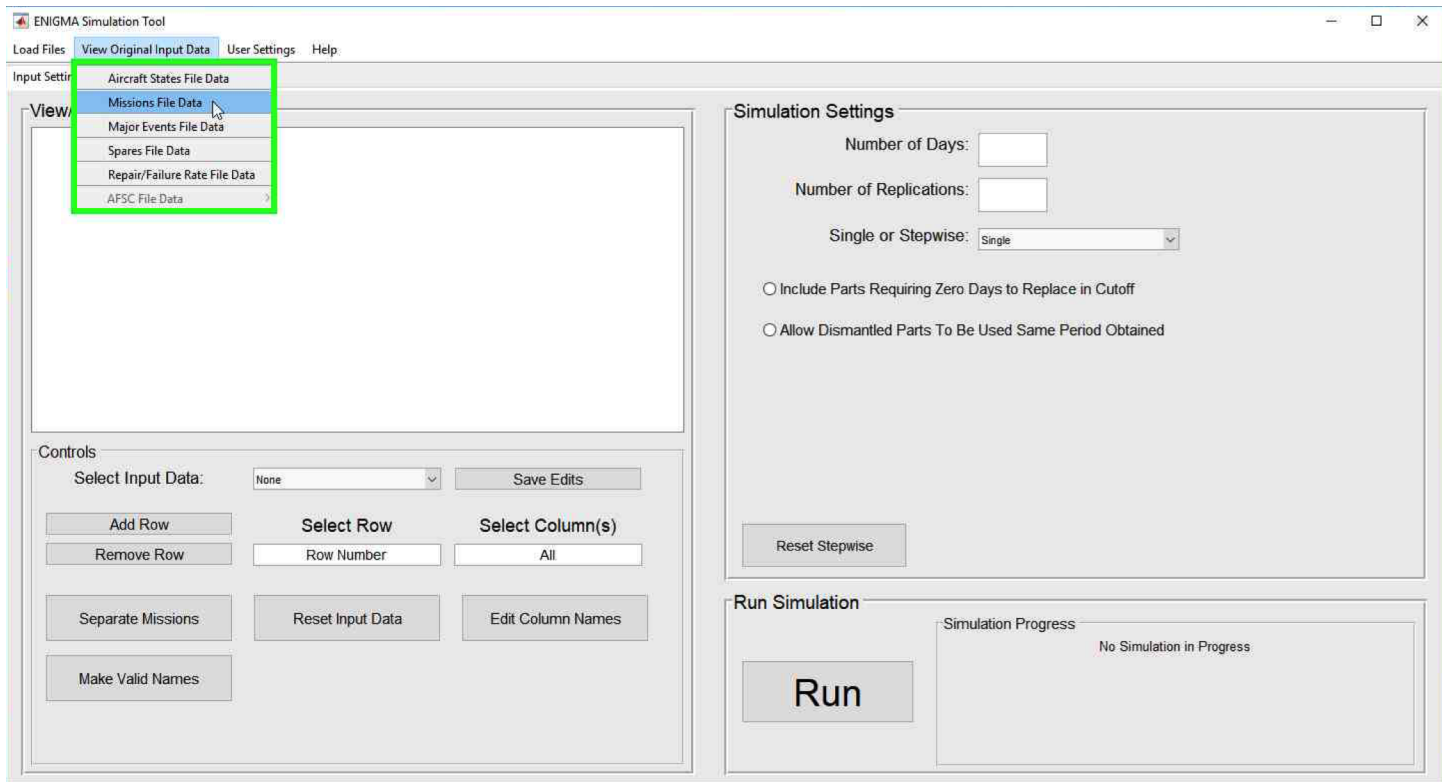


Figure 10: Select the Uploaded File to View

	1	2	3	4	5	6	7
1	DAY	BASE	ReturnBase	MDS	QTY	DURATION	AttritionRate
2		1 A	A	F15		5	3 1.0000e-03
3		2 A	A	F15		5	3 0.0020
4		3 A	A	F15		5	3 1.0000e-04
5		4 A	A	F15		5	3 1.0000e-04
6		5 A	A	F15		5	3 1.0000e-04
7		6 A	A	F15		5	3 1.0000e-04
8		7 A	A	F15		5	3 1.0000e-04
9		8 A	A	F15		5	3 1.0000e-04
10		13 A	A	F15		5	3 1.0000e-04
11		14 A	A	F15		5	3 1.0000e-04
12		15 A	A	F15		5	3 1.0000e-04
13		16 A	A	F15		5	3 1.0000e-04
14		17 A	A	F15		3	3 1.0000e-04
15		1 B	B	F16		8	3 1.0000e-03
16		2 B	B	F16		8	3 0.0020
17		3 B	B	F16		8	3 1.0000e-04
18		4 B	B	F16		8	3 1.0000e-04

Figure 11: Example of Viewing Uploaded File

not affect any uploaded files. This panel can also create new data tables if the user does not have any files to upload, which will be described later in this section.

To begin editing a data table, select the type of data table using the *Select Input Data* drop down menu as shown in Figure 12. Once the type of data is selected, any data that is already assigned to this table will appear as an editable table. Click on the cells of the table and edit the information as shown in Figure 13. Click the *Save Edits* button, as shown in Figure 14, to save any edits made to the table.

If the window remains blank when the input data is selected, then there is no data currently assigned to this data table. Rows can be added and removed by clicking on the *Add Row* and *Remove Row* buttons respectively.

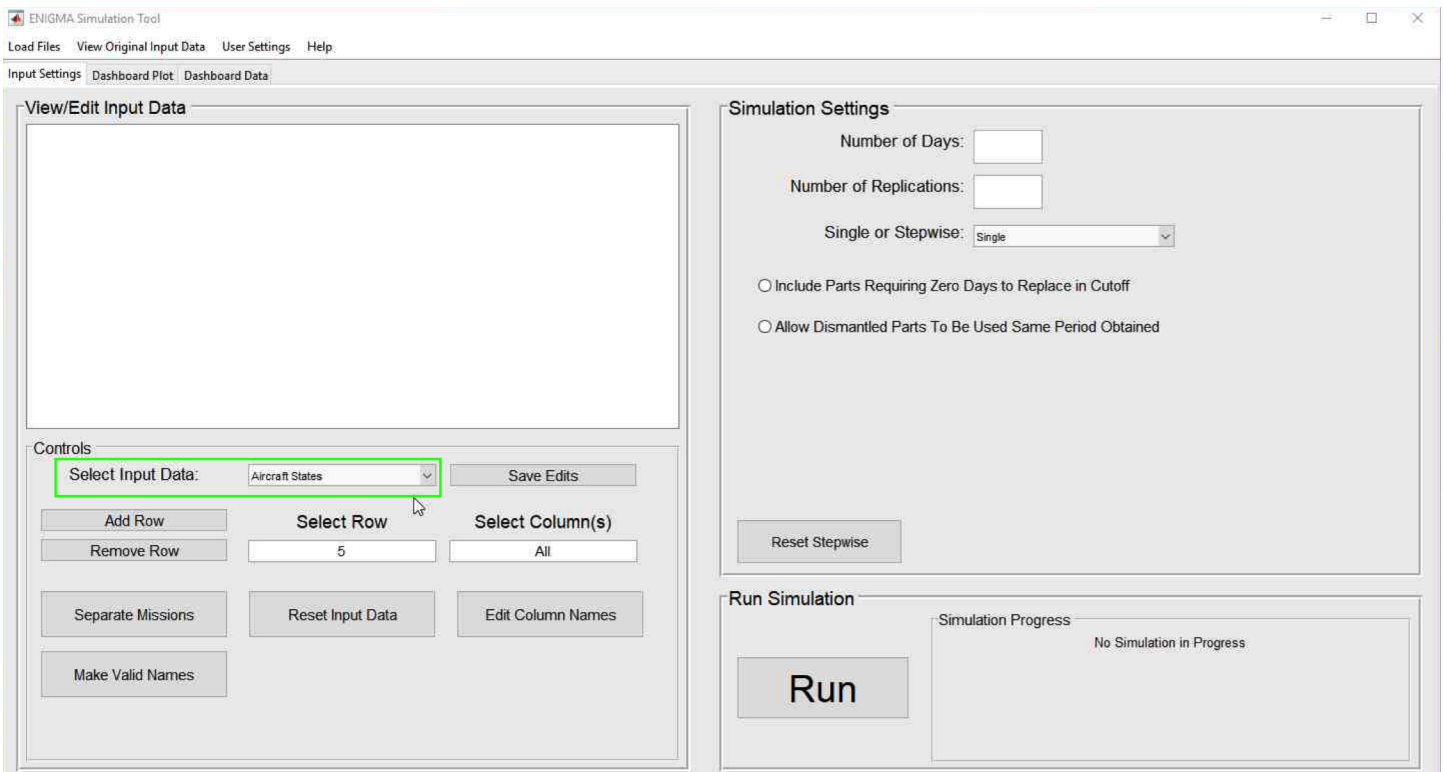


Figure 12: Select Input Data for Edit Table

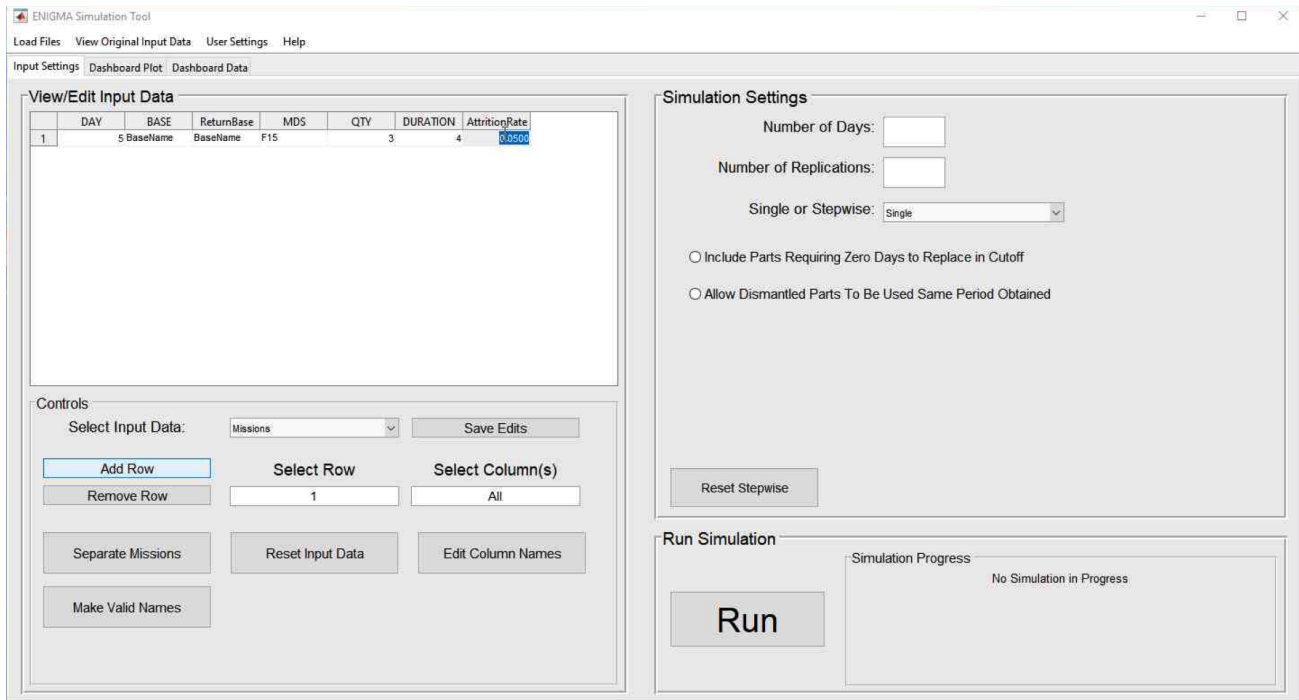


Figure 13: Edit Directly Into the Data Table

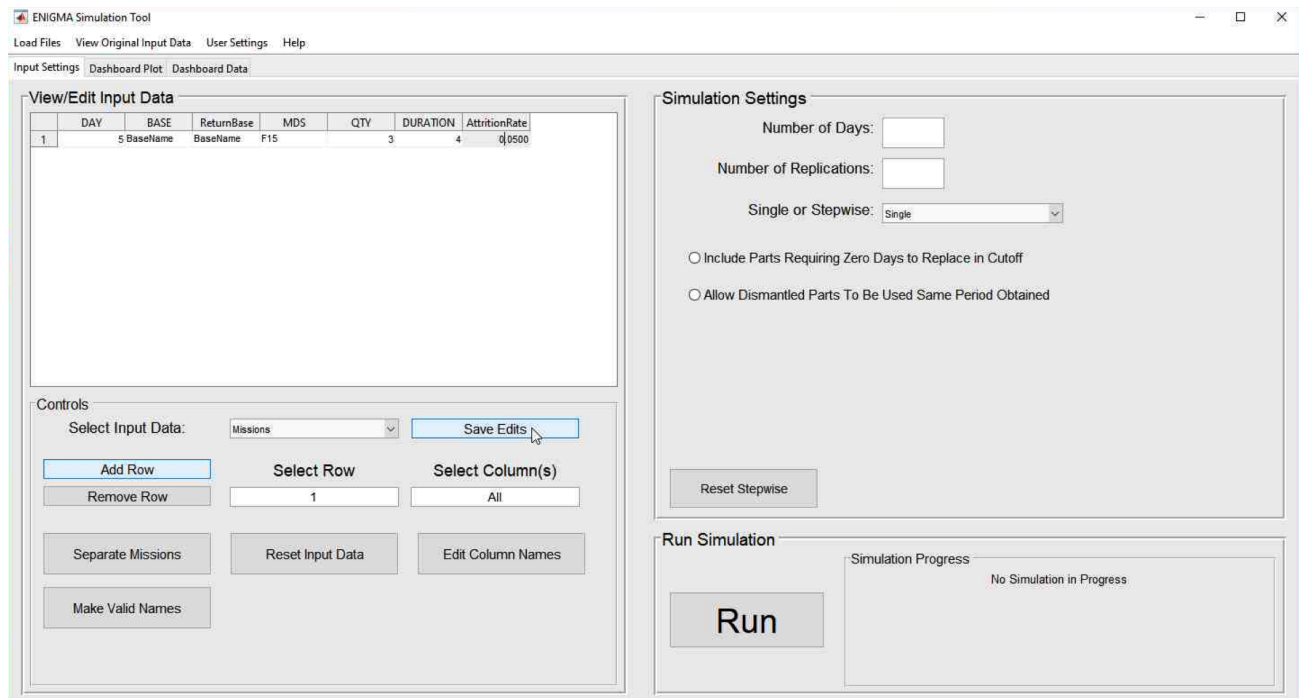


Figure 14: Save Edits

Removing/Adding Rows

Rows can be removed from the data table one at a time by inputting the row number in the text box under *Select Row* and then clicking the *Remove Row* button. If the specified row is in the table, it will then be removed. To add a row to the data table, simply click on the *Add Row* button as shown in Figure 15. A row can be added to any table including a blank table, a table with only column names, and a table already contains data. Each case will cause the the *Add Row* button to function differently. If the data table selected is blank, then the *Add Row* button will automatically generate appropriate column names and add a row with the appropriate data types corresponding to the column names as shown in Figure 16. If the data table already has headers, but it does not have any rows, then a window will appear prompting the user to input the appropriate data types as shown in Figure 17. If the data table already is already filled with data, then the *Add Row* button will add a blank row to the bottom of the table with the data types corresponding to the first row of data in the table.

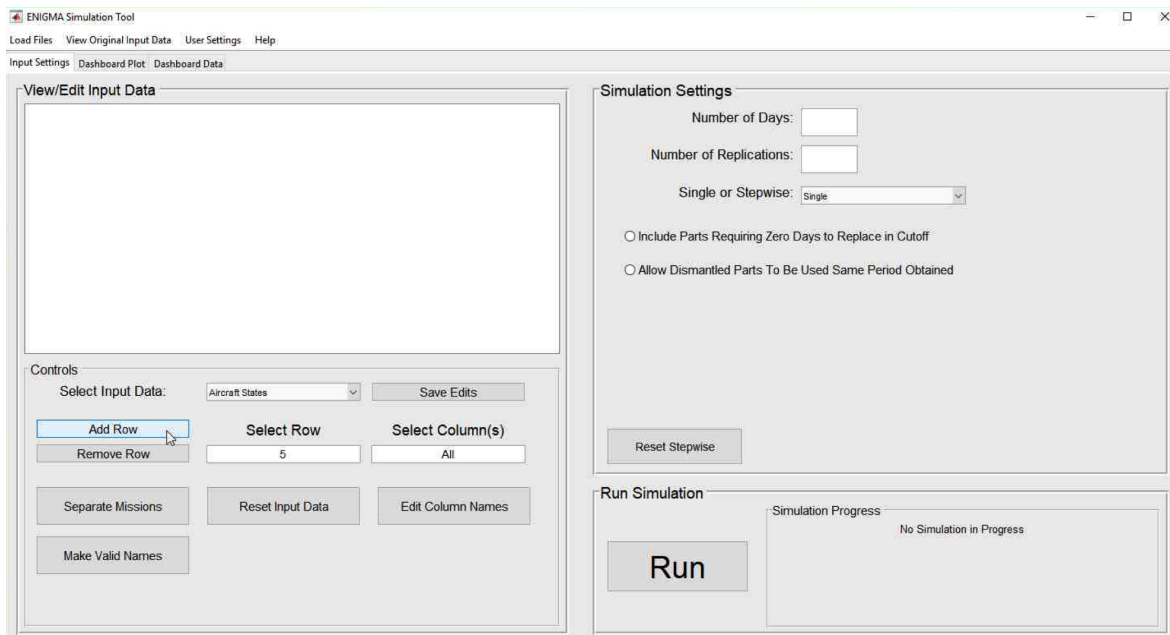


Figure 15: Add New Rows

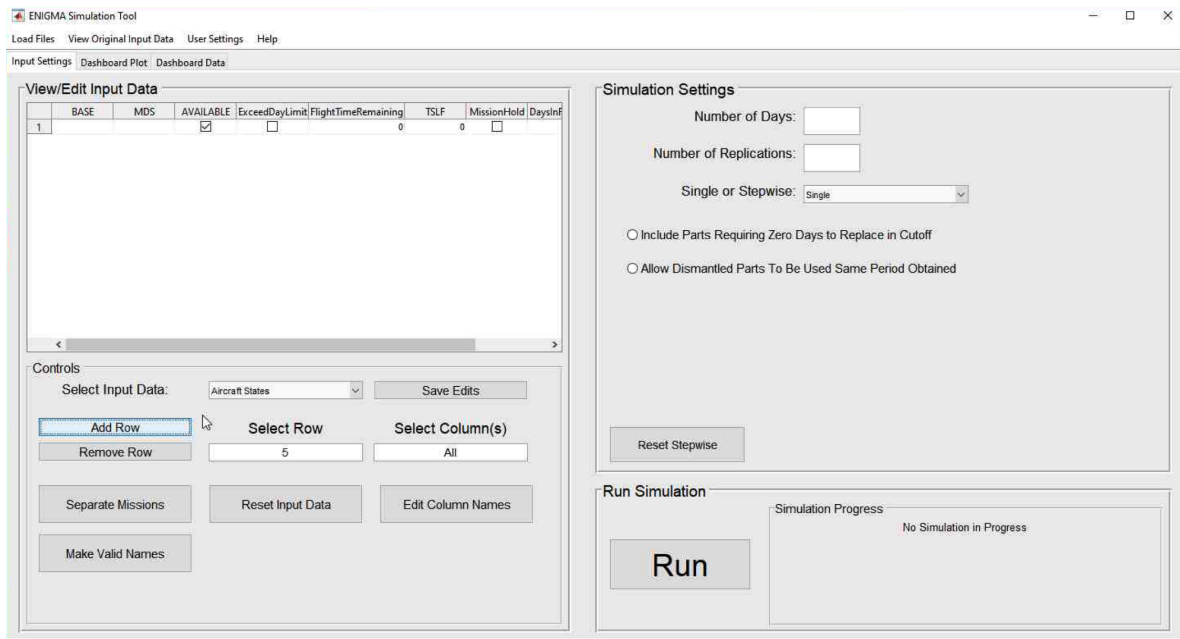


Figure 16: Result of Adding Row to Blank Data Table

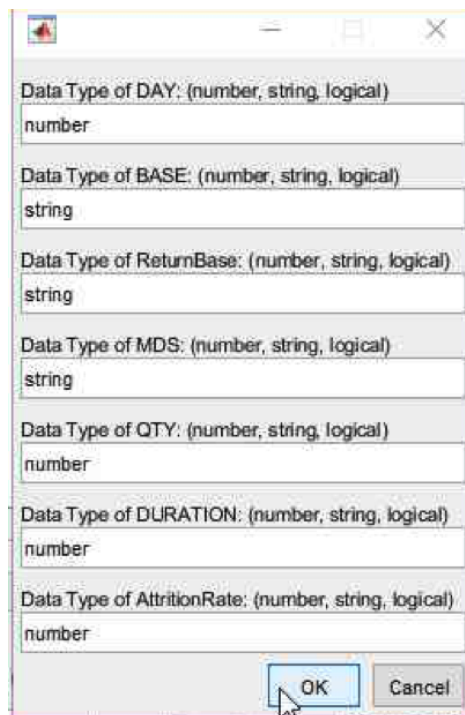


Figure 17: Adding Row to Data Table with Only Column Names Popup Window

Editing Column Names

The column names of a data table can also be changed by specifying the columns whose names need to be edited. The columns are specified via the *Select Column(s)* text box. The possible inputs that can be used in this text box are shown in Table 2. Once the column(s) are specified, click on the *Edit Column Names* button. This will open up a window for the user to input the new names of the selected columns. If the user does not enter a new name for a column, that column name will become empty.

Table 2: Possible Select Column(s) Inputs

Possible Input	Description	Example
All	Selects All Columns	All
Comma Separated	Select Multiple Columns	2, 3, 7
Single Number	Select a Single Column	3

Additional Editing Features

The user is also able to clear all of the edits performed on a data table by pressing the *Reset Input Data* button. This button resets the data table to be the same data as the uploaded file of the same type. If there is no uploaded file of the selected input data, then the data table is erased. This button has no effect on the original uploaded file.

The *Separate Missions* button is only applicable to the missions data table. This button will separate all of the mission inputs that require multiple aircraft into separate missions requiring only a single aircraft. As explained in Section 3.2.4, this is slightly different from the automatic separation that occurs during the simulation because if the missions are inputted as separate missions prior to beginning the simulation, then the same aircraft can be used to fly several of missions. In contrast, if there is a shortage of mission capable aircraft for a mission requiring several aircraft that has not been separated prior to running the simulation, then the simulation will indicate that some of the missions were not completed regardless of the number of

aircraft that return and remain mission capable. An example of using this button to separate missions is shown in Figure 18 and Figure 19.

View/Edit Input Data

	DAY	BASE	ReturnBase	MDS	QTY	DURATION	Attri
1	1	A	A	F15	2	3	1.0
2	2	A	A	F15	5	3	
3	3	A	A	F15	3	3	1.0
4	4	A	A	F15	4	3	1.0

Controls

Select Input Data:

Missions

Save Edits

Add Row

Remove Row

Select Row

5

Select Column(s)

All

Separate Missions

Reset Input Data

Edit Column Names

Make Valid Names

Figure 18: Missions Requiring Multiple Aircraft (Prior to Separation)

View/Edit Input Data

	DAY	BASE	ReturnBase	MDS	QTY	DURATION	At
1		1 A	A	F15	1	3	
2		1 A	A	F15	1	3	
3		2 A	A	F15	1	3	
4		2 A	A	F15	1	3	
5		2 A	A	F15	1	3	
6		2 A	A	F15	1	3	
7		2 A	A	F15	1	3	
8		3 A	A	F15	1	3	
9		3 A	A	F15	1	3	
10		3 A	A	F15	1	3	
11		4 A	A	F15	1	3	
12		4 A	A	F15	1	3	
13		4 A	A	F15	1	3	

Controls

Select Input Data:
Missions
Save Edits

Add Row
Remove Row

Select Row
5

Select Column(s)
All

Separate Missions
Reset Input Data
Edit Column Names

Make Valid Names

Figure 19: Result of Separating Missions (Result of Separation)

ENIGMA allows the user to be flexible with the names and labels of some inputs such as the names of bases, aircraft, and failure types; however, invalid names that will result in errors with the simulation. For example, names including special characters, spaces, or names beginning with numbers are invalid names. Figure 20 provides an example of a data table with invalid names. Instead of manually fixing each of the invalid names in the data table, the *Make Valid Names* button will automatically change invalid names into valid ones in the selected columns. The columns are selected

based on the *Select Column(s)* input and the same possible inputs used for selecting columns for editing column names is used for making valid names. The *Make Valid Names* button will automatically determine the data type of each column; thus it is recommended to use the input *All* as the columns to select for this feature. The result of the example of applying this feature to the invalid names in Figure 20 is shown in Figure 21.

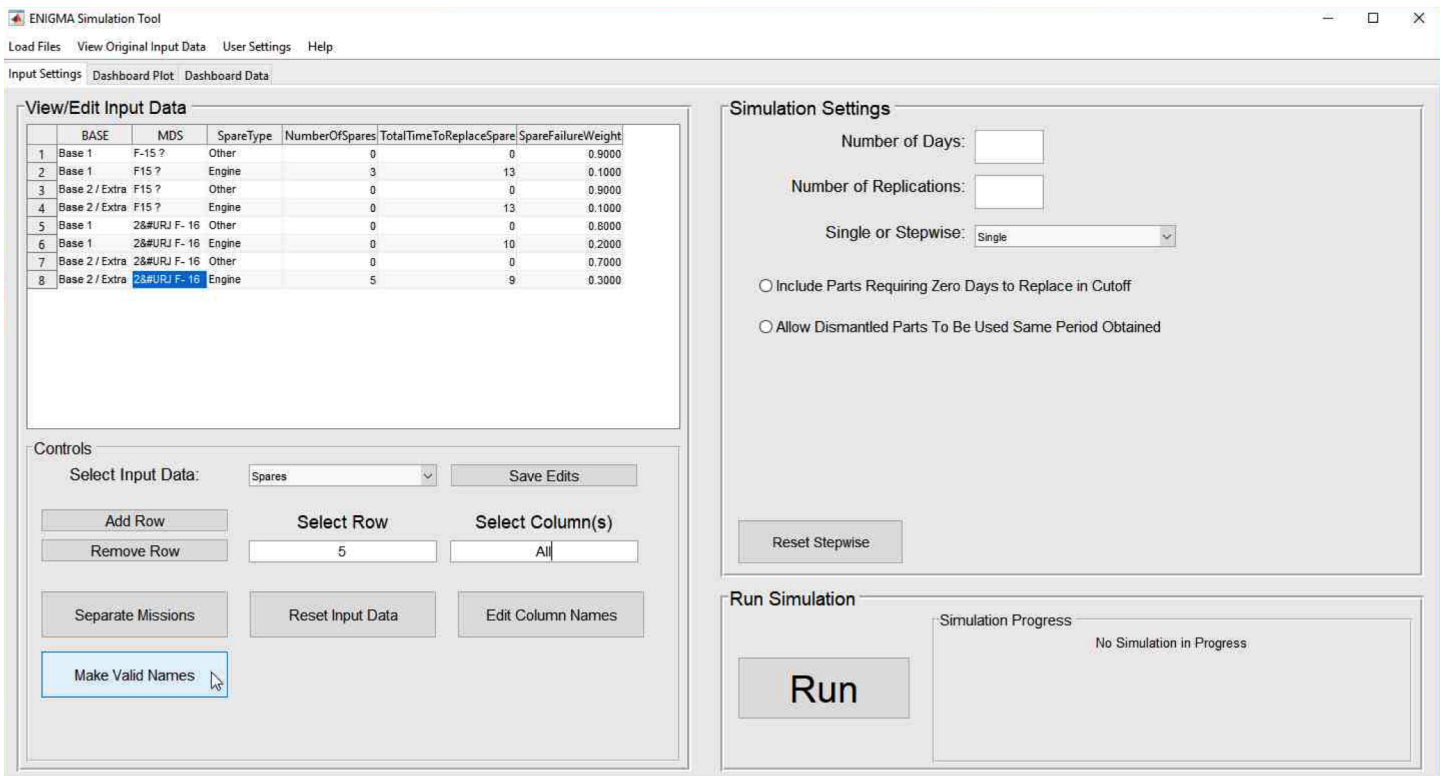


Figure 20: Example of Invalid names

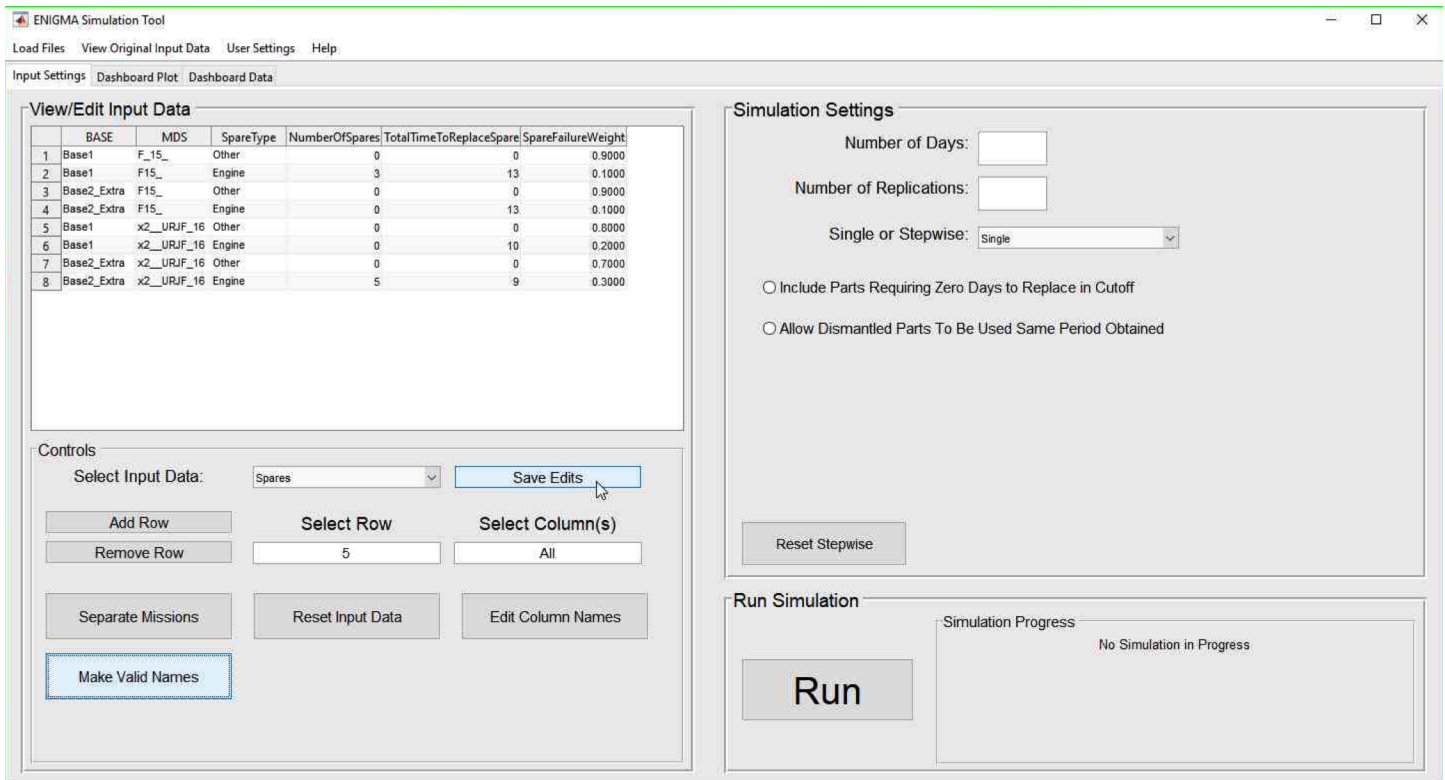


Figure 21: Making Invalid Names Valid Example

3.4.5 Input Data Requirements

In order to run a simulation on this version of ENIGMA, five data tables must be prepared. These tables can either be uploaded to the application or created in the application. The five data tables include a missions data table, an aircraft states data table, a major events data table, and two maintenance data tables. The missions data table and the major events data table may be empty if there are no missions or major events in the simulation as long as the appropriate column headers are still properly labeled; however, the aircraft states data table and the maintenance data tables must contain information about all bases and aircraft in order to properly run the simulation. The column names that must be used as the headers of each of these tables are defined in each of the following sections. Additional requirements for these data tables will be discussed further.

Aircraft States Data Table

The aircraft states data table is a table that defines the initial state of each individual aircraft in the simulation. Each individual aircraft must be entered into this file in order for it to be in the simulation. The column headers and their respective data they represent are defined in Table 3. Note that for data that is of logical data type in files that will be uploaded, the user must input *true* or *false* for the data in order for the program to properly identify it as a logical value.

Table 3: Aircraft States Data Table Headers

Column Header Name	Description	Type
BASE	The base that the aircraft is located.	String
MDS	The type of aircraft. Mission Design Series	String
AVAILABLE	Indicates whether or not an aircraft is of mission-capable status	Logical
ExceedDayLimit	Indicates if an aircraft has flown longer than the day limit. Recommendation: Set to False	Logical
FlightTimeRemaining	The amount of flight time remaining if an aircraft is still flying and has not returned to base. Recommendation: Set to 0	Number
TSLF	Time flown since the aircraft's last failure. Recommendation: Set to 0	Number
MissionHold	Indicates if an aircraft is of mission-capable status, but unable to fly sorties this period. Recommendation: Set to False	Logical
DaysInFailure	Identifies the number of days an aircraft has been in failure if its AVAILABLE status is set to False. Recommendation: Set to 0	Number
Attrition	Identifies if an aircraft is no longer usable. Warning: Do NOT set as True. If set as true, set BASE as 'N/A'. Recommendation: Set as False.	Logical

Maintenance Data Tables

There are two separate data tables that define the maintenance system in the simulation: the spares data table and the repair/failure rates data table. The spares data table defines the number of spares of each type of failure at each base for each type of aircraft in the simulation. The repair/failure rates data table defines the failure and repair rates at each base for each type of aircraft in the simulation. These tables must contain the repair and failure information of each type of aircraft at each base in order to function properly. For example, if there are 5 aircraft of Type 1 located at Base 1 and 3 aircraft of Type 2 located at Base 2, then both of the files must contain the maintenance information for both aircraft at each base. The information about the spares and the repair/failure rates of both aircraft types, Type 1 and Type 2, must be defined at both bases, Base 1 and Base 2; otherwise, aircraft will not be able to fly between bases. The column headers requirements for these files are shown in Table 4 and Table 5 for the spares data table and the repair/failure rates data table respectively.

Table 4: Spares Data Table Headers

Column Header Name	Description	Type
BASE	The base that the spare type is located.	String
MDS	The type of aircraft that the spare is used for. Mission Design Series of the aircraft the spare is used for.	String
SpareType	The Failure Type that the Spare is used for.	String
NumberOfSpares	The quantity of stored spares of the specified SpareType for the specified MDS at the specific BASE.	Number
TotalTimeToReplaceSpare	The number of days (Periods) required to replace a used spare with a new spare.	Number
SpareFailureWeight	The weight that determines the proportion of failures that will be of this SpareType when a part failure occurs for an aircraft of this MDS at this BASE.	Number

Table 5: Repair/Failure Rates Data Table Headers

Column Header Name	Description	Type
BASE	The base that the contains the rates for this MDS.	String
MDS	The type of aircraft the rates at this BASE. Mission Design Series	String
NUMSIM	The maximum number of simultaneous repairs that can occur for this MDS at this BASE	Number
MTBF	Mean Time Before Failure for this MDS at this BASE. Input must be greater than 0 hours.	Number
MTTR	Mean Time to Repair for this MDS at this BASE of a single aircraft. Input must be greater than 0 hours.	Number

Missions Data Table

The missions data table defines the quantity and duration of sorties throughout the simulation. The table provides some flexibility that allows aircraft to fly to different bases if the necessary information is included in the simulation. The column headers and the respective data that they represent are shown in Table 6.

Table 6: Missions Data Table Headers

Column Header Name	Description	Type
DAY	The day in the run sequence that this mission occurs.	Number
BASE	The base that the aircraft(s) flying this mission will fly from.	String
ReturnBase	The base that the aircraft(s) flying this mission will return to.	String
MDS	The type of aircraft the mission requires. Mission Design Series	String
QTY	The quantity of aircraft that this mission will be assigned.	Number
DURATION	The duration of this mission in hours.	Number
AttritionRate	The probability that an aircraft will no longer be usable after this mission due to attrition. Range of this input: [0, 1]	Number

Major Events Data Table

The major events data table is used to define any major events that may occur. The user can choose from predefined major events and utilize them at specific points throughout the simulation. Major events can only occur if they are identified correctly. If the major events are not identified properly, they will not occur in the simulation. The column headers and required data types for this data table are shown in Table 7. A full list and description of the currently available major events are shown in Table 44 of Appendix A. A list of the identifications of the available events are shown in Table 8. These major events are important because they give the user the ability to incorporate unexpected changes to operating conditions into the simulation. For example, some major events available can replicate the effect of a base being attacked by an adversary; another example of a major event is a logistical cutoff which prevents a base from accessing parts needed to make repairs on damaged aircraft. Aircraft that are still on missions from a previous period and have not returned before the major events are implemented will not be affected by the major events if the major events directly impact aircraft at the specified base.

Table 7: Major Events Data Table Headers

Column Header Name	Description	Type
Day	The day (Period) that the event occurs.	Number
BASE	The base that the event occurs at.	String
MDS	The type of aircraft that the event occurs to. Mission Design Series.	String
Event	The event identification string that is used to identify the event type.	String
EventData	Additional information needed for the event type. This is inputted as a string with the written between curly brackets. If multiple inputs are required, the inputs are separated by commas. Example - No Inputs: {} Example - One Input: {input} Example - Multiple Inputs: {input1,input2,...}	String

Table 8: Major Event Options

Major Event Options
AddNewAircraft
AdjustMTTR
AdjustNumberSimultaneousRepair
AdjustMTBF
AdjustAFSC
AccessLogistics
CutOffLogistics
DamageAllAircraft
DamageProportionAircraft
DestroyProportionAircraft
DamageAndDestroyProportionAircraft
DamageFixedNumberAircraft
DestroyFixedNumberAircraft
DamageAndDestroyFixedNumberAircraft
DamageProportionSpecificAircraft
DamagedFixedNumberSpecificAircraft
DestroyProportionSpecificAircraft
DestroyFixedNumberSpecificAircraft
DamageAndDestroyFixedNumberSpecificAircraft
DamageAndDestroyProportionSpecificAircraft

3.4.6 Running the Simulation

Pressing the *Run* button starts the simulation. When the simulation is running, progress information will display. Once the simulation has been completed, the progress information will disappear.

3.4.6.1 Simulation Settings

The simulation settings are adjusted in the *Simulation Settings* panel in the *Input Settings* tab of the application. These settings are required to define how the simulation should run. The user inputs the number of days in the simulation and the number of replications that the simulation will run in the *Number of Days* input space and the *Number of Replications* input space, respectively, as shown in Figure 22.

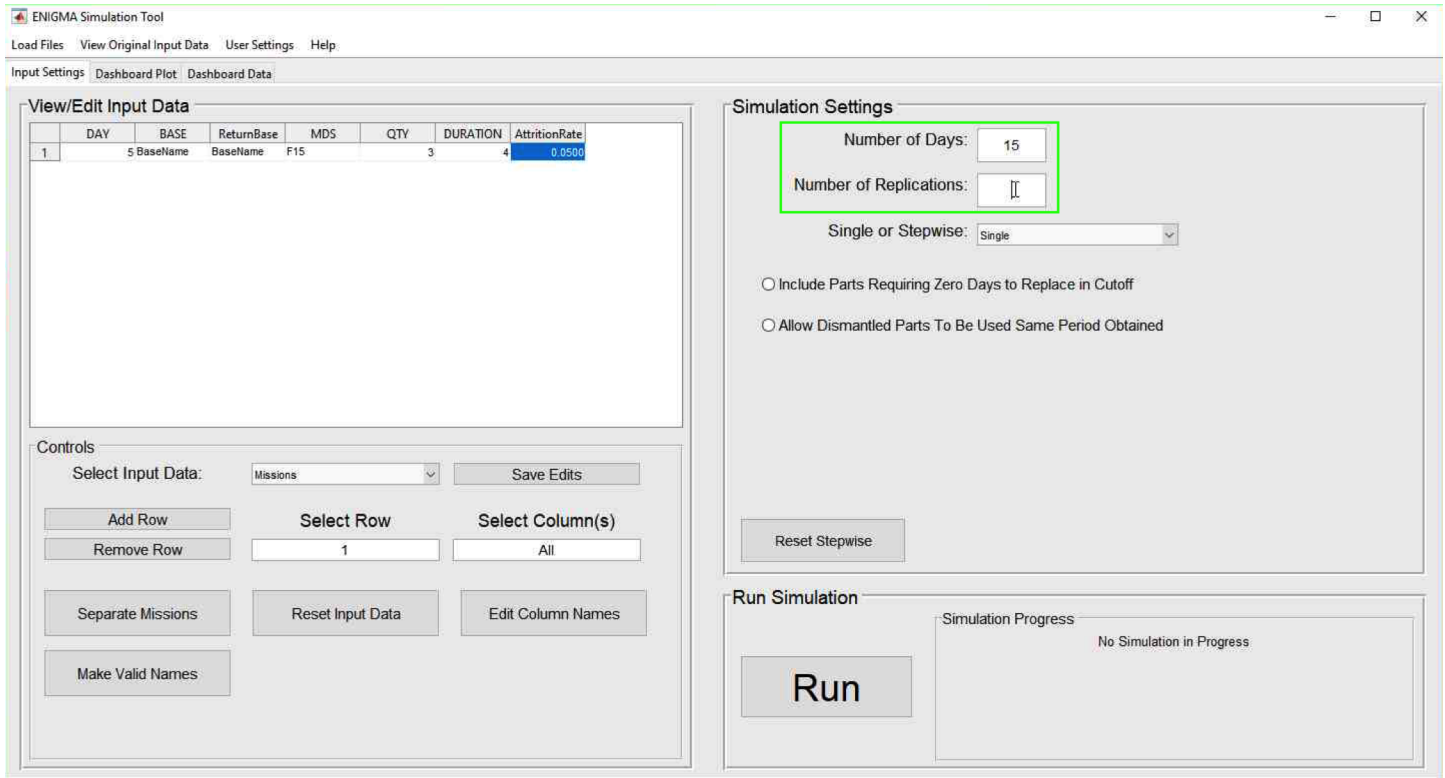


Figure 22: Input Number of Days and Number of Replications

The *Single or Step-wise* option is an important option for the user to select because it will determine how the simulation tool can be used. When *Single* is selected, the simulation will clear all output data of previous simulation runs every time the simulation is run. When *Step-wise* is selected, as shown in Figure 23, each run will be appended to previous runs. If the step-wise method is chosen, the user will only be able to adjust the missions data table, the major events data table, and the number of days between each sequential step-wise run. In order to restart a step-wise simulation sequence, press the *Reset Stepwise* button. This will clear all saved step-wise simulation information from previous runs.

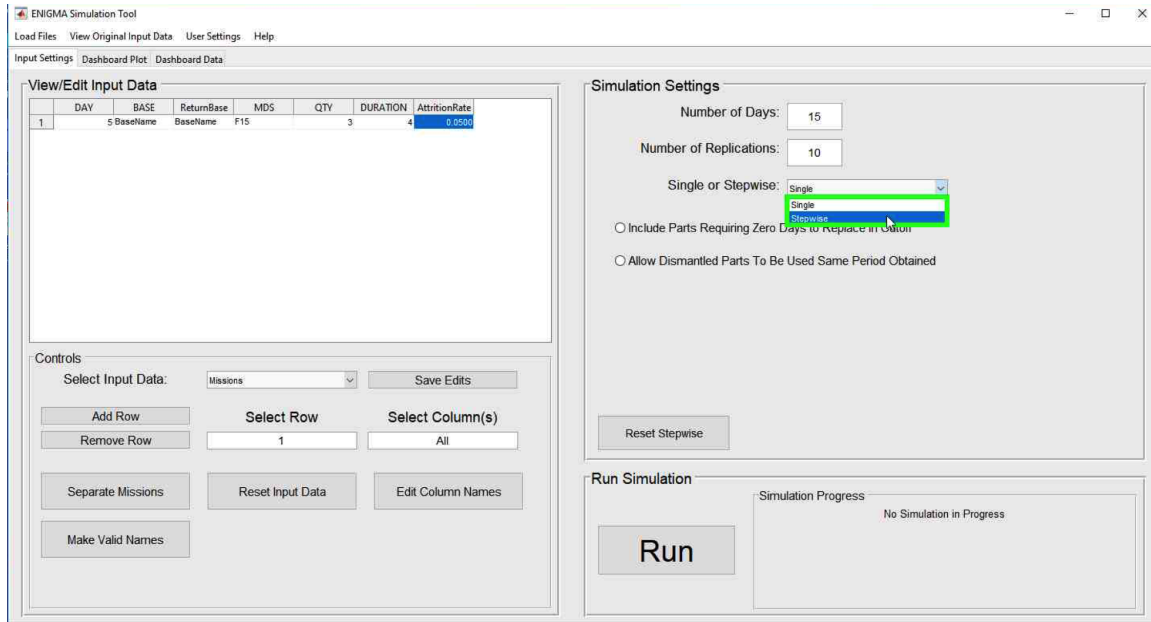


Figure 23: Selecting Step-wise

An example of running a simulation using the step-wise setting is shown in Figure 24 and Figure 25. Each sequence is run with the same missions data table and the same major events data table; however, the first sequence is run for 5 days and the second sequence is run for 7 days. These plots demonstrate how the step-wise setting allows users to make decisions throughout time by editing the missions data table and the major events data table between runs.

Major Events Settings

There are two more buttons in the *Simulation Settings* panel: the *Include Parts Requiring Zero Days to Replace in Cutoff* button and the *Allow Dismantled Parts To Be Used Same Period Obtained* button. These settings are specific to certain major events that the user can utilize in their simulation. Currently, the *Allow Dismantled Parts To Be Used Same Period Obtained* button is not enabled for this version of ENIGMA because the major event that it would be used for remains under development for future versions of ENIGMA.

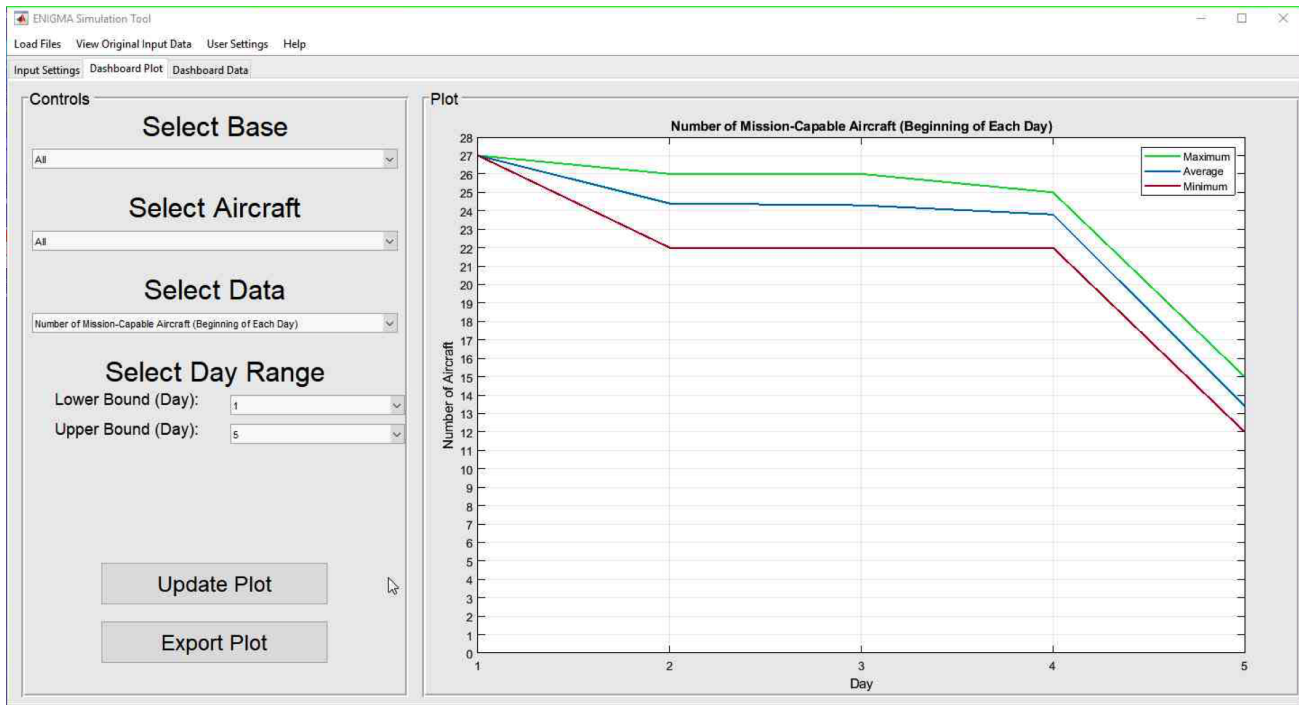


Figure 24: Example - Step-wise First Iteration (First[5 Days])

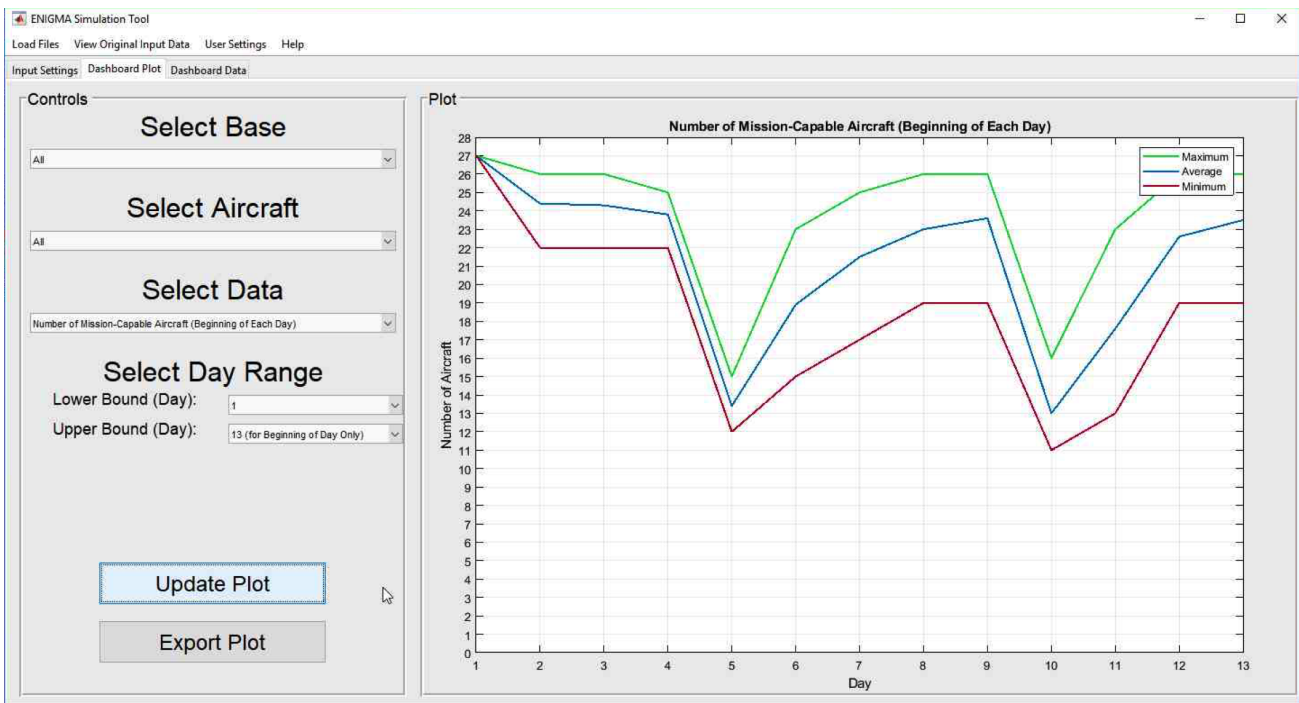


Figure 25: Example - Step-wise Second Iteration (First[5 Days] + Second[7 Days])

3.4.7 Post-Simulation Run Controls

Once a simulation run has been completed, the user is able to view and save the output information from the simulation as plots and as data tables. The *Dashboard Plot* and the *Dashboard Data* are the two tabs that the user can use to view and save output data. Both of these tabs are designed in the same way, except that the *Dashboard Plot* tab will plot the data and the *Dashboard Data* tab will display the data in a table. The user can specify the specific output information that they wish to view and to export as shown in Figure 26, which shows the *Dashboard Data* table output. In order to export the data, press the export button and save the file in the desired format as shown in Figure 27 and Figure 28.

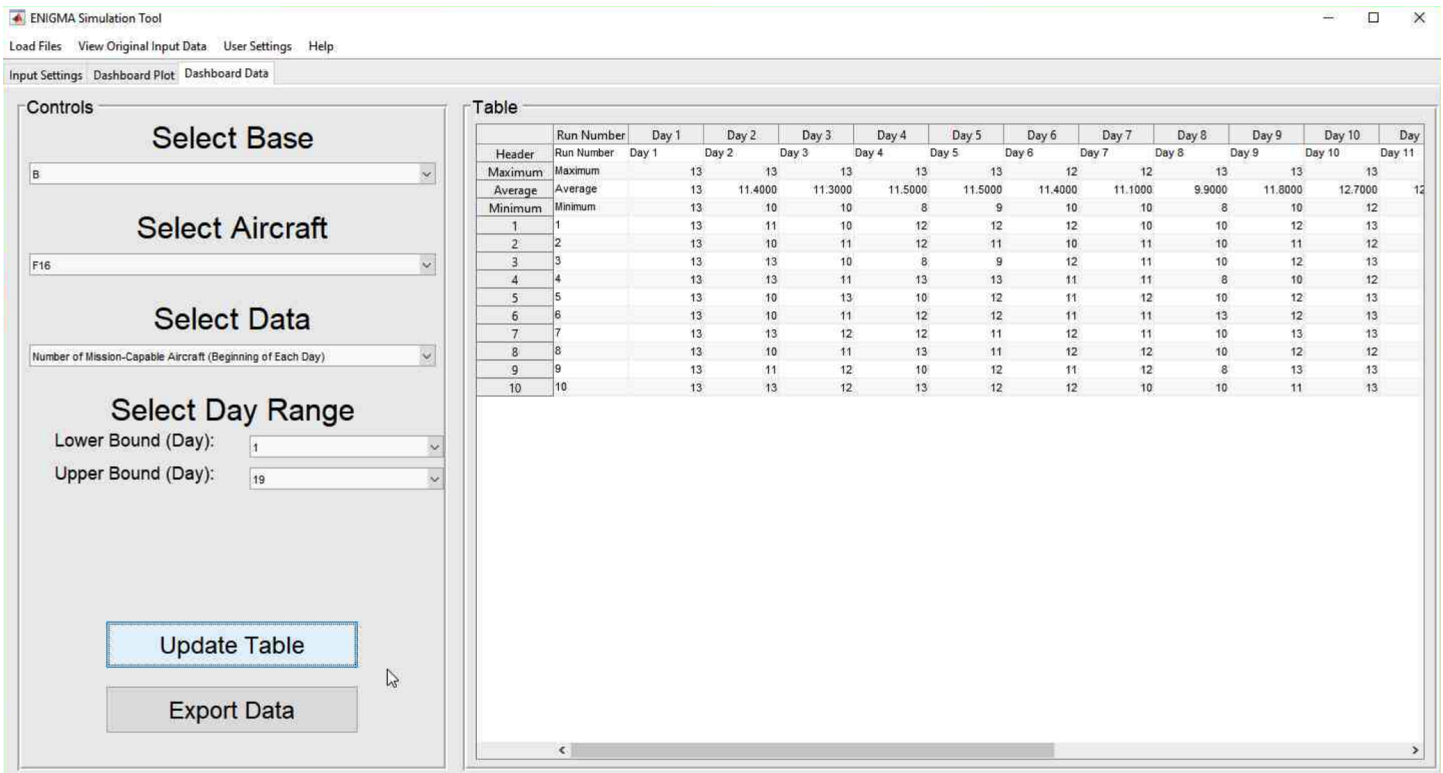


Figure 26: Example Displaying Output

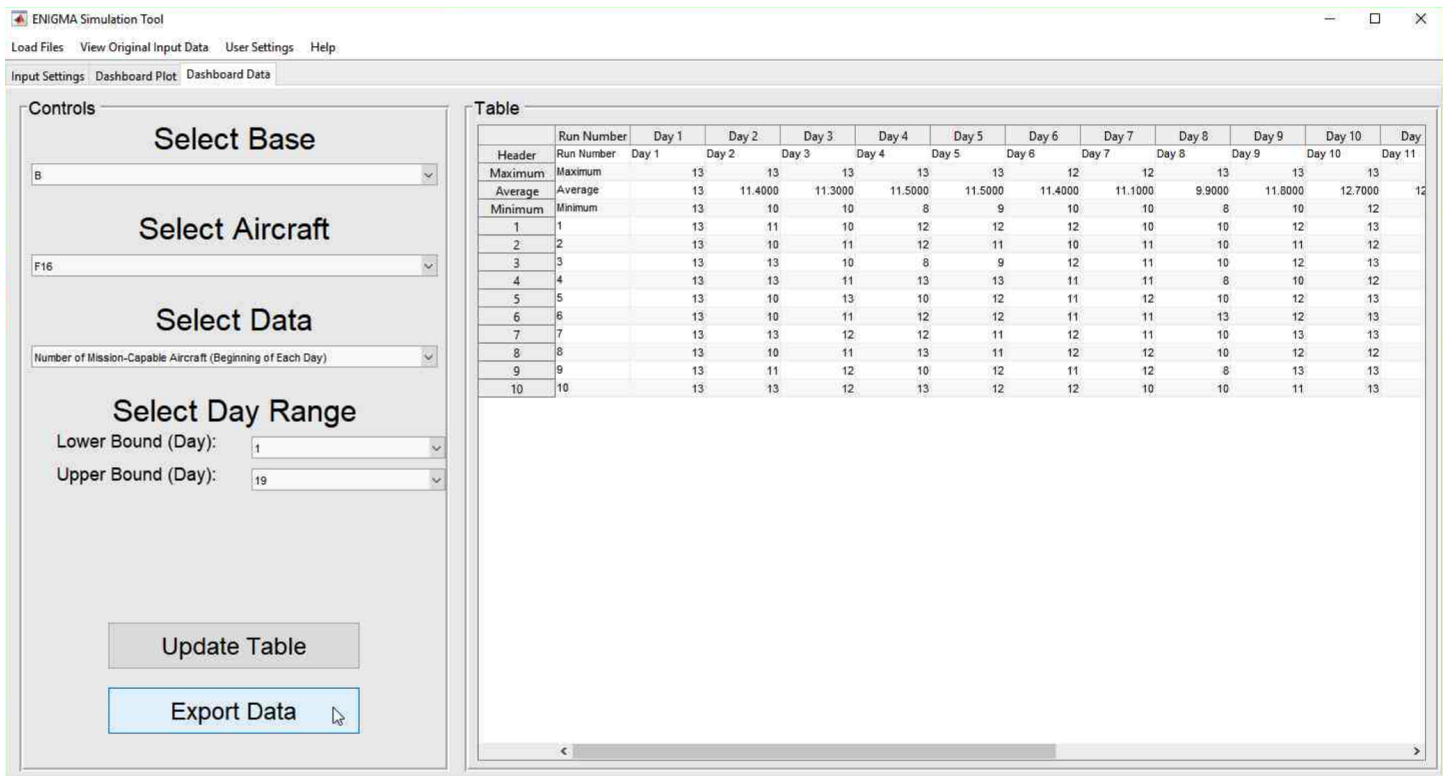


Figure 27: Exporting Output As a File

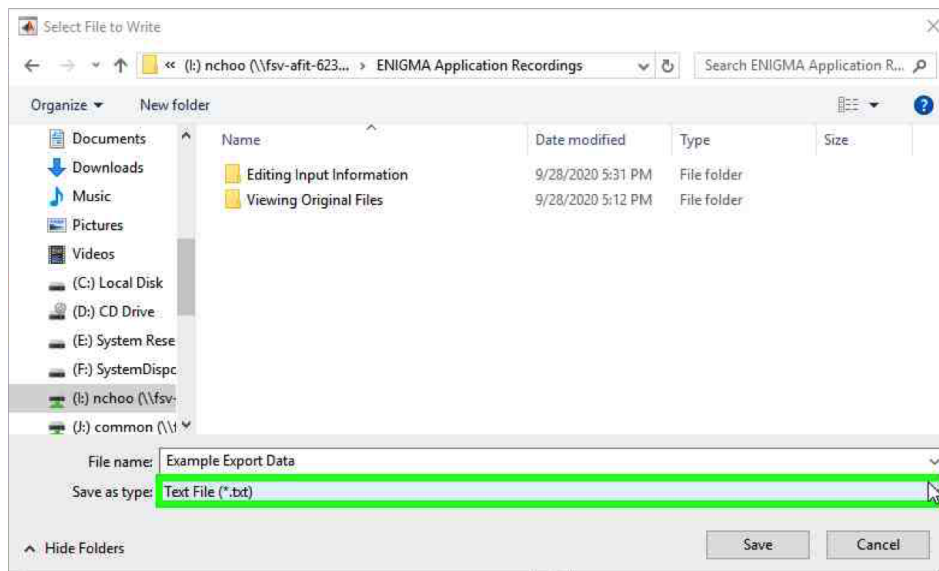


Figure 28: Exporting File

IV. Results and Analysis

4.1 Preamble

As with all simulations, it is important to validate the simulation to ensure that the simulation will provide results that can provide meaningful insights into the real world situations being investigated. If simulation tools are not validated, then users will not know how reliable the simulation tools are in representing the system being modeled. The purpose of this chapter is to explain the methodology and the results of testing ENIGMA to make sure that the simulation functions as expected.

Checking the Code

There are two steps that should be done when checking that a simulation tool works properly: verification and validation. Verification is the process of ensuring that the model design and the software code are implemented and work as they were designed to function. Validation is the process of making sure the model properly reflects the reality of the system that it is modeling. The simulation tool was verified to function properly by following the execution of each line of code used to build the simulation tool for a variety of different scenarios that would challenge the capability of the tool. The verification process of the tool showed that the logic of the code functioned as expected and that the model design was implemented properly. Since the simulation tool uses an abstract environment and since the model was not based on any specific system, the model was validated by checking whether or not the inputs would affect the outputs in the intuitive manner.

4.2 Model Checking

Although each line of code of ENIGMA was checked for the appropriate logic, it remained important to validate the behavior of the simulation. Unfortunately, since

ENIGMA is designed to be a tool without any fixed inputs, it would be infeasible to test every possible combination of inputs that a user could input into the simulation. According to Barton, linear regression meta-models can be used to provide insights into the behavior of a simulation model by providing the relationships between the inputs and the outputs of the simulation[19]. A meta-model is a model of another model. The meta-model will be chosen to provide insight into the behavior of this simulation will be a linear regression model relating the simulation inputs and outputs.

There are five assumptions that must be satisfied in order for the resulting linear regression model to be appropriate. The first assumption is homoscedasticity, which means that there is constant variance throughout the model. The second assumption is that the residuals are normally distributed with a mean of zero. The third assumption is that there is a linear relationship between the regressors and the response variable. The fourth assumption is that there is no multicollinearity amongst the regressors. The fifth assumption is that there is no autocorrelation in the model. If these five assumptions are satisfied, then the linear regression model that is developed appropriately represents the relationship between the regressors and the response variable.

In order to develop a linear regression model on the inputs and outputs of the simulation, an experiment must be run on the simulation by varying input combinations to obtain a response surface. Since it would be infeasible to test every possible combination of inputs for ENIGMA, an efficient design of experiments must be utilized. Sanchez and Wan state that latin hypercube designs are useful for testing complicated simulations when knowledge about the response surface is limited because they can provide an efficient space-filling design with far fewer sample tests than the computationally expensive space-filling factorial designs[20]. Space-filling designs are important to use for testing simulations because they can provide insight

into the whole region of the response surface. It is also desirable to have an orthogonal design; orthogonal designs ensure that any two input variables to the simulation will be uncorrelated, resulting in uncorrelated regression coefficient estimates of regression models[21]. Cioppa and Lucas developed a method for generating space-filling nearly-orthogonal latin hypercube designs for making experiments for testing simulations with fewer than 30 input factors, or variables ($NumberOfVariables \leq 29$)[21]. Sanchez then used this methodology of generating space-filling nearly-orthogonal latin hypercubes to create a tool to make the experiments for testing simulations; this tool is available at <http://harvest.nps.edu/>[22]. This tool was utilized to generate the experiment for validating that simulation of ENIGMA behaves as expected.

Since the only requirement for many of the input ranges of the ENIGMA inputs is to be non-negative, the experimental ranges that were used for the experimental design tool had to be narrowed down so that the test ranges were not too large; thus, the input ranges of the experiment were chosen to reflect a general fighter squadron. The minimum and the maximum of each range were determined through discussion with United States Air Force pilots and maintenance personnel who have flown and have worked on fighter aircraft. At the end of Section 4.2.2, Table 23 shows the ranges of the inputs that were used to develop the experimental design. The experimental design is shown in Table 45 of Appendix A. The two outputs of interests from the experiment were the average proportion of aircraft that are mission capable and the average proportion of missions flown. Each test of the experiment was replicated 100 times and each replication was run for 100 periods (days) to mitigate the effects of the warm-up period in each simulation run. JMP Pro 15.0.0 was used to generate the regression models from the outputs of the experimental design.

4.2.1 Model Validation Through a Main-Effects Metamodel

The purpose of modeling the experimental results using only the input variables with no interaction as the regressors is to observe the main effects of the regressors on the response variables, which in this case are the average proportion of aircraft that are mission capable and the average proportion of missions flown. The main-effects model is shown in Equation (24).

$$Y = \beta_0 + \sum_{i=1}^n \beta_i X_i + \epsilon \quad (24)$$

Where β_i is the regression coefficient for the regressor X_i , which is the i th input factor; Y is the response variable; n is the number of input factors; and ϵ represents random error with a mean of zero. The regression coefficients that are included in the model are determined through the forward step-wise method in JMP Pro 15.0.0. Main effects models of the average proportion of aircraft that are mission capable and the average proportion of missions completed are shown in the next sections. There are five assumptions required to use linear regression analysis: there is a linear relationship between the regressors and response variable, the residuals are normally distributed with a mean of zero, the residuals have constant variance throughout the model, there is no multicollinearity, and there is no autocorrelation. If these assumptions are violated, the model may not perfectly reflect the true relationship between the regressors and response variable.

Average Proportion of Aircraft that are Mission Capable

All of the input factors were deemed to be significant in the main-effects meta-model for the average proportion of aircraft that were mission capable. Table 9 shows the parameter estimates for each of the input factors. The adjusted- R^2 for this model is approximately 0.85 as shown in Table 10. The variance inflation factor (VIF) scores indicate that there is essentially no multicollinearity between the regressors. Each of

the parameter estimates support the idea that each regressor impacts the average proportion of aircraft that are mission capable. Table 11 shows the regressors that have the most impact on the average proportion of aircraft that are mission capable are the input factors that determine aircraft usage. The second most influential regressors are the factors that influence the repair capability of the maintenance system. Overall, factors accounting for levels of use, failure, and ability to repair significantly influence the average proportion of aircraft that are mission capable as expected. Additionally, the coefficients possess the expected positive or negative contribution validating the model. Unfortunately, Figure 29 shows that the assumption of constant variance is not satisfied for this model. Figure 30 also appears to show that the assumption of normally distributed residuals is violated. Table 12 also shows that it appears there is significant autocorrelation in the model. These apparent violations to a few of the linear regression assumptions may indicate that only using the main effects does not appropriately represent the relationship between the regressors and the average proportion of aircraft that are mission capable.

Term	Estimate	Std Error	t Ratio	Prob> t	VIF
Intercept	0.8561411	0.019018	45.02	<.0001*	.
Aircrafts Per Wing	0.0078477	0.000732	10.72	<.0001*	1.0167134
Duration of each Mission	-0.040322	0.000692	-58.24	<.0001*	1.0303206
MTBF	0.0103057	0.000106	97.28	<.0001*	1.0075546
MTTR	-0.022272	0.000558	-39.93	<.0001*	1.0133313
Number Of Aircraft Repaired At A Time	0.0286162	0.001062	26.95	<.0001*	1.0184133
Engine Spare Stock Capacity	0.014694	0.00085	17.29	<.0001*	1.0098745
Engine Resupply Time	-0.005264	0.000632	-8.32	<.0001*	1.0321795
Proportion of Failures Engine Failures	-1.857082	0.085235	-21.79	<.0001*	1.015316
Attrition Rate	-67.10747	4.680953	-14.34	<.0001*	1.0063935
Missions Per Day	-0.007808	0.000149	-52.38	<.0001*	1.0033936

Table 9: Parameter Estimates Main-Effects Metamodel (Average Proportion of Aircraft that are Mission Capable)

RSquare	0.849941
RSquare Adj	0.849485
Root Mean Square Error	0.075774
Mean of Response	0.654811
Observations (or Sum Wgts)	3300

Table 10: Summary of Fit Main-Effects Metamodel (Average Proportion of Aircraft that are Mission Capable)

Source	LogWorth	PValue
MTBF	969.584	0.00000
Duration of each Mission	507.898	0.00000
Missions Per Day	434.922	0.00000
MTTR	283.899	0.00000
Number Of Aircraft Repaired At A Time	144.028	0.00000
Proportion of Failures Engine Failures	97.697	0.00000
Engine Spare Stock Capacity	63.421	0.00000
Attrition Rate	44.535	0.00000
Aircrafts Per Wing	25.662	0.00000
Engine Resupply Time	15.913	0.00000

Table 11: Effects Summary Main-Effects Metamodel (Average Proportion of Aircraft that are Mission Capable)

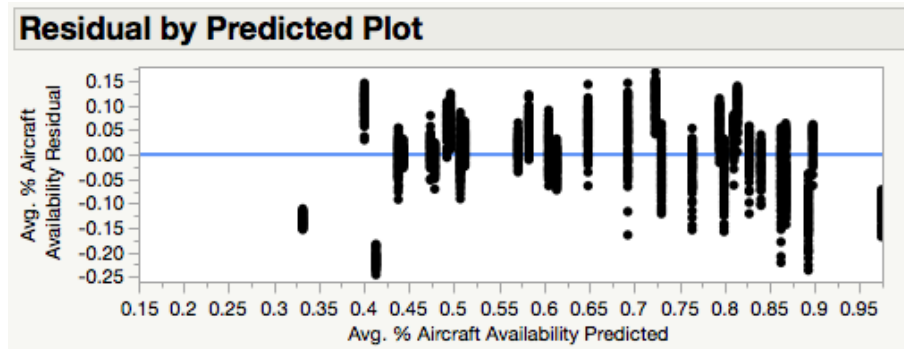


Figure 29: Residuals by Predicted: Average Proportion of Aircraft that are Mission Capable (Main Effects Model)

Durbin-Watson			
Durbin-Watson	Number of Obs.	AutoCorrelation	Prob<DW
0.3456728	3300	0.8266	<.0001*

Table 12: Durbin-Watson Statistic of Average Proportion of Aircraft that are Mission Capable (Main Effects Model)

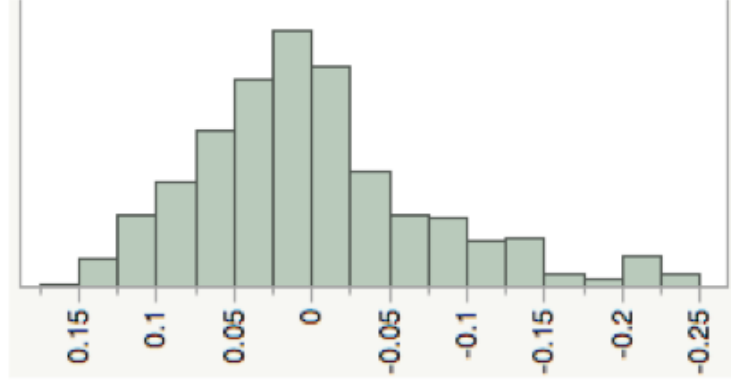


Figure 30: Distribution of Residuals: Average Proportion of Aircraft that are Mission Capable (Main Effects Model)

Average Proportion of Missions Completed

The main-effects metamodel for the average proportion of missions that are flown does not include all input factors because some of the input factors were not determined to be statistically significant when performing step-wise regression. The time it takes to resupply an engine was determined not to be significant in the model. Table 13 provides the parameter estimates of the regressors that were included in the model. Table 14 shows that the adjusted- R^2 was relatively low with a value of approximately 0.706. The VIF scores indicate that there was essentially no multicollinearity amongst the regressors in this model. All the parameter estimates for this model intuitively made sense and supported the idea that the simulation behaves properly. Table 15 also shows the input factors that influence the rate of aircraft part failures have the most impact on the average proportion of missions that are flown. Overall, the factors that impacted use, failures, and repairs of aircraft significantly influenced the average number of missions accomplished as expected. Each of the regression coefficients has the expected positive or negative contribution validating the model. Unfortunately, Figure 31 shows that the assumption of constant variance is not satisfied. Figure 32 shows that the distribution of residuals appears to violate the assumption of normally distributed residuals. Table 16 also shows that

autocorrelation appears to be significant in the model. These violations to the linear regression assumptions may indicate that the main effects model does not appropriately represent the relationship between the regressors and the average proportion of missions accomplished. One difference between this main-effects model focus on the average number of missions flown and the main-effects model focused on the average proportion of aircraft that are mission capable is that the number of aircraft in the squadron has a larger effect on the proportion of missions that are flown than on the average proportion of aircraft that are mission capable.

Term	Estimate	Std Error	t Ratio	Prob> t	VIF
Intercept	0.6222433	0.023485	26.50	<.0001*	.
Aircrafts Per Wing	0.0180739	0.000934	19.35	<.0001*	1.0101589
Duration of each Mission	-0.030331	0.000881	-34.44	<.0001*	1.0168344
MTBF	0.0084046	0.000135	62.07	<.0001*	1.0038318
MTTR	-0.008314	0.000714	-11.64	<.0001*	1.0131807
Number Of Aircraft Repaired At A Time	0.0377803	0.001359	27.79	<.0001*	1.0184121
Engine Spare Stock Capacity	0.0120916	0.001088	11.12	<.0001*	1.0084289
Proportion of Failures Engine Failures	-0.792797	0.108787	-7.29	<.0001*	1.0087469
Attrition Rate	-59.09781	5.992162	-9.86	<.0001*	1.0058425
Missions Per Day	-0.007699	0.000191	-40.34	<.0001*	1.0030846

Table 13: Parameter Estimates Main-Effects Metamodel (Average Proportion of Missions Flown)

RSquare	0.706946
RSquare Adj	0.706144
Root Mean Square Error	0.097026
Mean of Response	0.876352
Observations (or Sum Wgts)	3300

Table 14: Summary of Fit Main-Effects Metamodel (Average Proportion of Missions Flown)

Source	LogWorth	PValue
MTBF	555.537	0.00000
Missions Per Day	288.768	0.00000
Duration of each Mission	221.537	0.00000
Number Of Aircraft Repaired At A Time	152.151	0.00000
Aircrafts Per Wing	78.345	0.00000
MTTR	29.998	0.00000
Engine Spare Stock Capacity	27.483	0.00000
Attrition Rate	21.906	0.00000
Proportion of Failures Engine Failures	12.405	0.00000

Table 15: Effects Summary Main-Effects Metamodel (Average Proportion of Missions Flown)

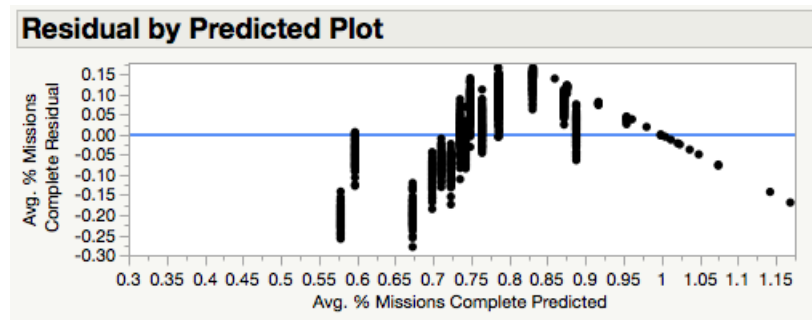


Figure 31: Residuals by Predicted: Average Proportion of Aircraft that are Mission Capable (Main Effects Model)

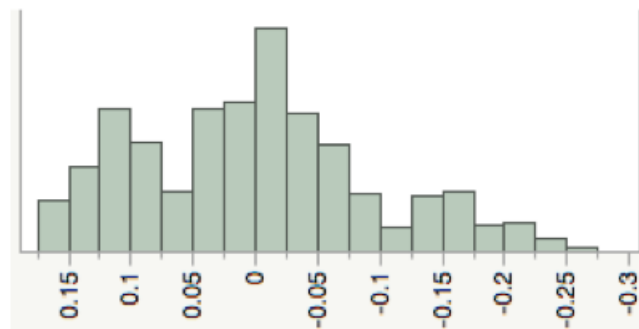


Figure 32: Distribution of Residuals: Average Proportion of Missions Accomplished (Main Effects Model)

Durbin-Watson			
Durbin-Watson	Number of Obs.	AutoCorrelation	Prob<DW
0.1045543	3300	0.9477	<.0001*

Table 16: Durbin-Watson Statistic of Average Proportion of Missions Accomplished (Main Effects Model)

4.2.2 Model Validation Through a Response-Surface Metamodel

It is also important to explore the model for interaction terms between the input factors. The purpose of this is to obtain a model that may be more reflective of the relationship between the regressors and the response variable. This response surface model is shown in Equation (25).

$$Y = \beta_0 + \sum_{i=1}^n \beta_i X_i + \sum_{i=1}^n \sum_{j=1}^n \beta_{i,j} X_i X_j + \epsilon \quad (25)$$

These meta-models were developed in the same way as the main-effects meta-model.

Average Proportion of Aircraft that are Mission Capable

The metamodel including interaction terms as regressors produced had a very high adjusted-R² value of approximately 0.975, as shown in Table 18. Although the adjusted-R² value is very high, indicating that most of the variance is accounted for by the metamodel, the variance inflation factor values indicate that there is very strong multicollinearity present amongst the regressors, as shown in Table 17. Additionally, one will note that some coefficient estimate signs have changed from the main effects model. As a result, the values of the parameter estimates are strongly influenced by the other parameters in the metamodel. Despite this, the model is shown to be well-behaved and Figure 33 shows the residuals of the model follow a well-behaved symmetric distribution. Additionally, Figure 34 shows that the variance remains relatively constant for all predictions of the average proportion of missions flown, which is a necessary assumption for linear regression models. Table 19 shows the Durbin-Watson statistic for this model is approximately 1.98, which indicates that there is essentially no autocorrelation since a Durbin-Watson statistic of 2 indicates that there is no autocorrelation for this model.

Term	Estimate	Std Error	t Ratio	Prob> t	VIF
Intercept	80.780398	12.63957	6.39	<.0001*	.
Aircrafts Per Wing	-0.520986	0.106086	-4.91	<.0001*	127788.2
Duration of each Mission	-0.007998	0.204095	-0.04	0.9687	535773.64
MTBF	-0.414163	0.076355	-5.42	<.0001*	3131215.4
MTTR	-0.135364	0.024507	-5.52	<.0001*	11703.211
Number Of Aircraft Repaired At A Time	-5.386507	0.892318	-6.04	<.0001*	4304251.8
Engine Spare Stock Capacity	-3.659113	0.521198	-7.02	<.0001*	2271316.5
Engine Resupply Time	-0.54384	0.123399	-4.41	<.0001*	235215.43
Proportion of Failures Engine Failures	-154.1468	35.41387	-4.35	<.0001*	1048622.1
Attrition Rate	434.33767	67.90437	6.40	<.0001*	1267.0745
Missions Per Day	0.0284103	0.008519	3.33	0.0009*	19610.113
(Aircrafts Per Wing-21.0303)*(Duration of each Mission-4.7503)	-2.004923	6.766868	-0.30	0.7670	1.5738e+9
(Aircrafts Per Wing-21.0303)*(MTBF-29.0012)	-9.164028	1.738375	-5.27	<.0001*	2.7986e+9
(Duration of each Mission-4.7503)*(MTBF-29.0012)	5.0978698	0.992223	5.14	<.0001*	1.9537e+9
(MTBF-29.0012)*(MTTR-6)	-4.432535	1.192191	-3.72	0.0002*	2.9136e+9
(MTTR-6)*(MTTR-6)	27.270591	3.780648	7.21	<.0001*	1.2591e+9
(MTBF-29.0012)*(Number Of Aircraft Repaired At A Time-3.06061)	-2.36377	0.386826	-6.11	<.0001*	201665138
(Number Of Aircraft Repaired At A Time-3.06061)*(Number Of Aircraft Repaired At A Time-3.06061)	-39.55914	6.487347	-6.10	<.0001*	340509701
(Number Of Aircraft Repaired At A Time-3.06061)*(Engine Spare Stock Capacity-2.51515)	-45.08478	7.416151	-6.08	<.0001*	484544597
(Engine Spare Stock Capacity-2.51515)*(Engine Spare Stock Capacity-2.51515)	-21.0016	4.082905	-5.14	<.0001*	311012871
(Duration of each Mission-4.7503)*(Engine Resupply Time-10.5152)	7.9422405	1.095856	7.25	<.0001*	62836626
(MTTR-6)*(Engine Resupply Time-10.5152)	-6.138973	1.251554	-4.91	<.0001*	104120139
(Engine Spare Stock Capacity-2.51515)*(Engine Resupply Time-10.5152)	-23.26914	3.801994	-6.12	<.0001*	407534235
(Engine Resupply Time-10.5152)*(Engine Resupply Time-10.5152)	-8.807223	2.42229	-3.64	0.0003*	365811804
(Aircrafts Per Wing-21.0303)*(Proportion of Failures Engine Failures-0.07515)	-3902.67	708.9884	-5.50	<.0001*	1.3638e+9
(Proportion of Failures Engine Failures-0.07515)*(Proportion of Failures Engine Failures-0.07515)	-51154.28	51545.8	-0.99	0.3211	495708421
(Duration of each Mission-4.7503)*(Attrition Rate-0.00053)	-9387.584	31100.76	-0.30	0.7628	1.0992e+9
(MTBF-29.0012)*(Attrition Rate-0.00053)	14808.895	4083.323	3.63	0.0003*	660993423
(Engine Resupply Time-10.5152)*(Attrition Rate-0.00053)	31555.738	4402.4	7.17	<.0001*	19997228
(Aircrafts Per Wing-21.0303)*(Missions Per Day-30.0303)	1.5800184	0.247286	6.39	<.0001*	47284562
(MTTR-6)*(Missions Per Day-30.0303)	-1.245592	0.222366	-5.60	<.0001*	75499683
(Engine Resupply Time-10.5152)*(Missions Per Day-30.0303)	3.9621382	0.586601	6.75	<.0001*	620370806
(Proportion of Failures Engine Failures-0.07515)*(Missions Per Day-30.0303)	-511.3026	84.31354	-6.06	<.0001*	535386497

Table 17: Parameter Estimates Response Surface (Average Proportion of Aircraft that are Mission Capable)

RSquare	0.975086
RSquare Adj	0.974842
Root Mean Square Error	0.030979
Mean of Response	0.654811
Observations (or Sum Wgts)	3300

Table 18: Summary of Fit Response Surface (Average Proportion of Aircraft that are Mission Capable)

Durbin-Watson		
Durbin-Watson	Number of Obs.	AutoCorrelation
1.9833445	3300	0.0064

Table 19: Durbin-Watson Statistic of Average Proportion of Aircraft that are Mission Capable (Response Surface)

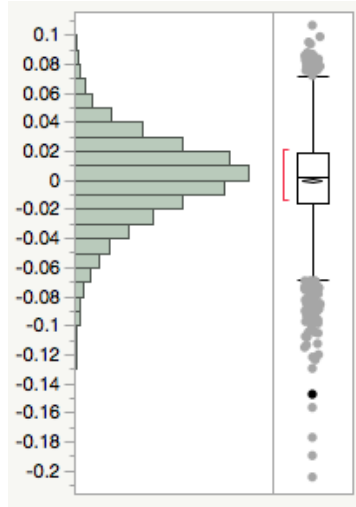


Figure 33: Residuals Response Surface(Average Proportion of Aircraft that are Mission Capable)

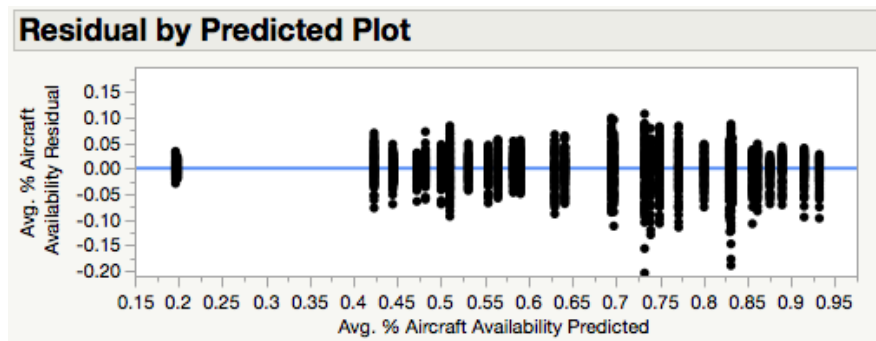


Figure 34: Residuals by Predicted: Average Proportion of Aircraft that are Mission Capable

Average Proportion of Missions Completed

Table 21 shows that the adjusted- R^2 for this model is approximately 0.987, indicating that a majority of the variance is explained by the interaction model. As with the other interaction model describing the average proportion of aircraft that are mission capable, Table 20 shows that the variance inflation factors are extremely high, indicating that there is strong multicollinearity present in the model. Thus, the parameter estimates are strongly influenced by the other terms in the model. The variance of the residuals from the predictions remain relatively constant for the

whole model as shown in Figure 36. Table 22 shows the Durbin-Watson statistic for this model is approximately 1.92, which indicates that there is essentially no autocorrelation since a Durbin-Watson statistic of 2 indicates that there is no autocorrelation for this model. Although Figure 35 shows that the residuals for this model are symmetric, there is a steep isolated peak in the center of the distribution. This is probably a result of the fact that a majority of the tests were able to complete each of its missions, as shown in Figure 37. The distribution in Figure 37 may be a result of basing the input ranges on discussions from the Air Force personnel since the Air Force probably operates in a way that allows it to complete its missions and since the MTBF was generally dominated by the MTTR in most cases.

The response surfaces created describing the relationship between the input variables and the outputs of the simulation helped to validate that the model is well-behaved and functions as expected. The main effects models helped show that the variables affected the outputs of the simulation as expected. The interaction models showed that the simulation tool is well-behaved. Overall, the meta models were useful for validation of the simulation, but is not useful for real-world application since the air tasking order varies aircraft use by day in the real-world.

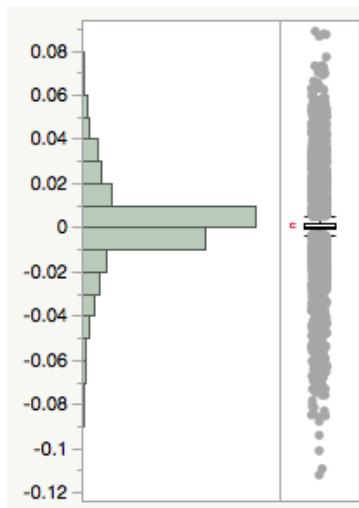


Figure 35: Residuals Response Surface (Average Proportion of Missions Flown)

Term	Estimate	Std Error	t Ratio	Prob> t	VIF
Intercept	-737.9662	31.30954	-23.57	<.0001*	.
Aircrafts Per Wing	34.465434	1.471572	23.42	<.0001*	59788367
Duration of each Mission	-6.817815	0.295904	-23.04	<.0001*	2738399.1
MTBF	-0.466082	0.020221	-23.05	<.0001*	533999.05
MTTR	-5.232711	0.225973	-23.16	<.0001*	2419370
Number Of Aircraft Repaired At A Time	13.431113	0.570513	23.54	<.0001*	4278270.9
Engine Spare Stock Capacity	-0.190799	0.008382	-22.76	<.0001*	1428.5541
Engine Resupply Time	13.301765	0.55991	23.76	<.0001*	11774884
Proportion of Failures Engine Failures	-1272.4	54.46875	-23.36	<.0001*	6031796.1
Attrition Rate	-177976.8	7607.48	-23.39	<.0001*	38669448
Missions Per Day	0.6050143	0.026196	23.10	<.0001*	450833.36
(Duration of each Mission-4.7503)*(Duration of each Mission-4.7503)	-184.5465	8.165211	-22.60	<.0001*	6.2224e+9
(Aircrafts Per Wing-21.0303)*(MTBF-29.0012)	-16.6464	0.710074	-23.44	<.0001*	1.1354e+9
(Duration of each Mission-4.7503)*(MTBF-29.0012)	-7.96651	0.333783	-23.87	<.0001*	537574965
(MTBF-29.0012)*(MTBF-29.0012)	-1.166992	0.037201	-31.37	<.0001*	225216242
(Duration of each Mission-4.7503)*(MTTR-6)	188.51524	8.062932	23.38	<.0001*	1.635e+10
(MTTR-6)*(MTTR-6)	150.22687	6.594181	22.78	<.0001*	9.3139e+9
(Aircrafts Per Wing-21.0303)*(Number Of Aircraft Repaired At A Time-3.06061)	544.61817	23.25391	23.42	<.0001*	1.854e+10
(Duration of each Mission-4.7503)*(Number Of Aircraft Repaired At A Time-3.06061)	-119.0182	5.129801	-23.20	<.0001*	994978632
(MTTR-6)*(Engine Spare Stock Capacity-2.51515)	-223.3461	9.557922	-23.37	<.0001*	9.211e+9
(Aircrafts Per Wing-21.0303)*(Engine Resupply Time-10.5152)	341.99997	14.6719	23.31	<.0001*	1.55e+10
(Engine Resupply Time-10.5152)*(Engine Resupply Time-10.5152)	-97.46087	4.528582	-21.52	<.0001*	3.1089e+9
(Aircrafts Per Wing-21.0303)*(Proportion of Failures Engine Failures-0.07515)	-29368.27	1252.513	-23.45	<.0001*	1.035e+10
(Duration of each Mission-4.7503)*(Proportion of Failures Engine Failures-0.07515)	2264.2821	74.15691	30.53	<.0001*	25633625
(MTTR-6)*(Proportion of Failures Engine Failures-0.07515)	-11750.84	518.12	-22.68	<.0001*	3.2187e+9
(Number Of Aircraft Repaired At A Time-3.06061)*(Proportion of Failures Engine Failures-0.07515)	-17231.47	738.1662	-23.34	<.0001*	1.656e+9
(Engine Resupply Time-10.5152)*(Proportion of Failures Engine Failures-0.07515)	42820.402	1825.561	23.46	<.0001*	2.542e+10
(Number Of Aircraft Repaired At A Time-3.06061)*(Attrition Rate-0.00053)	-3470036	148205	-23.41	<.0001*	1.772e+10
(Engine Resupply Time-10.5152)*(Attrition Rate-0.00053)	2243900.3	94626.41	23.71	<.0001*	2.246e+10
(Aircrafts Per Wing-21.0303)*(Missions Per Day-30.0303)	26.174351	1.118545	23.40	<.0001*	2.3524e+9
(Engine Resupply Time-10.5152)*(Missions Per Day-30.0303)	-29.93965	1.247567	-24.00	<.0001*	6.823e+9
(Attrition Rate-0.00053)*(Missions Per Day-30.0303)	-45711.41	1602.415	-28.53	<.0001*	84028492
(Missions Per Day-30.0303)*(Missions Per Day-30.0303)	4.9494351	0.204568	24.19	<.0001*	1.6898e+9

Table 20: Parameter Estimates Response Surface(Average Proportion of Missions Flown)

RSquare	0.987799
RSquare Adj	0.98768
Root Mean Square Error	0.019867
Mean of Response	0.876352
Observations (or Sum Wgts)	3300

Table 21: Summary of Fit Response Surface (Average Proportion of Missions Flown)

Durbin-Watson		
Durbin-Watson	Number of Obs.	AutoCorrelation
1.9253778	3300	0.0373

Table 22: Durbin-Watson Statistic of Average Proportion of Missions Accomplished (Response Surface)

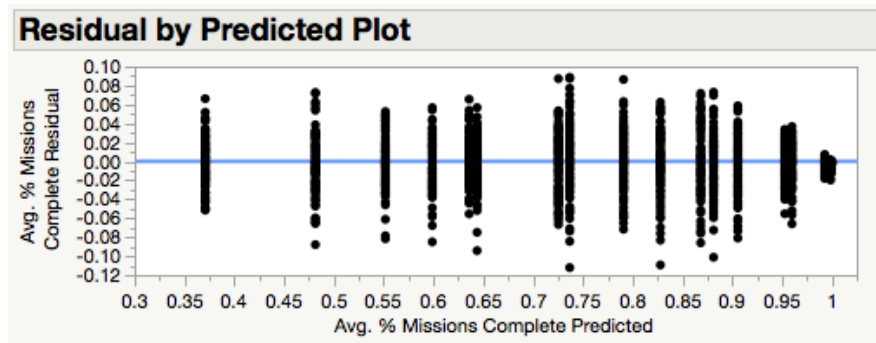


Figure 36: Residuals by Predicted: Average Proportion of Missions Flown (Response Surface)

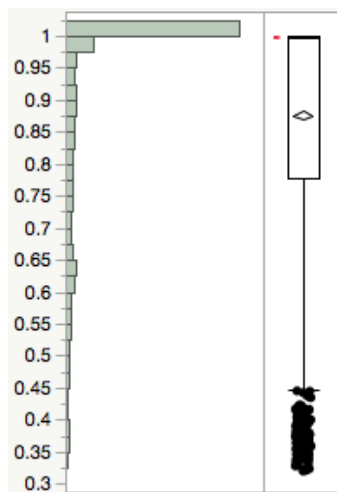


Figure 37: Distribution of Average Proportion of Missions Flown (Response Surface Metamodel)

Table 23: Ranges of Inputs for Testing

Input	Minimum	Maximum	Unit	Description
Attrition Rate	0.00005	0.001	Proportion	Proportion of missions that result in attrition, both accidental and shot down.
Aircraft per Squadron	18	24	Quantity	The number of aircraft in the squadron.
Number of Missions per Day	15	45	Quantity	The total number of mission each day. Each inputted as a separate mission.
Duration of Each Mission	1.5	8	Hours	The duration of each mission.
MTBF	8	50	Hours	The Mean Time Before Failure based on flight hours.
MTTR	2	10	Hours	The Mean Time to Repair a damaged aircraft.
Number of Simultaneous Repairs	1	5	Quantity	The number of damaged aircraft that can be repaired simultaneously.
Engine Safety Stock	0	5	Quantity	The quantity of slots that can hold spare engines.
Engine Resupply Time	7	14	Days	The time required to fix/replace a spare engine.
Proportion of Failures that are Engine Failures	0.05	0.1	Proportion	The proportion of failures that are engine failures.

4.3 Checking the Signs of the Main-Effect Models' Parameter Estimates

The purpose of this section is to check if the signs of the parameter estimates of the main-effects models provide the correct insight into scenarios even though the main-effects models appear to violate some linear regression assumptions. This will be done by exploring a variety of scenarios and compare them to a common baseline scenario. This baseline scenario is defined in Table 24.

Property	Baseline Value
Number of Aircraft	24
Number of Daily Missions Scheduled	35
Duration of Each Mission	4 hours
Probability of Attrition of Each Mission	0.001
Types of Failures	<i>Engine: Proportion of Failures – 0.08, Time Required to Replace Spare – 12 Days, Number of Spares – 5</i> <i>Other: Proportion of Failures – 0.92, Time Required to Replace Spare – 3 Days, Number of Spares – 5</i>
MTTR	3 hours
Maximum Number of Simultaneous Repairs	1
MTBF	45 hours
Major Events	None

Table 24: Baseline Scenario for Checking Main-Effects Parameter Estimates

The scenarios that will be investigated will look into the effect of changing a single input on the outputs of the average proportion of aircraft that are mission capable and the average proportion of missions that are accomplished; these scenarios are described in Table 25.

Each of the scenarios and the baseline scenario will be run for 50 days with 20 replications. The plots of the output data will show the average of the replications and the 95% confidence intervals. In order to compare the scenarios to the baseline, the averages of both the scenarios and the baseline will be displayed in the same plot. Additionally, each scenario will be added to the plot without removing the previous scenarios to show how the scenarios compared to one another. The outputs of the baseline scenario for the investigation are shown in Figure 38 and Figure 39 for the

Scenario	Focus	Description
1	Quantity of Missions	Increase the quantity of missions for a short period of time and slowly decrease the quantity
2	Attrition Rates	Vary the attrition rate of the missions.
3	Reinforcements	Fly aircraft from one base to another base to assist in the mission requirements.
4	Repair Rate	Decrease the repair rate at some point during the simulation.
5	Failure Rate	Increase the rate of part failures at some point during the simulation.
6	Damage/Destroy Grounded Aircraft	Damage and destroy randomly selected aircraft located at a base.
7	Effect of Spares	Vary the number of spares that are stored on-site. Observe the effect of the quantity of spares in the event of a logistical cutoff.

Table 25: Scenarios to Compare to Baseline

average proportion of aircraft that are mission capable and the average proportion of missions accomplished respectively. The overall average of the outputs of each of the scenarios are calculated to be used as a reference to compare against the outputs of the scenarios. The overall average of the average proportion of aircraft that are mission capable is approximately 0.803 and the overall average proportion of missions accomplished is 1.000. This reflects that all of the missions are accomplished in the baseline scenario.

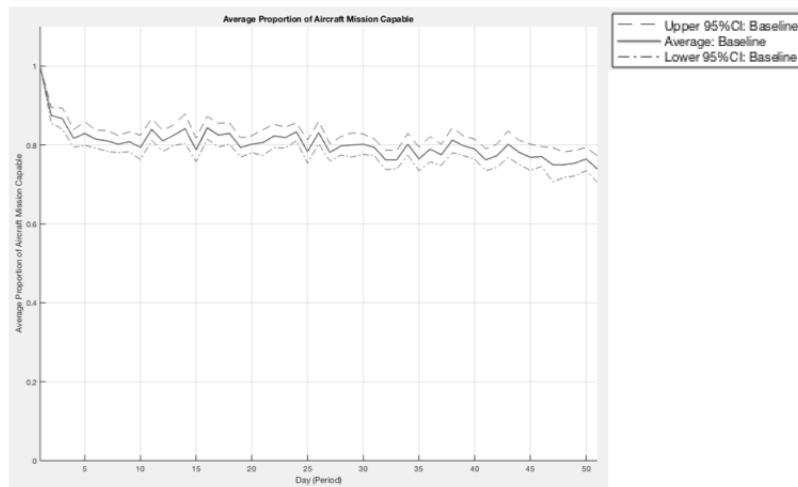


Figure 38: Average Proportion of Aircraft That are Mission Capable: Baseline Scenario

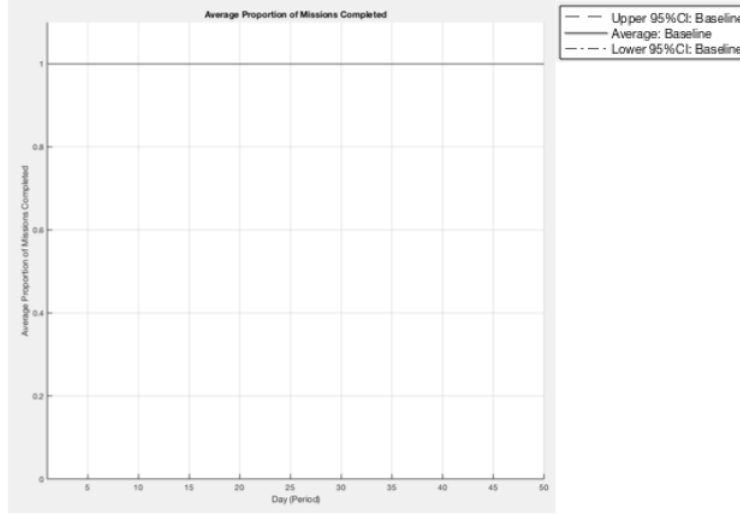


Figure 39: Average Proportion of Missions Accomplished: Baseline Scenario

The first scenario investigates the effect of changing the quantity of daily missions. On day 10 of the simulation, the number of daily missions is increased from 35 missions to 65 missions; on day 25, the number of daily missions is decreased from 65 missions to 50 missions; and on day 35, the number of daily missions decreases from 50 back to 35 missions. The average proportion of aircraft that are mission capable for this scenario is shown in red in Figure 40. The overall average for the average proportion of aircraft that are mission capable for this scenario investigating the quantity of missions is approximately 0.697; this shows that the average proportion of aircraft that are mission capable decreases with an increase in the quantity of missions. This change matches the sign of the parameter estimate of the main effects model for the input of the quantity of daily missions since the parameter estimate is negative. Similarly, the overall average of the average proportion of missions accomplished is approximately 0.973, which is less than the baseline average; this change is consistent with the sign of the parameter estimate for this input. The effect of increasing the quantity of daily missions on the average proportion of missions accomplished is shown in red in Figure 41.

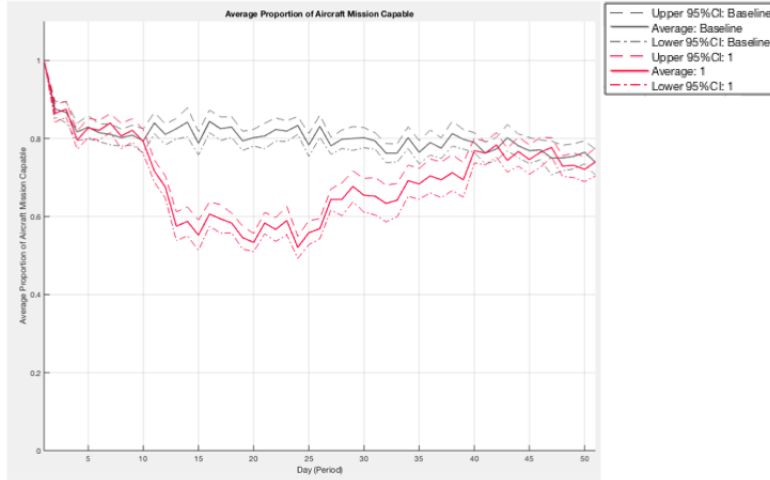


Figure 40: Scenario 1 - Quantity of Missions: Average Proportion of Aircraft that are Mission Capable

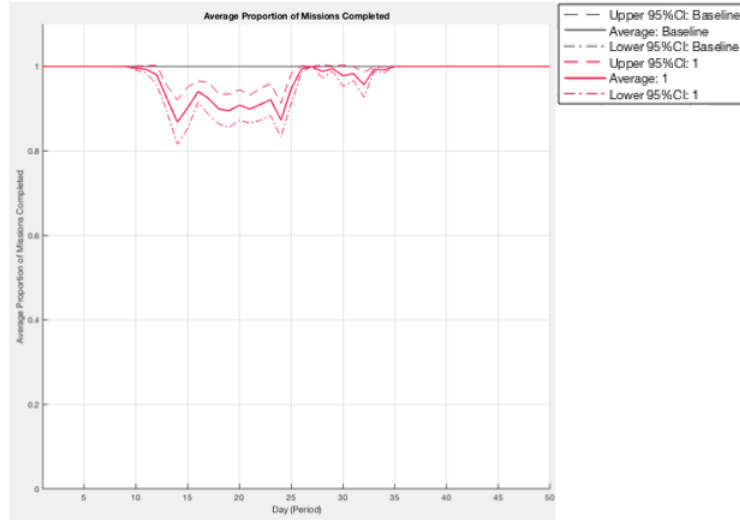


Figure 41: Scenario 1 - Quantity of Missions: Average Proportion of Missions Accomplished

The second scenario investigates the effect of increasing the attrition rate of each mission from 0.001 to 0.01. The average proportion of aircraft that are mission capable of this scenario is shown in pink in Figure 42; the overall average is approximately 0.505. This shows that as the attrition rate increases, the average proportion of aircraft that are mission capable decreases. This change is consistent with the sign of the parameter estimate of attrition rate of the main-effects model for the average

proportion of aircraft that are mission capable. The average proportion of missions accomplished of this scenario is shown in pink in Figure 43; the overall average for the average proportion of missions accomplished is 0.920. This reduction in the average proportion of missions accomplished as a result of an increase in the attrition rate is consistent with the sign of the parameter estimate of the input of attrition rate in the main-effects model for the average proportion of missions accomplished.

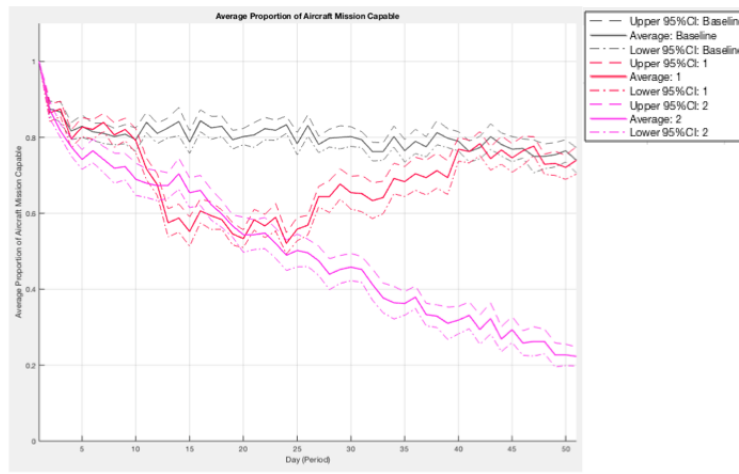


Figure 42: Scenario 2 - Attrition Rate: Average Proportion of Aircraft that are Mission Capable

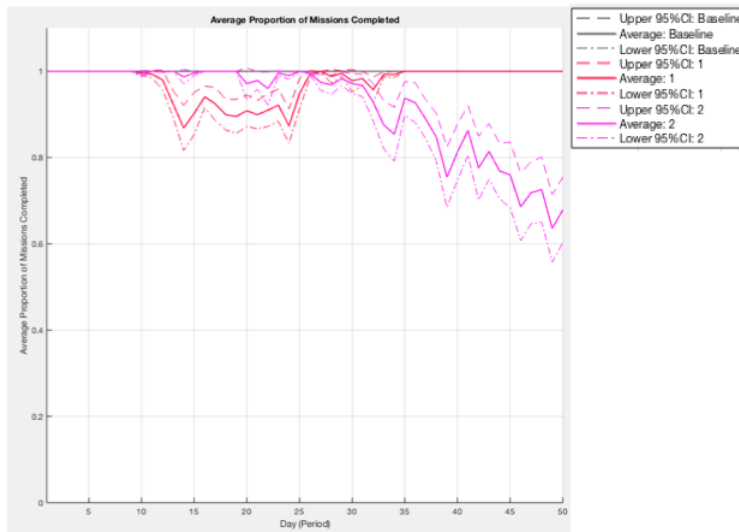


Figure 43: Scenario 2 - Attrition Rate: Average Proportion of Missions Accomplished

The third scenario investigates the effect of increasing the quantity of aircraft that are at the base. On day 10 of the simulation, 10 aircraft are flown to the base to increase the number of aircraft that are able to fly missions. This scenario is shown in purple in Figure 44 and Figure 45 for the average proportion of aircraft that are mission capable and the average proportion of missions accomplished respectively. The overall average for the average proportion of aircraft that are mission capable for this scenario is approximately 0.849 and the overall average for the average proportion of missions accomplished is 1.000.

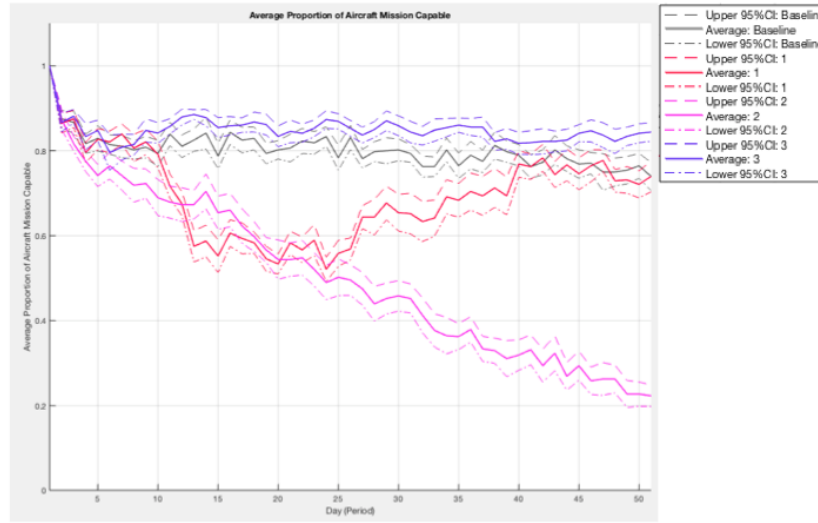


Figure 44: Scenario 3 - Reinforcements: Average Proportion of Aircraft that are Mission Capable

The increase in the average of the average proportion of aircraft that are mission capable is consistent with the sign of the parameter estimate of the input of aircraft per wing; however, there is no change in the overall average proportion of missions accomplished. The reason there was no increase in the average proportion of missions accomplished is because the quantity of aircraft in the baseline scenario was able to accomplish all of the scheduled missions; any additional aircraft added to the base would not increase the number of missions accomplished in this scenario because all of

the missions are already being accomplished. Thus, although there was no change in the overall average proportion of missions accomplished, the signs of the input factor for the aircraft per wing are consistent with the outputs obtained in this scenario.

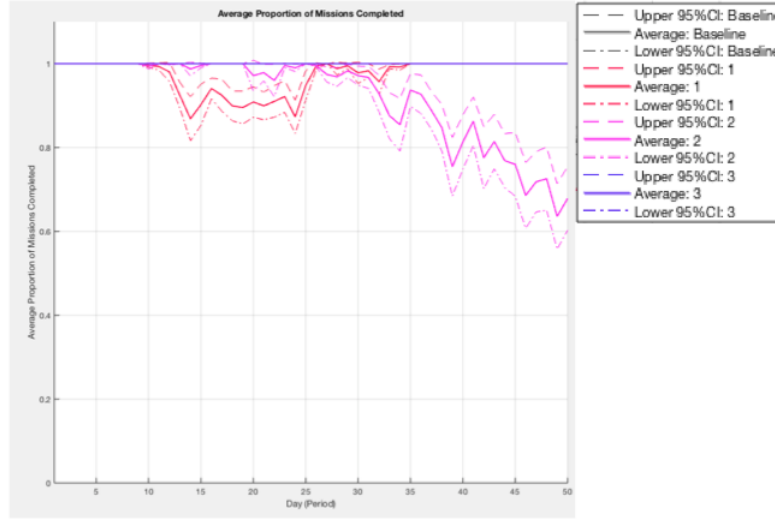


Figure 45: Scenario 3 - Reinforcements: Average Proportion of Missions Accomplished

The fourth scenario investigates the effect of reducing the repair rate. This is done by increasing the MTTR from 3 hours to 10 hours on day 10. The effect of this scenario is shown in blue in Figure 46 and Figure 47 for the average proportion of aircraft that are mission capable and the average proportion of missions accomplished respectively. The overall average proportion of aircraft that are mission capable is approximately 0.509 and the overage average proportion of missions accomplished is approximately 0.884. Both of these averages are smaller than the baseline averages; this shows that increasing the MTTR has a negative impact on the average proportion of aircraft that are mission capable and the average proportion of missions accomplished. These differences are consistent with the signs of the parameter estimates of MTTR for the main-effects models for the average proportion of aircraft that are mission capable and the average proportion of missions accomplished.

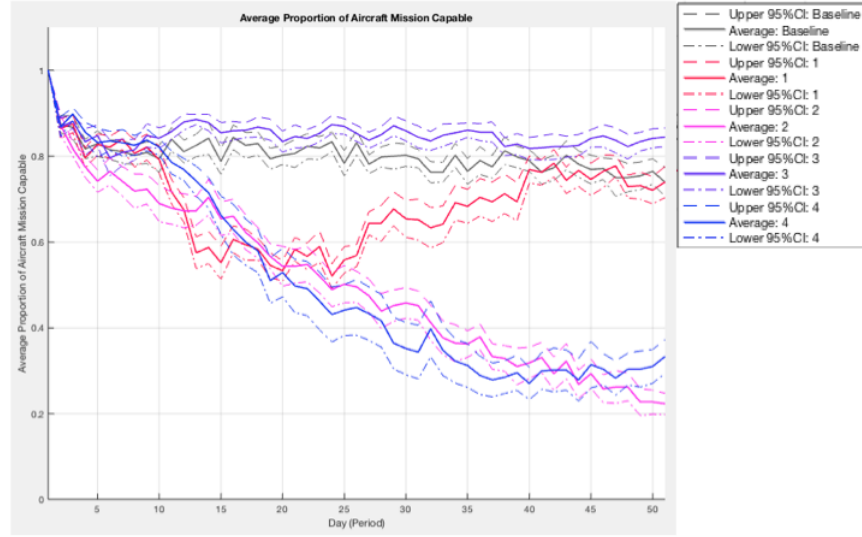


Figure 46: Scenario 4 - Repair Rate: Average Proportion of Aircraft that are Mission Capable

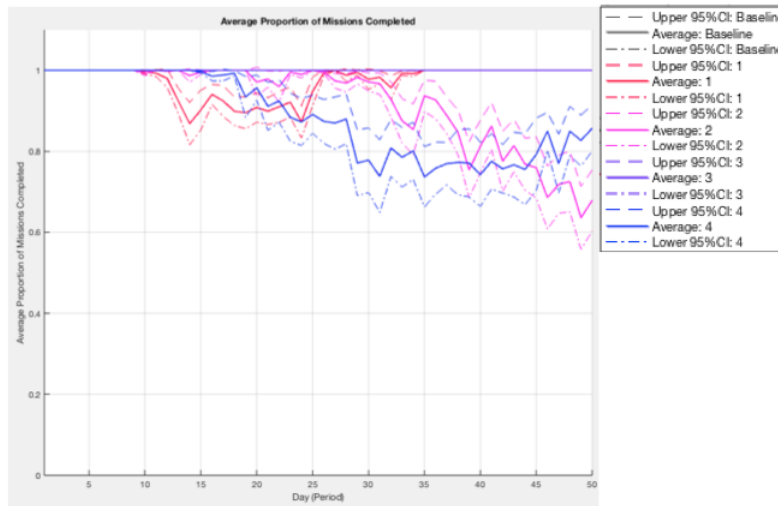


Figure 47: Scenario 4 - Reinforcements: Average Proportion of Missions Accomplished

The fifth scenario investigates the effect of increasing the failure rate of aircraft. The failure rate is increased by decreasing the MTBF from 45 hours to 25 hours on day 10. The effect of changing the MTBF is shown as the light blue in Figure 48 and Figure 49 for the average proportion of aircraft that are mission capable and the average proportion of missions accomplished respectively. The overall average

proportion of aircraft that are mission capable is approximately 0.610 and the overall average proportion of missions accomplished is approximately 0.982. Since both of the averages of the outputs for this scenario are less than the baseline average, the sign of the MTBF input parameter estimates of both the main-effects models for the average proportion of aircraft that are mission capable and the average proportion of missions accomplished are consistent with the change observed in this scenario.

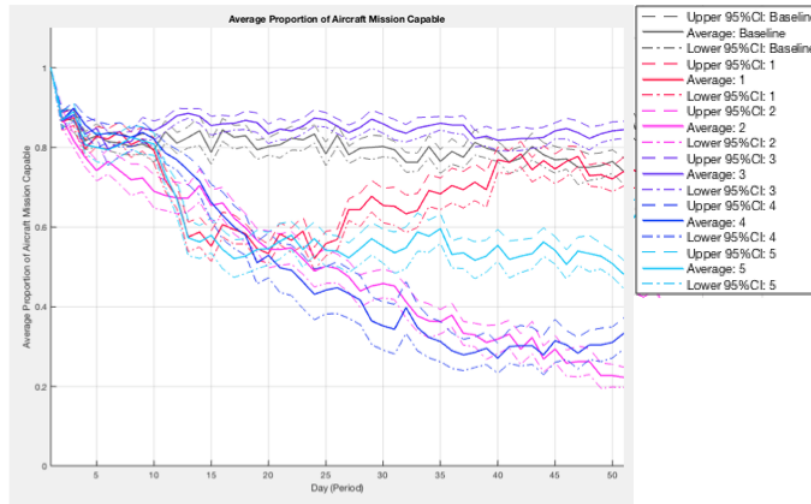


Figure 48: Scenario 5 - Failure Rate: Average Proportion of Aircraft that are Mission Capable

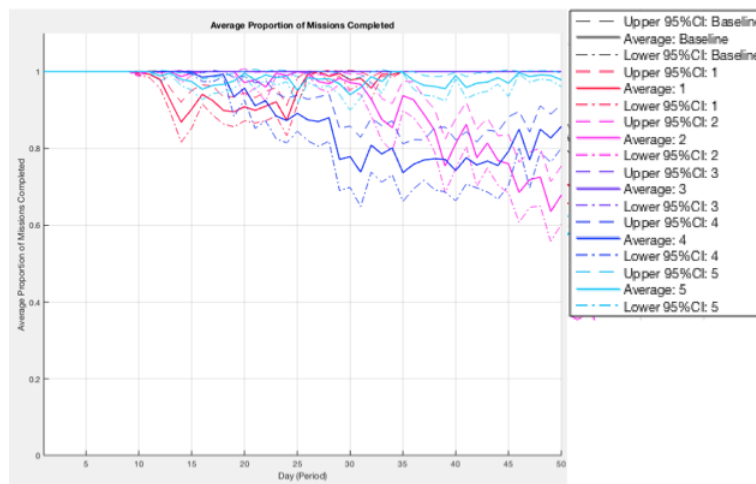


Figure 49: Scenario 5 - Failure Rate: Average Proportion of Missions Accomplished

The sixth scenario re-investigates the effect of changing the number of aircraft that are at the base; however, a major event representing an attack on the base will be used to change the number of aircraft that are at the base. On day 15, 15 aircraft will be damaged and 2 aircraft will be destroyed; thus, the number of aircraft that are at the base will decrease. The green line shows the effect of destroying and damaging aircraft in Figure 50 and Figure 51 for the average proportion of aircraft that are mission capable and the average proportion of missions accomplished respectively. The overall average proportion of aircraft that are missions capable for this scenario is approximately 0.717 and the overall average proportion of missions accomplished is approximately 0.993. Since the changes in the average outputs for both the average proportion of aircraft that are mission capable and the average proportion of missions accomplished compared to the baseline have decreased, the effect of changing the number of aircraft that are at the base on the outputs observed is consistent with the sign of the parameter estimates of the main effect models for the input of the number of aircraft per wing.

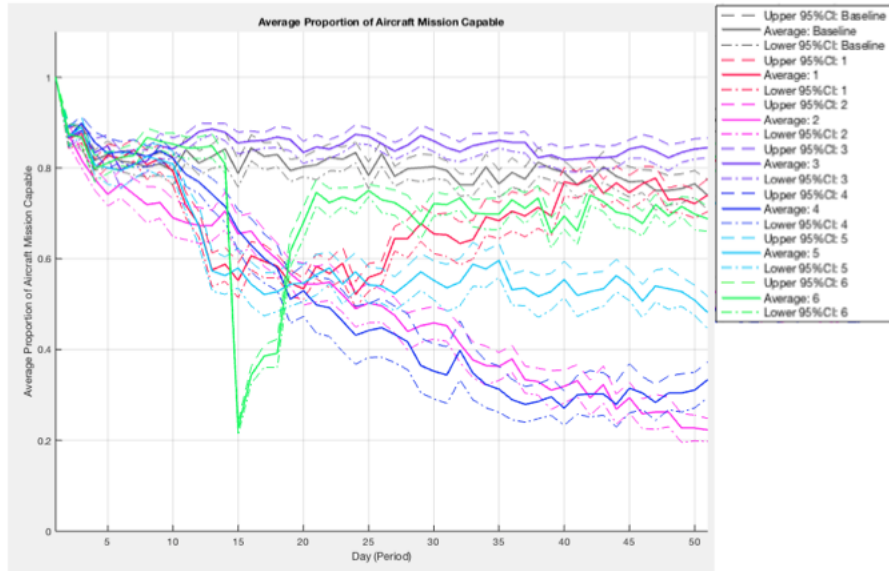


Figure 50: Scenario 6 - Damage/Destroy Aircraft: Average Proportion of Aircraft that are Mission Capable

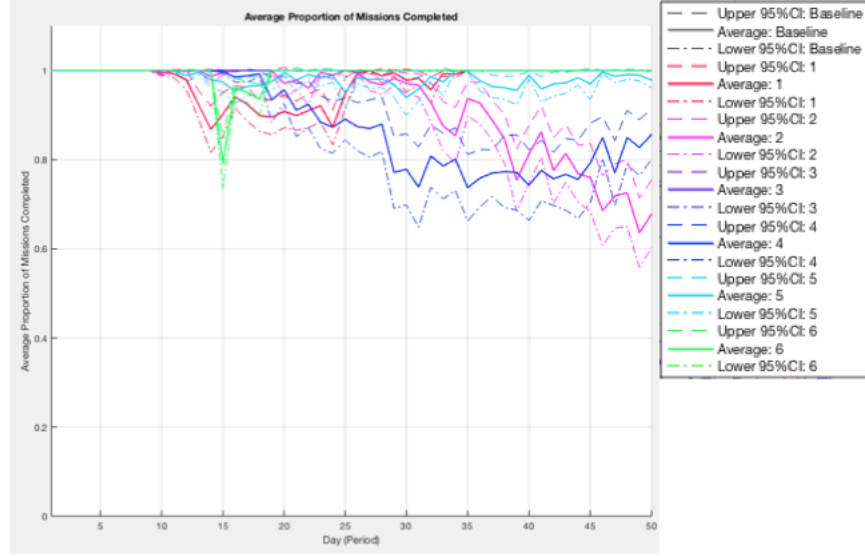


Figure 51: Scenario 6 - Damage/Destroy Aircraft: Average Proportion of Missions Accomplished

The seventh scenario investigates the effect of changing the number of spares that are kept on-site from 5 of each spare to 0 of each spare. The effect of removing spares from the baseline scenario is shown in orange in Figure 52 and Figure 53 for the average proportion of aircraft that are mission capable and the average proportion of missions accomplished respectively. The overall average proportion of aircraft that are mission capable decreased to approximately 0.556 from the baseline; the overall average proportion of missions accomplished decreased to approximately 0.988 from the baseline average of 1.000. The signs of the parameter estimates for the effect of the number of spares in the main-effect models for the average proportion of aircraft that are mission capable and the average proportion of missions accomplished are consistent with the observed impacts in this scenario.

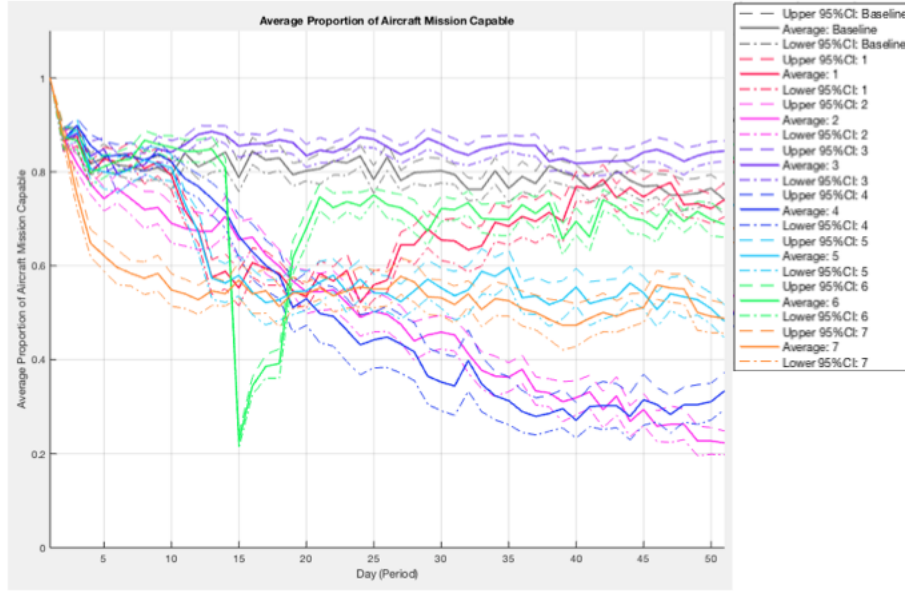


Figure 52: Scenario 7 - Effect of Spares: Average Proportion of Aircraft that are Mission Capable

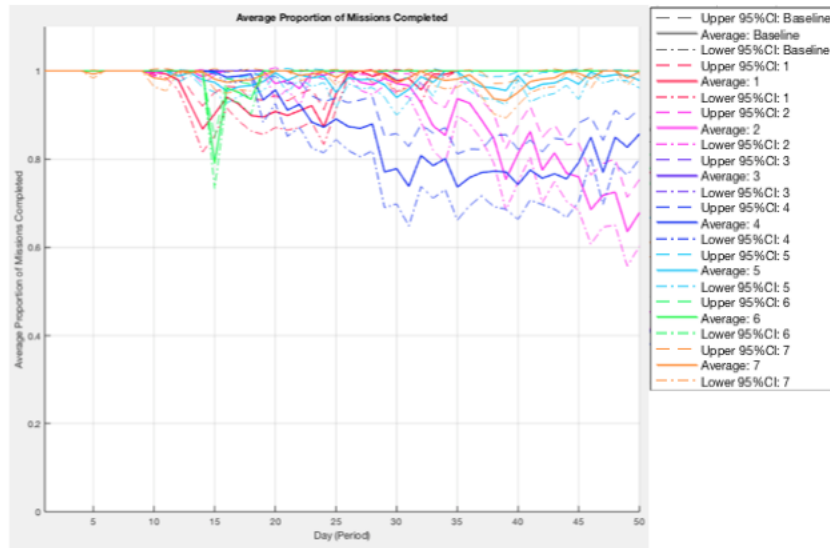


Figure 53: Scenario 7 - Effect of Spares: Average Proportion of Missions Accomplished

Table 26 gives a summary comparing the sign of the coefficients of the main-effect models to the impact of the changes to the inputs of the baseline scenario. The table shows that the impact of each of the inputs observed in the investigations of each scenario matched the sign of the coefficient of each of the main-effects models.

This shows that even though some of the linear regression assumptions appeared to be violated in the main-effect models for the average proportion of aircraft that are mission capable and the average proportion of missions accomplished, the main-effect models were still able to provide appropriate insight into how the inputs affected the outputs of the simulation. Since the signs of the parameter estimates of the main-effect models matched the intuitive positive or negative value and since the coefficient analysis showed that the main-effects models did produce parameter estimates that had positive or negative signs that matched the impact of the inputs observed in the scenario investigation, the main-effects models are believed to be able to be used to validate the behavior of the model.

	Average Proportion of Aircraft Mission Capable		Average Proportion of Missions Accomplished	
Factor	Sign of Main Effects	Scenario Observation	Sign of Main Effects	Scenario Observation
Number of Missions	-	-	-	-
Attrition Rate	-	-	-	-
Number of Aircraft	+	+	+	+
MTTR	-	-	-	-
MTBF	+	+	+	+
Damage/Destroy Grounded Aircraft	N/A	-	N/A	-
Spares	+	+	+	+

Table 26: Coefficient Analysis: Summary of the Comparison of the Scenarios to the Baseline

4.4 Analysis of MTBF Inequality

Previously, Equation (23) was derived to determine the minimum MTBF required to ensure that the expected number of failures in a period did not exceed the expected number of repairs in a period for a specific set of inputs to the simulation. Using this inequality, an equation is produced that relates the inputs to one other such that the expected number of failures in a period is the same as the expected number of repairs in a period, as shown in Equation (26). Since the original inequality that was derived focused on the MTBF input variable so that an appropriate input space for the validation experiment could be used, this section will explore the predictability of the average aircraft availability using the MTBF as the dependent variable, given that all other inputs are known, to show whether or not the approach to determine a lower MTBF range was appropriate.

$$MTBF = \frac{-D}{\ln \left(1 - \frac{E(R)}{\min(A, M)} \right)} \quad (26)$$

This equation can be used to determine the inputs to the simulation that will maintain a specified average aircraft availability. The example that will demonstrate the capability of this equation in this section will be the task to determine the lower boundary of the input range of the MTBF that was used to create the experiments to validate the behavior of the simulation. The other inputs, which will be held constant, will be the combination of inputs that yield the worst-case scenario of the experimental design used to validate the behavior of ENIGMA. This worst-case scenario combination within the input ranges identified in Table 23 would be 18 total aircraft in the simulation, 45 daily missions, a MTTR of 10 hours, a maximum of 1 aircraft that can be repaired at any given time, and a mission duration of 8 hours each mission. Setting the input of the number of missions to 45 will ensure that

each mission capable aircraft will fly a sortie each period because the number of mission capable aircraft in the system will never exceed 45 aircraft in this scenario. Equation (26) was based on the assumption that each aircraft can fly a maximum of one sortie each period; thus, excess missions will not be flown. Additionally, since attrition rate is not accounted for in the development of Equation (26), the attrition rate of each mission will be set to 0 to ensure that attrition does not occur. Figure 54 illustrates how changing the MTBF affects the expected number of aircraft availability for the defined worst-case scenario described above.

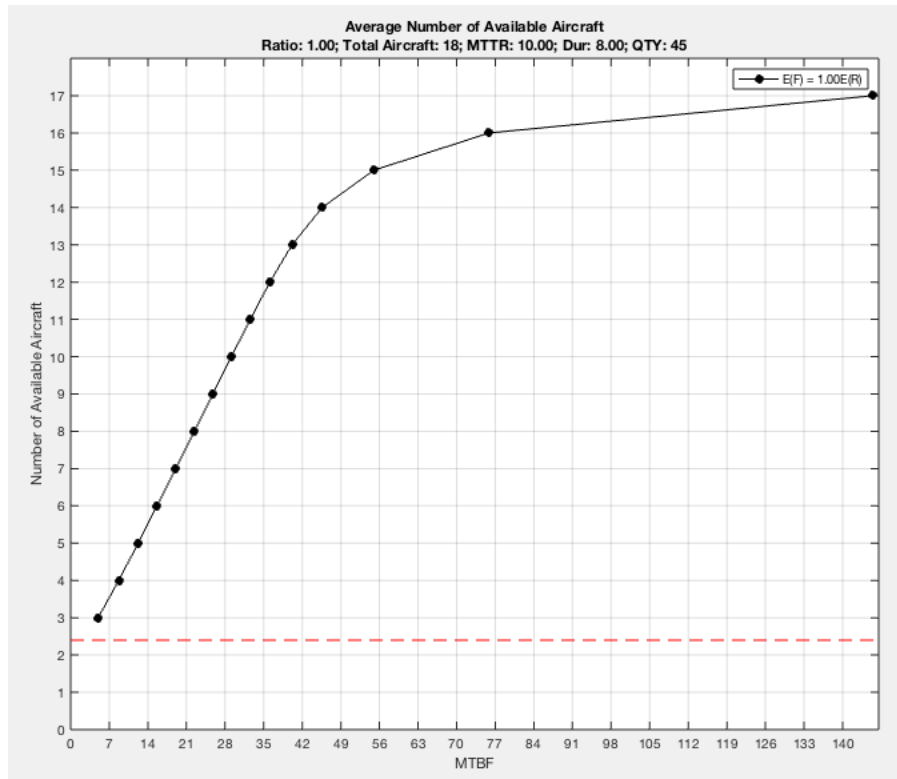


Figure 54: Plotting $E(F) = E(R)$ to relate MTBF to Average Aircraft Availability

Figure 54 shows the predicted relationships between the MTBF and the average aircraft availability for the worst-case scenario described above. The dashed red line is the lower bound for average available aircraft in this scenario. This boundary occurs because the rate of repair is able to maintain a certain average aircraft availability

even if an aircraft is guaranteed to have a part failure each mission. In this case, Figure 54 has a red dashed line is above 2 aircraft, which means that there are no MTBF values that will be able to maintain an average aircraft availability of 2 or less for this scenario.

This scenario was run on each of the possible MTBF values that was predicted to maintain an integer level of average aircraft availability. The input files were created to satisfy the assumptions used to develop Equation (26). There were 50 replications for each test, each running for 100 periods (days) with a 20 period (day) warm-up period to remove the initialization bias. The output data obtained was the average aircraft availability throughout each replication. Figure 55 shows the box plots of each of the outputs of each run on top of the predicted average aircraft availability. The boxplot levels are the 25% percentile, the median, the 75%, and the whiskers that indicate the farthest point within 1.5 times the inter-quartile length from the quartiles.

In this particular plot, the predicted average aircraft availability appears to deviate from the experimental outputs; however, since the predictions are very close to the recorded outputs for the lower average aircraft availability, the deviation was not a concern for determining the lower boundary of the MTBF range for the experiment used to validate the model. Additionally, although the predicted values deviate from the outputs, this example anecdotally supports the idea that Equation (26) *may* be used to predict the average aircraft availability in a simulation when the inputs satisfy the assumptions used to derive Equation (26) because the predicted values were within the whiskers of each of the boxplots. However, further testing must be done before Equation (26) is used for such predictions of other scenarios because the deviation shows that the equation does not perfectly represent the output of the simulation.

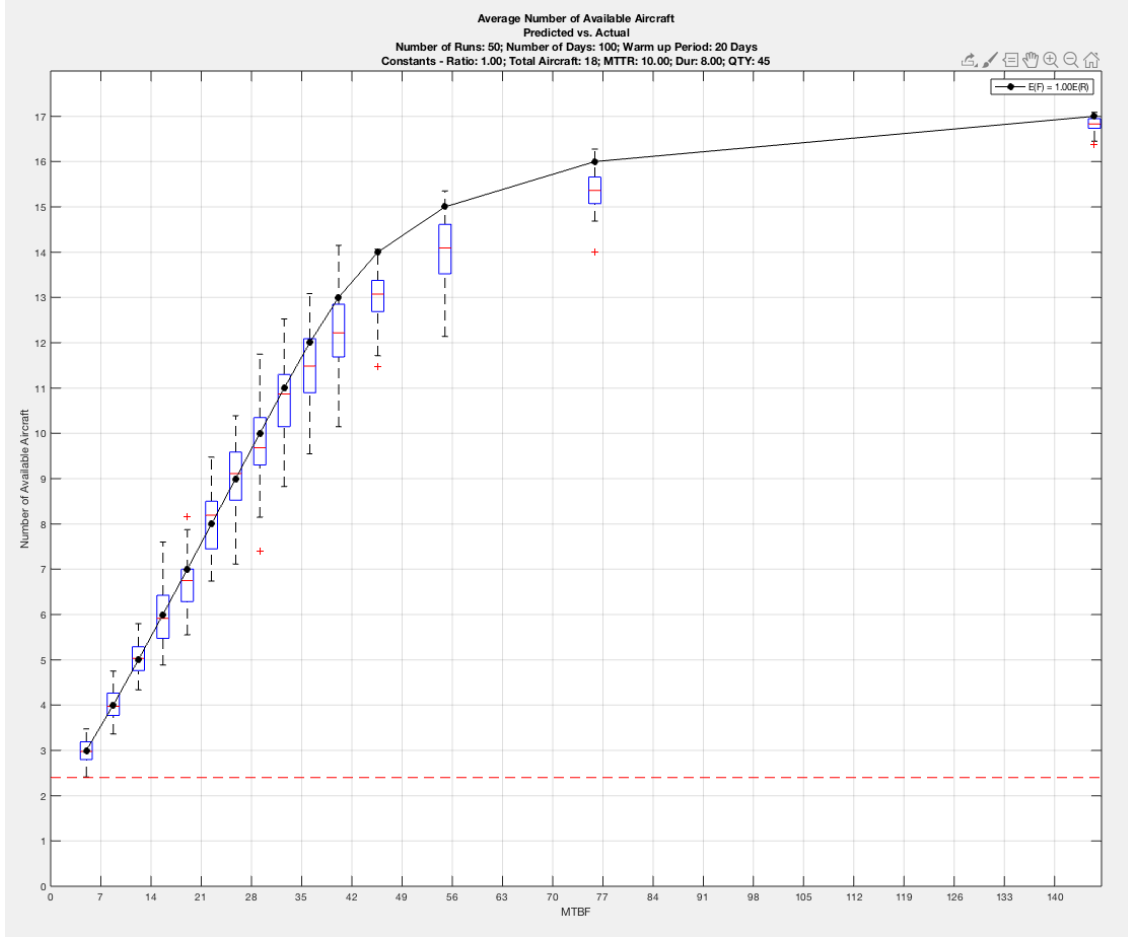


Figure 55: Testing Varying Levels of MTBF

4.5 Operational Testing: A Few Examples

This section will demonstrate examples of possible operational scenarios that the user can model using ENIGMA. The seven scenarios that were chosen as examples will show the effect of changing operational environments on the average aircraft availability and the number of missions accomplished throughout the simulation. Each scenario is run for 50 days in the simulation with 25 replications. Each scenario explores changing a selected parameter to demonstrate its effect on the aircraft availability and number of missions accomplished in the specific operational scenario. The different baseline and excursions of each scenario are deliberately chosen to demon-

strate the effect of changing input parameters. Each of the individual excursions follow the same inputs as the baseline scenario, except for the specified parameter being explored. In each scenario, it is assumed that aircraft are able to fly multiple missions in a single period and each mission requires a single aircraft. Each scenario will produce two plots: one displaying the average aircraft availability and the other displaying the average number of sorties flown throughout the operational scenario. The plots also display the 95% confidence intervals of the mean for the outputs to emphasize the change in the outputs. To save space in the plots, the term *Excursion* will be replaced by the term *Test* in each of the output plots for all operational scenario examples being explored.

4.5.1 Scenario 1: Number of Missions

In this scenario, the effects of changing the number of missions that are scheduled each day is demonstrated. This scenario is shown because the user is able to select when and how many missions occur; thus, it may be interesting to observe the effect of the number of missions on the average aircraft availability and the average number of missions flown.

Baseline Scenario and Excursions

Table 27 shows the parameter values of the inputs that define the baseline scenario. Table 28 identifies the changes to the baseline that are done to demonstrate the effects of changing the number of missions during the operational scenario. The baseline scenario has a stationary 24 missions each period. Excursion 1 increases the number of daily missions from 24 to 35 on day 10 and then decreases the number of daily missions from 35 back to 24 on day 25. Excursion 2 increases the number of daily missions from 24 to 50 on day 10, then decreases the number of daily missions from 50 to 35 on day 25, and then decreases the number of daily missions from 35 back to

24 on day 35. Excursion 3 increases the number of daily missions from 24 to 75 on day 10, then decreases the number of daily missions from 75 to 50 on day 25, then decreases the number of daily missions from 50 to 35 on day 25, and then decreases the number of daily missions from 35 back to 25 on day 40.

Table 27: Baseline Properties Scenario 1

Property	Value
Number of Aircraft at this Base	24
Number of Single Aircraft Missions Each Day	24
Duration of Each Mission	4 hours
Attrition Rate of Each Mission	0.001
Types of Failures	Engine: - Proportion of Failures: 0.08 -Number of Spares: 0 -Time to replace Spare: 12 Days Other: -Proportion of Failures: 0.92 -Number of Spares: 0 -Time to replace Spare: 3 Days
MTTR	7 hours
Maximum Number of Simultaneous Repairs	4
MTBF	45 hours
Major Events	None

Table 28: Scenario 1 Excursion

Day of Event	Excursion 1	Excursion 2	Excursion 3
10	Increase number of daily missions to 35	Increase number of daily missions to 50	Increase number of daily missions to 75
25	Decrease number of daily missions to 24	Decrease number of daily missions to 35	Decrease number of daily missions to 50
35	N/A	Decrease number of daily missions to 24	Decrease number of daily missions to 35
40	N/A	N/A	Decrease number of daily missions to 24

Results

Figure 56 and Figure 57 show the averages and the 95% confidence intervals of the mean of the aircraft availability and the number of sorties flown throughout scenario 1. As noted in Table 28, the number of missions are increased to a larger number in each excursion. Figure 57 shows that when the quantity of missions increased, the number of sorties flown also increased; however, the demonstration does show that there is a limit to the number of sorties that can be flown in a single period. As the number of missions each period increases from 24 daily missions to 35 daily missions in excursion 1, the quantity of aircraft are able to successfully handle all of the additional sorties even with the decrease in aircraft availability shown in Figure 56.

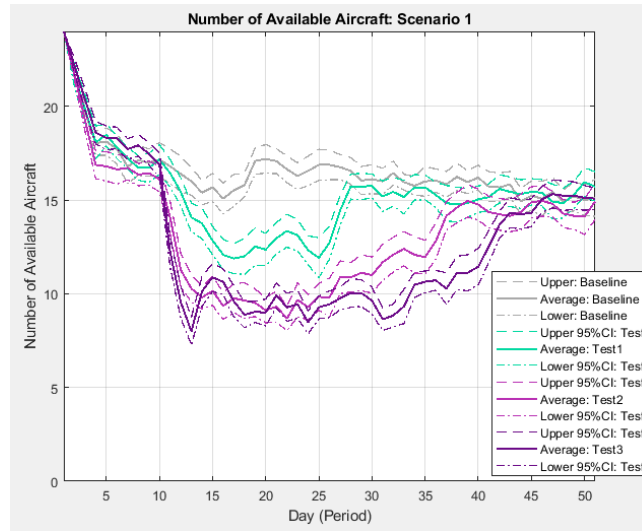


Figure 56: Scenario 1 Excursions: Aircraft Availability

In contrast, both excursion 2 and excursion 3 show that the aircraft are able to handle the increased number of missions for the first day, but are not able to sustain the high number of missions since the aircraft availability was too low to complete the additional number of sorties. This limit to the number of sorties that can be flown is the cause of these two excursions maintaining the same aircraft availability and number of missions accomplished between days 10 to 25. The quantity of avail-

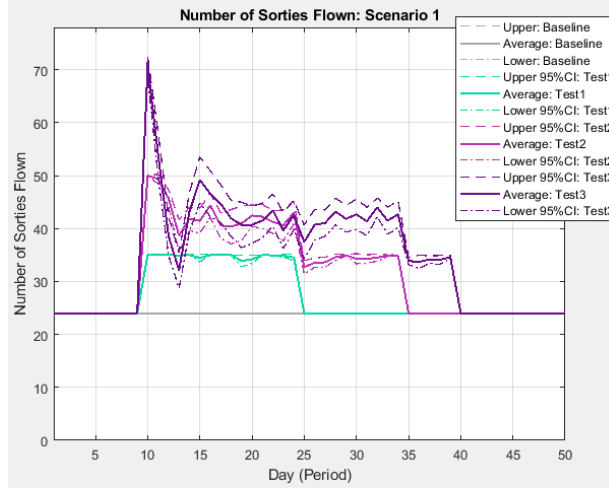


Figure 57: Scenario 1 Excursions: Sorties Flown

able aircraft are able to fly a limited number of missions in a single day because the simulation accounts for the duration of each mission. Overall, the scenario demonstrates that increasing the number of missions will decrease the aircraft availability and increase the number of sorties flown while there is enough aircraft and time to fly all of the missions.

4.5.2 Scenario 2: Attrition Rates

Each mission has a specified attrition rate that indicates the probability that an aircraft will no longer be usable for the remainder of the simulation. These excursions run the same mission sequence as the baseline, except that the attrition rate of each mission will be different for each excursion. The purpose of these excursions is to observe the effect of large attrition rates.

Baseline and Excursions

Table 29 shows the inputs of the baseline scenario. Table 30 identifies the changes to the baseline to demonstrate the effects of changing attrition rates of each mission. The excursions are chosen to demonstrate the effect of increasing the attrition rate of each mission in the operational scenario. Each mission of the baseline has an attrition

rate of 0.001; each mission of excursion 1 has an attrition rate of 0.01; each mission of excursion 2 has an attrition rate of 0.03; and each mission of excursion 3 has an attrition rate of 0.1.

Table 29: Baseline Properties Scenario 2

Property	Value
Number of Aircraft at this Base	24
Number of Single Aircraft Missions Each Day	35
Duration of Each Mission	4 hours
Attrition Rate of Each Mission	0.001
Types of Failures	Engine: - Proportion of Failures: 0.08 -Number of Spares: 0 -Time to replace Spare: 12 Days Other: -Proportion of Failures: 0.92 -Number of Spares: 0 -Time to replace Spare: 3 Days
MTTR	7 hours
Maximum Number of Simultaneous Repairs	4
MTBF	45 hours
Major Events	None

Table 30: Scenario 2 Excursions

Change	Excursion 1	Excursion 2	Excursion 3
Set attrition rate to:	0.01	0.03	0.1

Results

Figure 58 and Figure 59 show the effects of increasing the attrition rate of each mission. Figure 58 clearly shows that the rate of aircraft loss increases as the attrition rate increases; consequently, the number of sorties flown decreases as a result of decreases in the number of mission capable aircraft. The slope of the decrease of the aircraft availability becomes less steep over time because less missions are able to be

flown with fewer mission capable aircraft, which reduces the total number of possible failures and aircraft losses each period.

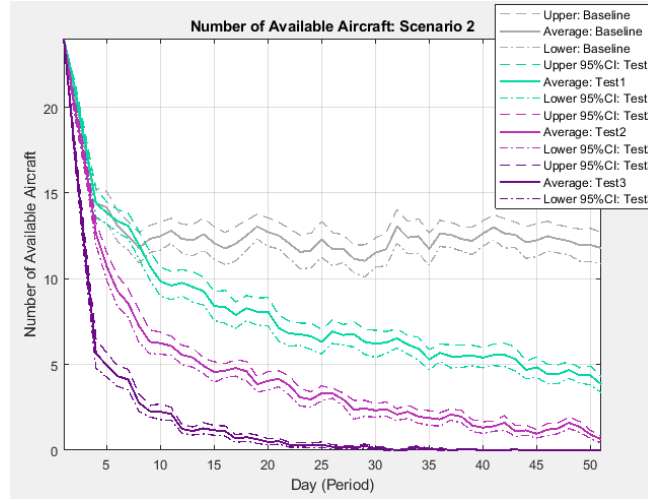


Figure 58: Scenario 2 Excursions: Aircraft Availability

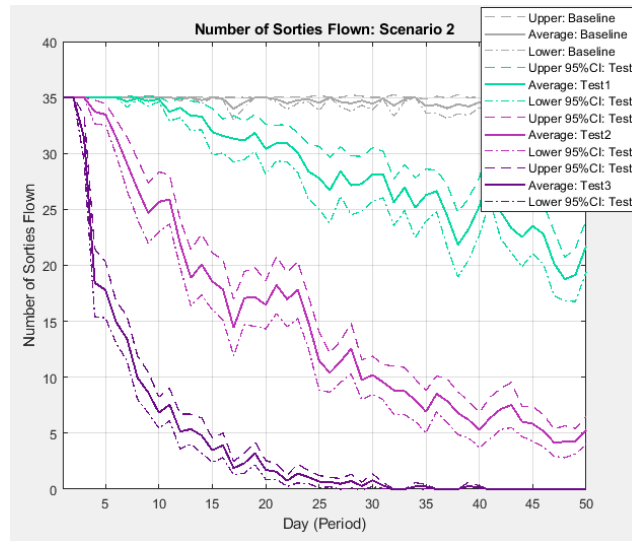


Figure 59: Scenario 2 Excursions: Sorties Flown

4.5.3 Scenario 3: Flying Aircraft to Another Base

Aircraft are able to fly from one base to another base in ENIGMA. This scenario demonstrates the effect of flying a variety of number of aircraft from one base to another base. One of the bases in this scenario will be flying missions that have high attrition rates; thus, the average aircraft availability at the base will quickly decrease. The excursions will demonstrate the effect of increasing the number of aircraft that are flown from one base to another base experiencing a high level of attrition.

Baseline and Excursions

Table 31: Baseline Properties Scenario 3

Property	Value
Number of Aircraft at this Base	24
Number of Single Aircraft Missions Each Day	35
Duration of Each Mission	4 hours
Attrition Rate of Each Mission	0.001
Types of Failures	Engine: - Proportion of Failures: 0.08 -Number of Spares: 0 -Time to replace Spare: 12 Days Other: -Proportion of Failures: 0.92 -Number of Spares: 0 -Time to replace Spare: 3 Days
MTTR	7 hours
Maximum Number of Simultaneous Repairs	4
MTBF	45 hours
Major Events	None

Table 31 shows the inputs of the baseline scenario. Table 32 identifies the changes to the baseline that are done to demonstrate the effects of changing the number of aircraft that are sent to reinforce the base experiencing a high attrition rate. The baseline is set so that no aircraft are sent to reinforce the base experiencing a high level of attrition; excursion 1 sends 10 aircraft to the base experiencing a high level

of attrition on day 10; excursion 2 sends 20 aircraft to the base experiencing a high level of attrition on day 10; and excursion 3 flies 30 aircraft to the base experiencing a high level of attrition on day 10. In each of the individual excursions, an increasing quantity of aircraft are flown from one base to another base that is experiencing missions with a high level of attrition as shown in Table 32.

Table 32: Scenario 3 Excursions

Day of Event	Excursion 1	Excursion 2	Excursion 3
Day 10	Fly 10 aircraft from one base to the base of interest. Mission details of this transfer: Duration: 5 hours Attrition Rate: 0.001	Fly 20 aircraft from one base to the base of interest. Mission details of this transfer: Duration: 5 hours Attrition Rate: 0.001	Fly 30 aircraft from one base to the base of interest. Mission details of this transfer: Duration: 5 hours Attrition Rate: 0.001

Results

The baseline of this scenario has a high attrition rate set for each of its missions as shown in Table 31. This results in the aircraft availability of this scenario to approach zero very quickly as shown in Figure 60. Figure 60 shows that the aircraft that reinforce the base arrive on Day 10 of the simulation, but once again are quickly lost to attrition as they fly sorties. As expected, Figure 61 demonstrates that as the number of aircraft that are reinforce the base experiencing a high level of attrition increases, the number of periods that the aircraft are able to fly all of the missions increases as well. This shows that there is a benefit to having a large quantity of aircraft. Most importantly, this scenario demonstrates the ability of aircraft to fly to different bases in ENIGMA.

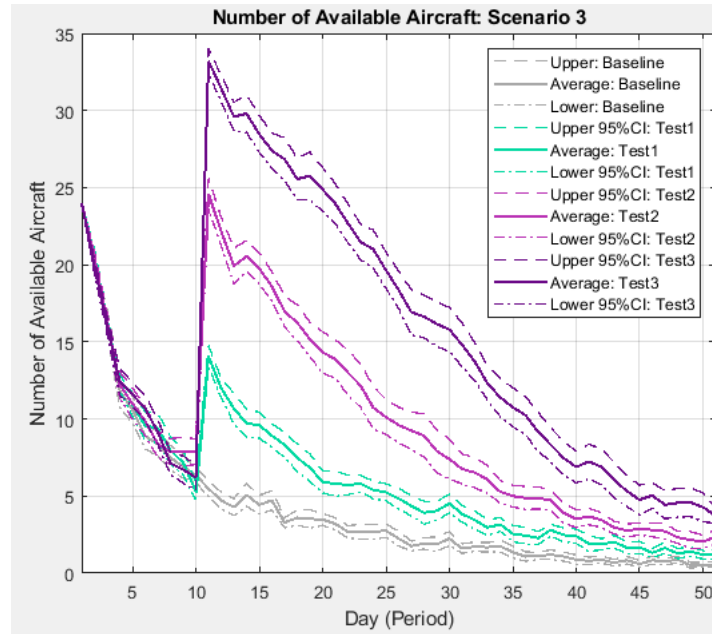


Figure 60: Scenario 3 Excursions: Aircraft Availability

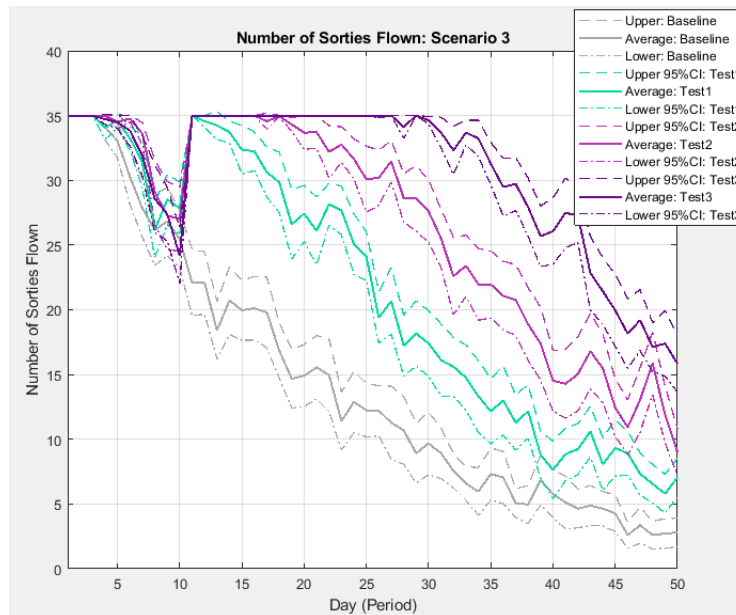


Figure 61: Scenario 3 Excursions: Sorties Flown

4.5.4 Scenario 4: Mean Time To Repair

This scenario demonstrates the effect of changing the value of the MTTR at some point during the simulation. The MTTR will increase to show a reduction in the rate of repairing damaged aircraft. A change in the MTTR in this simulation can represent a change to the maintenance system. These changes could occur for many reasons including the loss of maintenance personnel or the even structural changes to the maintenance process. Although these are two examples may be reasons for why the MTTR could change, there are many other reasons why the maintenance process could be affected.

Baseline and Excursions

Table 33: Baseline Properties Scenario 4

Property	Value
Number of Aircraft at this Base	24
Number of Single Aircraft Missions Each Day	20
Duration of Each Mission	6 hours
Attrition Rate of Each Mission	0.001
Types of Failures	Engine: - Proportion of Failures: 0.08 -Number of Spares: 0 -Time to replace Spare: 12 Days Other: -Proportion of Failures: 0.92 -Number of Spares: 0 -Time to replace Spare: 3 Days
MTTR	3 hours
Maximum Number of Simultaneous Repairs	1
MTBF	45 hours
Major Events	None

Table 33 shows the values of the inputs that define the baseline scenario. Table 34 identifies the changes to the baseline that are done to demonstrate the effects of changes to the maintenance system. All changes to the maintenance system represented in each excursion negatively impact the MTTR; thus, the MTTR will increase in each excursion representing a decrease in the rate of repair of damaged aircraft.

Table 34: Scenario 4 Excursions

Day of Event	Excursion 1	Excursion 2	Excursion 3
Day 10	Change MTTR to 9 hours	Change MTTR to 12.5 hours	Change MTTR to 20 hours

Results

Table 33 and Table 34 show that the baseline has an MTTR of 3 hours; excursion 1 changes the MTTR from 3 hours to 9 hours on day 10; excursion 2 changes the MTTR from 3 hours to 12.5 hours on day 10; and excursion 3 changes the MTTR from 3 hours to 20 hours on day 10. Figure 62 shows that before the change in MTTR, each of the excursions appeared to have the same aircraft availability. This makes sense because all of the excursions are the same prior to the changes in the MTTRs on day 10. Figure 63 also shows the number of mission capable aircraft are able to fly all of its missions before the change in MTTR since the repair rate was fast enough to maintain an adequate level of aircraft availability. Decreasing the rate of repair results in both the aircraft availability to decrease and the number of sorties flown to decrease. This decrease in aircraft availability and the decrease in the number of sorties flown is a result of the decrease in the repair capability, which means that aircraft will not be able to recover as quickly from part failures.

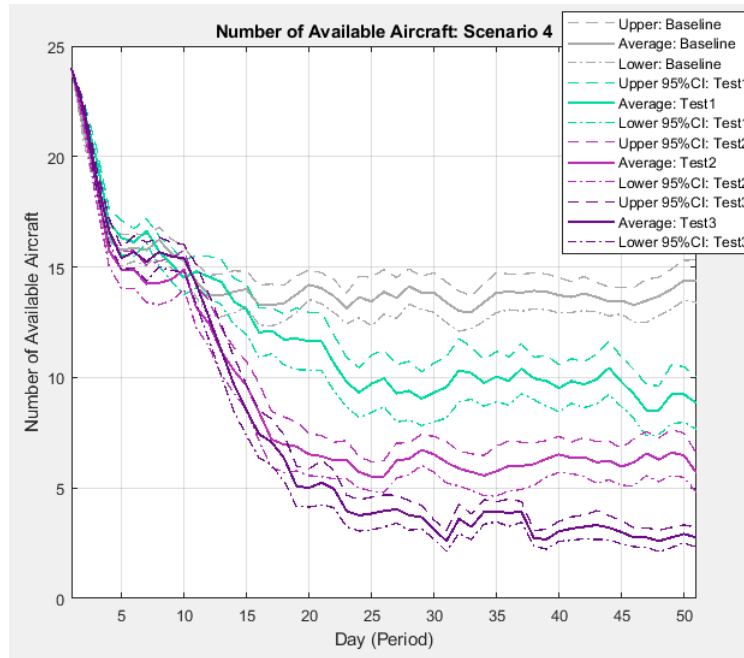


Figure 62: Scenario 4 Excursions: Aircraft Availability

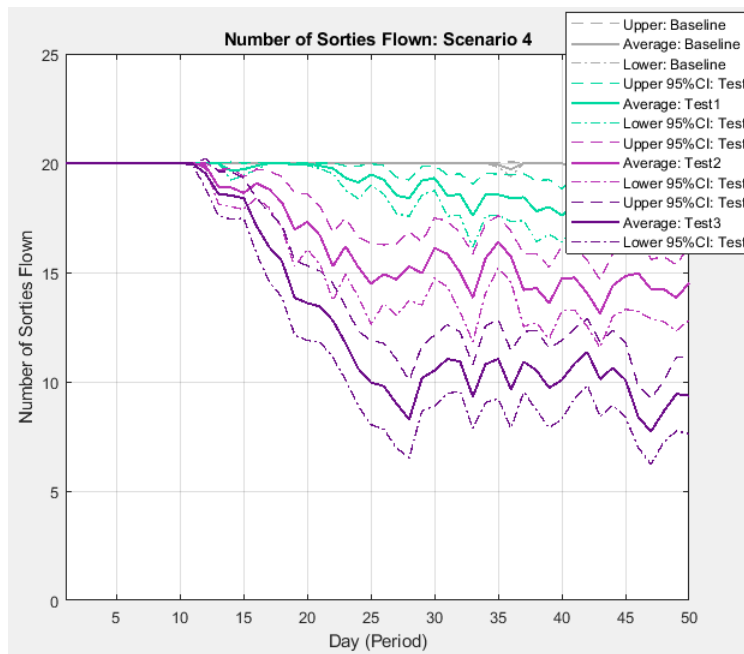


Figure 63: Scenario 4 Excursions: Sorties Flown

4.5.5 Scenario 5: Mean Time Before Failure

This scenario demonstrates the effect of changes to the MTBF on the average aircraft availability. Initially, the MTBF will be a certain level, but the MTBF will change to varying new MTBF values to show how a change in MTBF can affect the average aircraft availability. The MTBF can change for a variety of reasons including changes to the operational environment. Changes to the operational environment can affect the MTBF because the different conditions can affect the stress on aircraft parts resulting in changes to the rates of failures.

Baseline and Excursions

Table 35: Baseline Properties Scenario 5

Property	Value
Number of Aircraft at this Base	24
Number of Single Aircraft Missions Each Day	24
Duration of Each Mission	6 hours
Attrition Rate of Each Mission	0.001
Types of Failures	Engine: - Proportion of Failures: 0.08 -Number of Spares: 0 -Time to replace Spare: 12 Days Other: -Proportion of Failures: 0.92 -Number of Spares: 0 -Time to replace Spare: 3 Days
MTTR	3 hours
Maximum Number of Simultaneous Repairs	1
MTBF	45 hours
Major Events	None

Table 35 shows the parameter inputs that define the baseline scenario. Table 36 identifies the changes to the baseline that are done to demonstrate the effects of changing the MTBF during the operational scenario. The MTBF of the baseline scenario is set to 45 hours; the MTBF of excursion 1 is changed from 45 hours to 35

hours on day 10; the MTBF of excursion 2 is changed from 45 hours to 25 hours on day 10; and the MTBF of excursion 3 is changed from 45 hours to 18 hours on day 10.

Table 36: Scenario 5 Excursions

Day of Event	Excursion 1	Excursion 2	Excursion 3
Day 10	Change MTBF to 35 hours	Change MTBF to 25 hours	Change MTBF to 18 hours

Results

Decreasing the MTBF is equivalent to increasing the failure rate of aircraft. Figure 64 shows that the aircraft availability increases as the MTBF increases and this increase in aircraft availability results in the increase of the number of sorties flown as shown in Figure 65. Although the number of sorties flown increases with aircraft availability, the number of sorties flown cannot exceed the number of missions assigned that day. This is why the number of sorties flown does not exceed the scheduled number of daily missions as the MTBF increases. These excursions show that the rate of failure of aircraft components can impact aircraft availability.

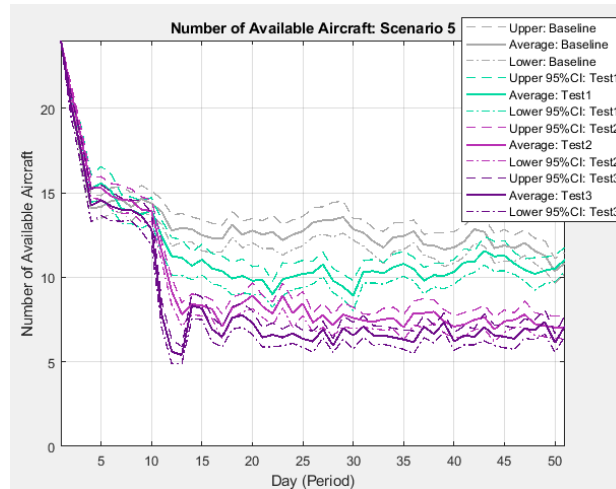


Figure 64: Scenario 5 Excursions: Aircraft Availability

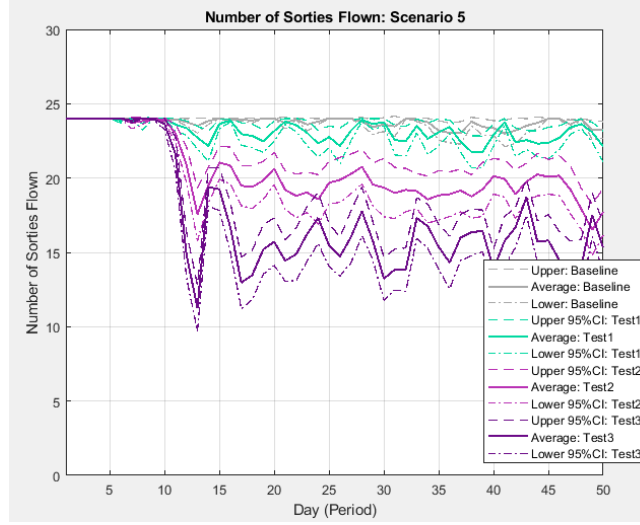


Figure 65: Scenario 5 Excursions: Sorties Flown

4.5.6 Scenario 6: Damage/Destruction of Base Aircraft

This scenario is used to demonstrate an event that results in damaged and destroyed grounded aircraft. There are many events that can result in grounded aircraft being damaged and destroyed. These events includes extreme environmental events and adversarial attacks. In this scenario, a specified number of aircraft are damaged by the event and a specified number of aircraft are destroyed by the event. The damaged aircraft are able to be repaired, but are not mission-capable until they are repaired. Additionally, aircraft that are already damaged prior to the event and are selected to be damaged will not be affected since the simulation assumes that each aircraft can have a maximum of one part failure at a time. The aircraft that are selected to be destroyed are removed from the simulation.

Baseline and Excursions

Table 37 shows the values of the inputs that define the baseline scenario. Table 38 identifies the changes to the baseline that are done to demonstrate the effects of changing the ratio of aircraft that are damaged and destroyed during the event that occurs in the operational scenario. The baseline scenario does not experience any

event that results in the damage and destruction of grounded aircraft. Excursion 1 experiences an event on day 15 that results in 15 aircraft being damaged and 2 aircraft being destroyed. Excursion 2 experiences an event on day 15 that results in 8 damaged aircraft and 9 destroyed aircraft. Excursion 3 experiences an event on day 15 that results in 2 damaged aircraft and 15 destroyed aircraft.

Table 37: Baseline Properties Scenario 6

Property	Value
Number of Aircraft at this Base	24
Number of Single Aircraft Missions Each Day	35
Duration of Each Mission	4 hours
Attrition Rate of Each Mission	0.001
Types of Failures	Engine: - Proportion of Failures: 0.08 -Number of Spares: 0 -Time to replace Spare: 12 Days Other: -Proportion of Failures: 0.92 -Number of Spares: 0 -Time to replace Spare: 3 Days
MTTR	7 hours
Maximum Number of Simultaneous Repairs	4
MTBF	45 hours
Major Events	None

Table 38: Scenario 6 Excursions

Day of Event	Excursion 1	Excursion 2	Excursion 3
Day 15	Damage 15 Aircraft; Destroy 2 Aircraft	Damage 9 Aircraft; Destroy 8 Aircraft	Damage 2 Aircraft; Destroy 15 Aircraft

Results

In each excursion, the number of aircraft that are targeted are all the same, but since each excursion has a different proportion of aircraft being damaged, the recoveries of each of the excursions will be different. Figure 66 shows how the availability

of aircraft changes as a result of the event. The aircraft availability reaches a low point on Day 15 as a result of the event, but the aircraft availability recovers once the maintenance is able to repair the damaged aircraft. Figure 66 shows that as the proportion of aircraft targeted are destroyed increases, the aircraft availability recovers to a smaller number of aircraft availability. This is because the aircraft that are destroyed are no longer usable resulting in less aircraft being in the system. This scenario shows that losing aircraft can significantly impact the bases operational capability by decreasing the number of aircraft available to fly missions, as shown in Figure 67.

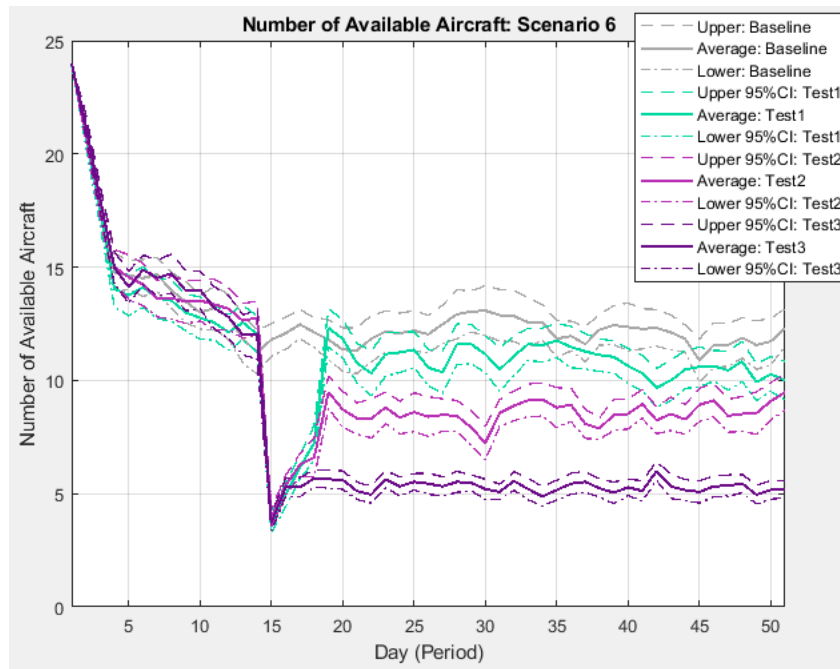


Figure 66: Scenario 6 Excursions: Aircraft Availability

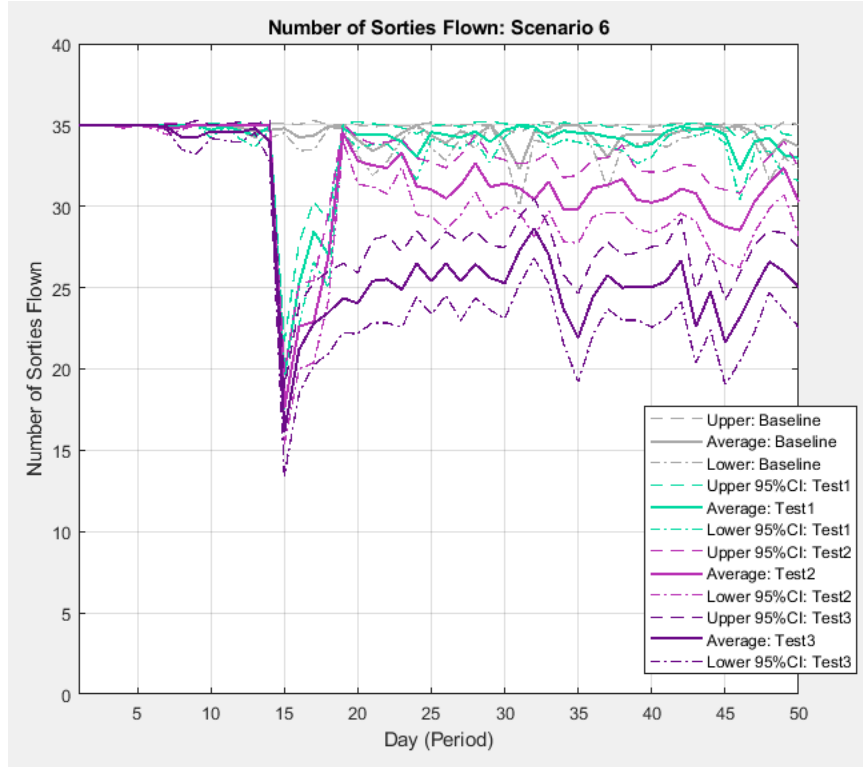


Figure 67: Scenario 6 Excursions: Sorties Flown

4.5.7 Scenario 7: Logistics (Access to New Spares)

This scenario is used to demonstrate when logistics are cut off to a base such that new spares are unable to arrive at the base. This scenario could occur for a variety of reasons including an adversarial action or manufacturing issues. In this situation, new spares may be ordered, but until the logistics are accessed again, the base will only be able to use spares that are already at the base to repair aircraft. This scenario has a set cutoff date when new spares will no longer be accessible, and the parameter that will be varied are the number of spares that are maintained at the base.

Baseline and Excursions

Table 39 shows the inputs of the baseline scenario. Table 40 identifies the changes to the baseline that are done to demonstrate the effects of increasing the number of on-site spares stored in the event of a logistical cutoff. The logistical cutoff begins

on day 15 and new spares will not be able to be accessible again until day 40. The baseline scenario has zero spares for each of the types of failures; excursion 1 has 5 spares for each type of failure; excursion 2 has 10 spares for each type of failure; and excursion 3 has 20 spares for each type of failure.

Table 39: Baseline Properties Scenario 7

Property	Value
Number of Aircraft at this Base	24
Number of Single Aircraft Missions Each Day	20
Duration of Each Mission	4 hours
Attrition Rate of Each Mission	0.001
Types of Failures	Engine: - Proportion of Failures: 0.08 -Number of Spares: 0 -Time to replace Spare: 12 Days Other: -Proportion of Failures: 0.92 -Number of Spares: 0 -Time to replace Spare: 3 Days
MTTR	7 hours
Maximum Number of Simultaneous Repairs	4
MTBF	45 hours
Major Events	Day 15: Cut Off Logistics Day 40: Regain Access to Logistics

Table 40: Scenario 7 Excursions

Change	Excursion 1	Excursion 2	Excursion 3
Set Number of Spares	5	10	20

Results

This scenario demonstrates the effect of increasing the number of spares on hand in the event of a logistical cut off that prevents obtaining new spares. Figure 68 shows that increasing the number of spares increases the aircraft availability. The

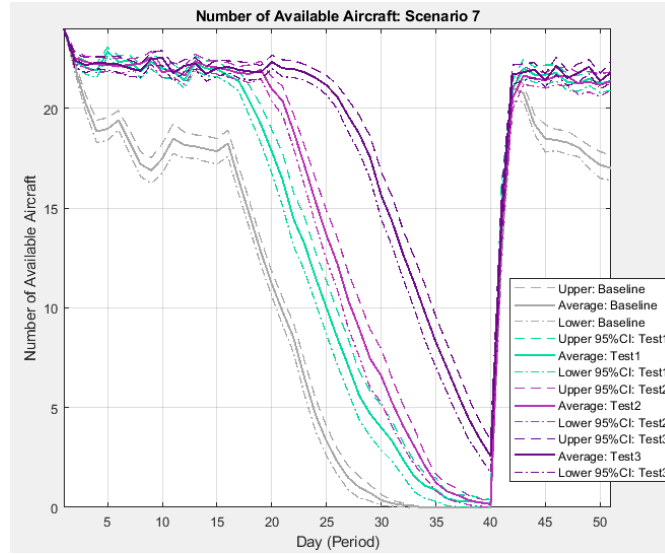


Figure 68: Scenario 7 Excursions: Aircraft Availability

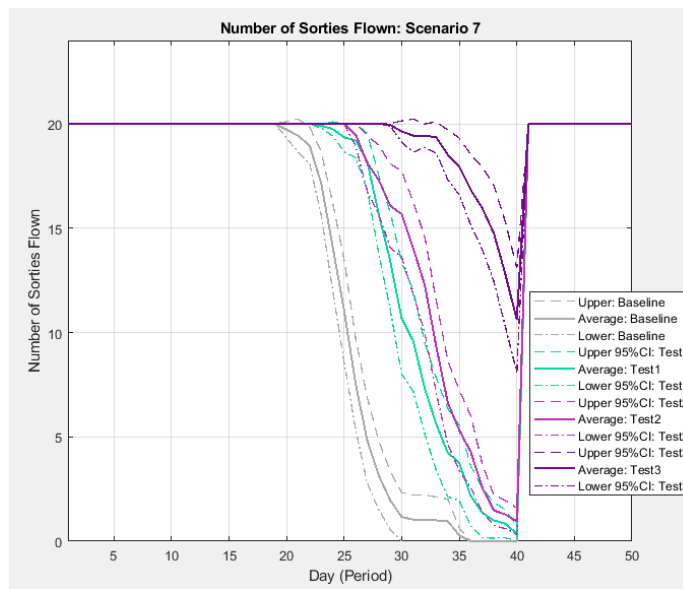


Figure 69: Scenario 7 Excursions: Sorties Flown

three excursions also show that in situations where there is not a logistical cut off (Days 1 through 15), increasing the number of spares does not necessarily improve the aircraft availability since each excursion maintains similar aircraft availability as one another; however, all the excursion show that any number of spares is better than no spares since they all maintain higher aircraft availability than the baseline

that had zero spares. This limit of impact is shown between days 1 through 15 since additional spares maintain the same level of aircraft availability. When the logistical cut off does occur, increasing the number of spares increases the aircraft availability throughout the periods when new spares are inaccessible. Figure 69 appears to show that spares can significantly buffer the effect of the logistical cut off. This is especially true when observing excursion 3 because although Figure 68 shows that the aircraft availability drops rather quickly in the cutoff, Figure 69 shows that there isn't a huge decrease in the proportion of missions flown. This is emphasized especially on Day 40 for excursion 3 because the percent of missions that are flown is greater than 50% despite the aircraft availability being less than 20% of the total aircraft. This scenario shows that although spares may not be able to always maintain a high aircraft availability in a logistical cutoff, spares may have a large impact on maintaining the number of missions that can be accomplished.

4.6 Effects of Including Turnaround Time

The version of ENIGMA that is discussed in this paper assumes that there is no turnaround time between missions. This means that the preparation of aircraft and the minor maintenance that may take place in between missions is not modeled. It would be beneficial to examine the effects of including turnaround time on the outputs of the model. To demonstrate the effect of including turnaround time, each operational scenario from section *Operational Testing: A Few Examples* will be rerun with a specified turnaround time between each mission. Once again, each excursion has 25 replications and is run for 50 days (periods). All of the parameter inputs from the original scenarios will be used in these reruns, except that a turnaround time will also be included.

4.6.1 Expectations of Turnaround Time

The expectation of including turnaround times in the model is that the turnaround times between each mission will not affect the aircraft availability nor the number of missions flown as long as the turnaround times do not interfere with how many missions can be flown. For example, if an aircraft flies three two-hour missions each period, the aircraft would fly six hours total that period under the current model. If a turnaround time of 3 hours was included, then the total time used to prepare and fly the missions would be 15 hours, which is less than the 24 hour limit. Since the time limit is not exceeded, the aircraft would be able to continue flying all of the scheduled missions and the output would not affect the aircraft availability nor the quantity of missions accomplished. It is expected that the turnaround times would only begin to have an effect on aircraft availability and the number of sorties flown when the turnaround times begin to limit the number of missions that can be flown.

Table 41: Turnaround Times Simulation Inputs (No effect)

Property	Value
Number of Aircraft at this Base	18
Number of Single Aircraft Missions Each Day	18
Duration of Each Mission	2.5 hours
Attrition Rate of Each Mission	0.001
Types of Failures	Engine: -Proportion of Failures: 0.08 -Number of Spares: 0 -Time to Replace Spare: 12 Days Other: -Proportion of Failures: 0.92 -Number of Spares: 0 -Time to replace Spare: 3 Days
MTTR	7 hours
Maximum Number of Simultaneous Repairs	1
MTBF	25 hours
Major Events	None

Table 42: Turnaround Times Simulation Inputs (Effect)

Property	Value
Number of Aircraft at this Base	18
Number of Single Aircraft Missions Each Day	45
Duration of Each Mission	4.5 hours
Attrition Rate of Each Mission	0.001
Types of Failures	Engine: -Proportion of Failures: 0.08 -Number of Spares: 0 -Time to Replace Spare: 12 Days Other: -Proportion of Failures: 0.92 -Number of Spares: 0 -Time to replace Spare: 3 Days
MTTR	7 hours
Maximum Number of Simultaneous Repairs	1
MTBF	25 hours
Major Events	None

Example scenarios demonstrating this behavior are shown in Table 41 and Table 42. Both of these scenarios show how changing turnaround times may affect the average aircraft availability and the average number of sorties flown. Table 41 is a scenario where the turnaround time does not affect the aircraft availability nor how many missions are flown, as shown in Figure 70 and Figure 71, respectively. Although low turnaround times do not affect the aircraft availability nor the sortie generation of the scenario described by Table 41, Figure 72 and Figure 73 show that even small turnaround times significantly affect the aircraft availability and sortie generation in the scenario described by Table 42. As expected, as the turnaround time increases between missions, the average aircraft availability increases and the average number of missions flown decreases in scenarios where the turnaround times impact the number of missions that can be flown. The effect that the turnaround times can have on the aircraft availability and the sortie generation is the reason why it would be

beneficial to include turnaround times into future versions of ENIGMA. The following sections will show how turnaround times change the output results of the operational scenarios previously investigated.

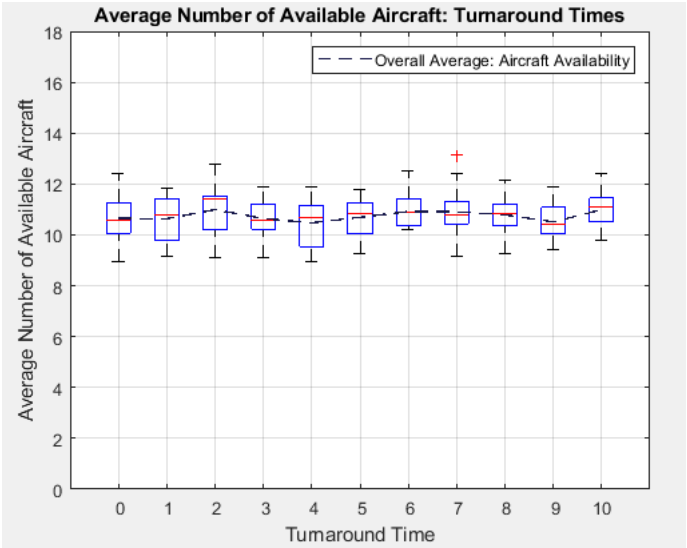


Figure 70: Aircraft Availability: Turnaround Time No Effect

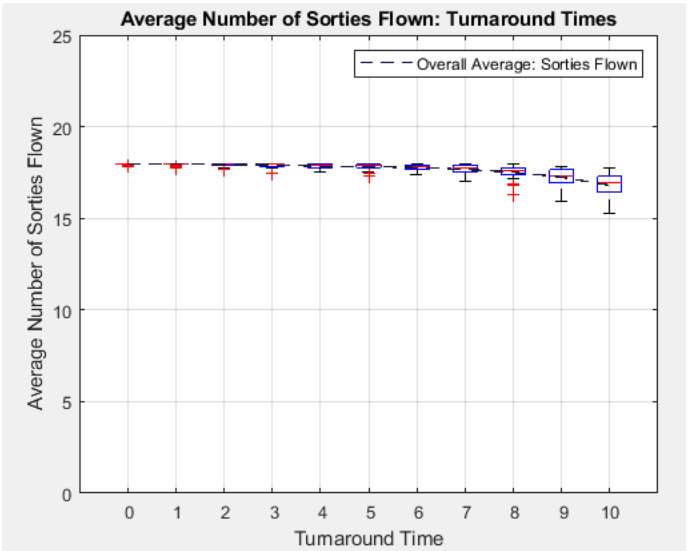


Figure 71: Number of Missions Flown: Turnaround Time No Effect

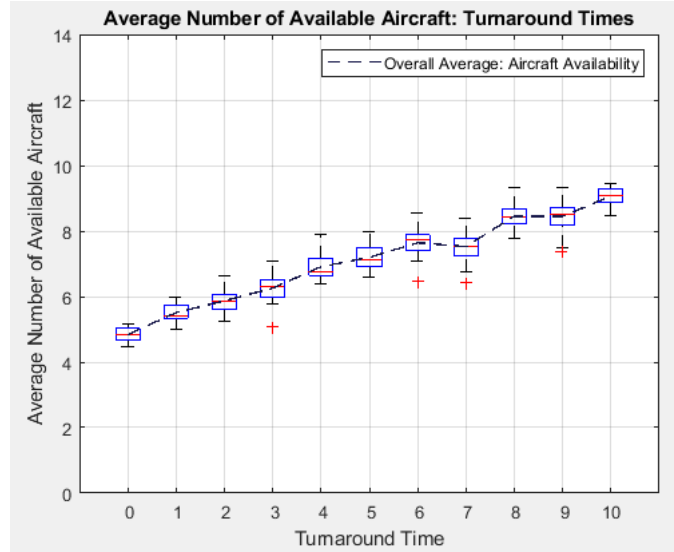


Figure 72: Aircraft Availability: Turnaround Time with Effect

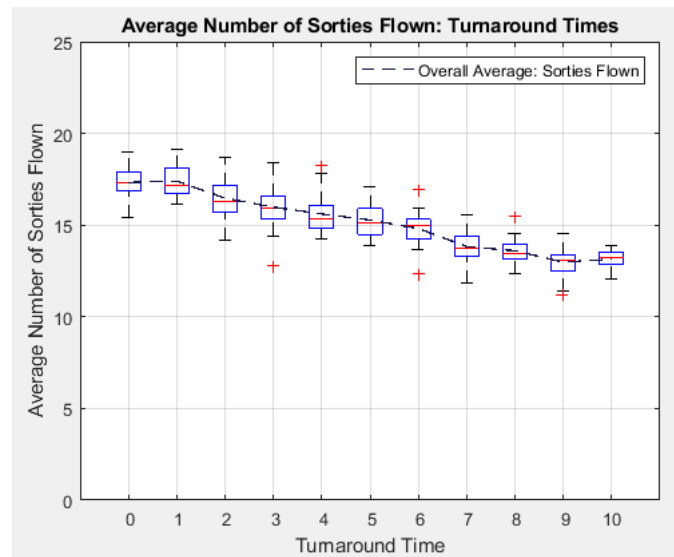


Figure 73: Number of Missions Flown: Turnaround Time with Effect

4.6.2 Scenario 1

Figure 74 and Figure 75 show the aircraft availability and the number of sorties flown for the operational scenario 1 with an added turnaround time of 5 hours between each mission. Comparing Figure 56 to Figure 74 shows that the difference in aircraft availability of each excursion decreased when turnaround time was included. This

may be a result of the turnaround time reducing the number of sorties that could be flown, as shown in Figure 75. Figure 57 shows that when turnaround times are not included, a greater number of sorties can be flown for this scenario. Thus, the turnaround time had an impact on the aircraft availability and sortie generation of this scenario because it reduced the number of missions that could be flown.

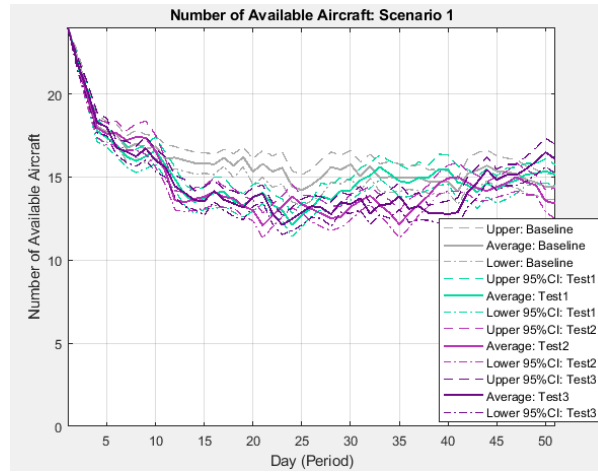


Figure 74: Operational Scenario 1 With Turnaround Time: Aircraft Availability

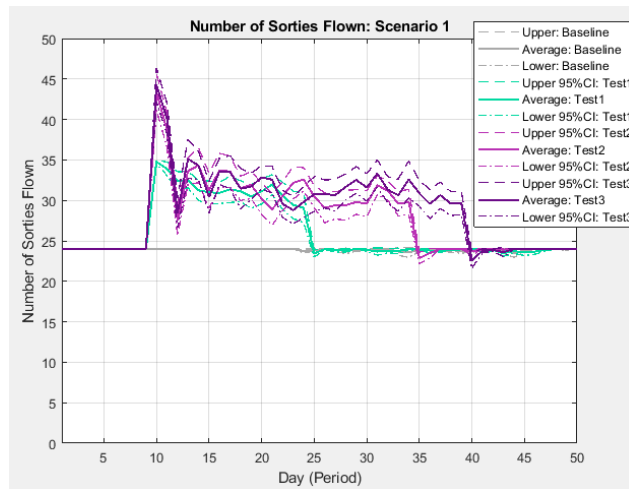


Figure 75: Operational Scenario 1 With Turnaround Time: Number of Sorties Flown

4.6.3 Scenario 2

Under careful examination of Figure 76 and Figure 58, a 4 hour turnaround time increases the aircraft availability in operational scenario 2. This is a result of flying less sorties which can be seen in the comparison of Figure 77 and Figure 59. Although the aircraft availability is increased as a result of the turnaround time, the aircraft are still quickly lost due to the high attrition rates of each mission.

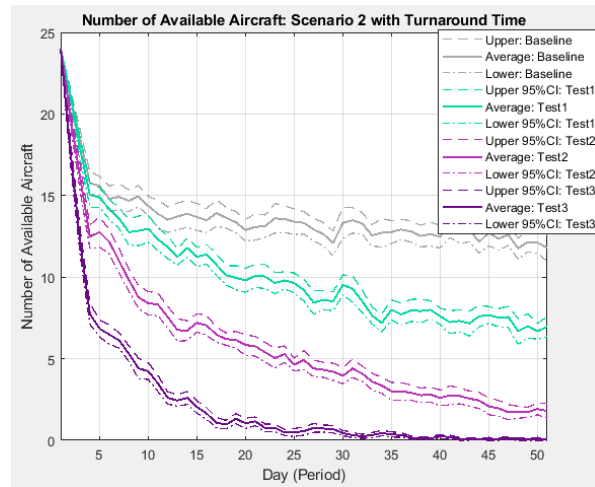


Figure 76: Operational Scenario 2 With Turnaround Time: Aircraft Availability

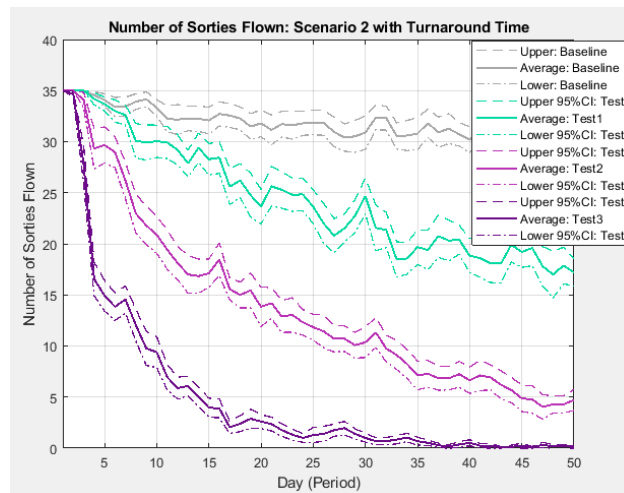


Figure 77: Operational Scenario 2 With Turnaround Time: Number of Sorties Flown

4.6.4 Scenario 3

Including a turnaround time of 4 hours in operational scenario 3 appears to also have an impact on aircraft availability and sortie generation. Comparing Figure 78 to Figure 60 shows that including the turnaround time slightly increases the aircraft availability. This increase in aircraft availability slightly increases the number of days that all of the scheduled missions are able to be flown as shown by comparing Figure 79 to Figure 61.

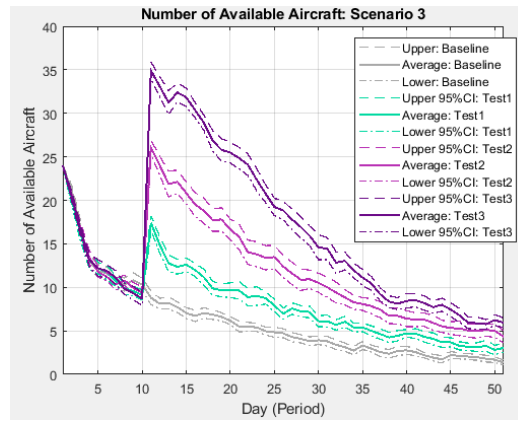


Figure 78: Operational Scenario 3 With Turnaround Time: Aircraft Availability

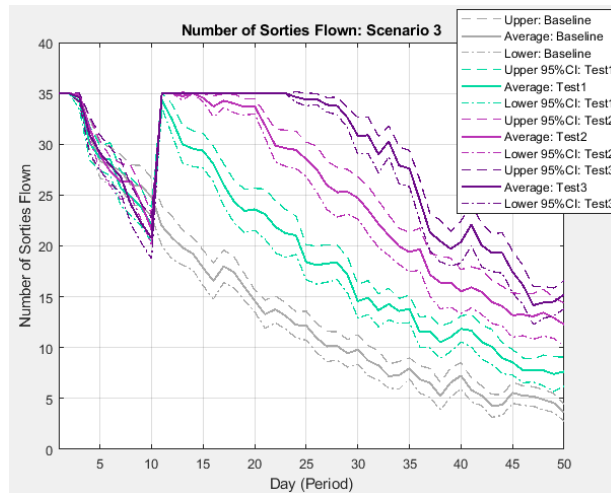


Figure 79: Operational Scenario 3 With Turnaround Time: Number of Sorties Flown

4.6.5 Scenario 4

Although there is a small change in the aircraft availability and the number of sorties flown in operational scenario 4 when a 4 hour turnaround time is included, the aircraft availability and the sortie generation appears to be very similar for this operational scenario. This can be seen by comparing Figure 80 with Figure 62 and Figure 81 with Figure 63, respectively. In this operational scenario, the duration of each mission is 6 hours, which means that an aircraft would only be able to fly four missions each day if there was no turnaround time included. If a four hour turnaround time is included, then each aircraft could fly a maximum of two sorties per day. Figure 58 shows that even with excursion 3 showing an aircraft availability of about 3-4 aircraft, only about 10 sorties are being completed each day. This means that each aircraft is flying about 2-3 missions each period in this scenario when turnaround time is not included. If turnaround time is included, then this scenario would only allow each aircraft to be able to fly 2 sorties each day, which is not much smaller than the 2-3 sorties per day when turnaround time is not included. This small impact of the turnaround time in this scenario explains why the only apparent difference between the aircraft availability and the number of sorties flown occurs in excursion 3 of this scenario.

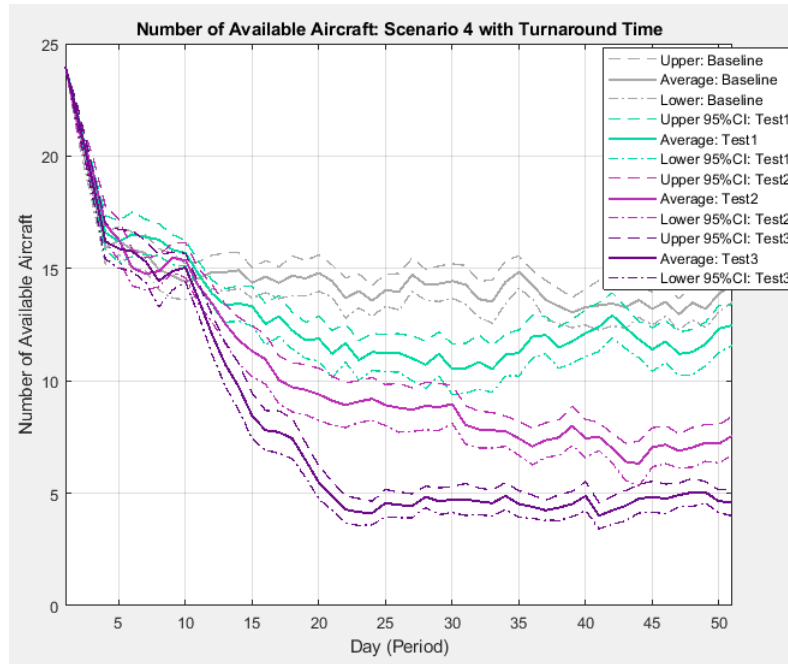


Figure 80: Operational Scenario 4 With Turnaround Time: Aircraft Availability

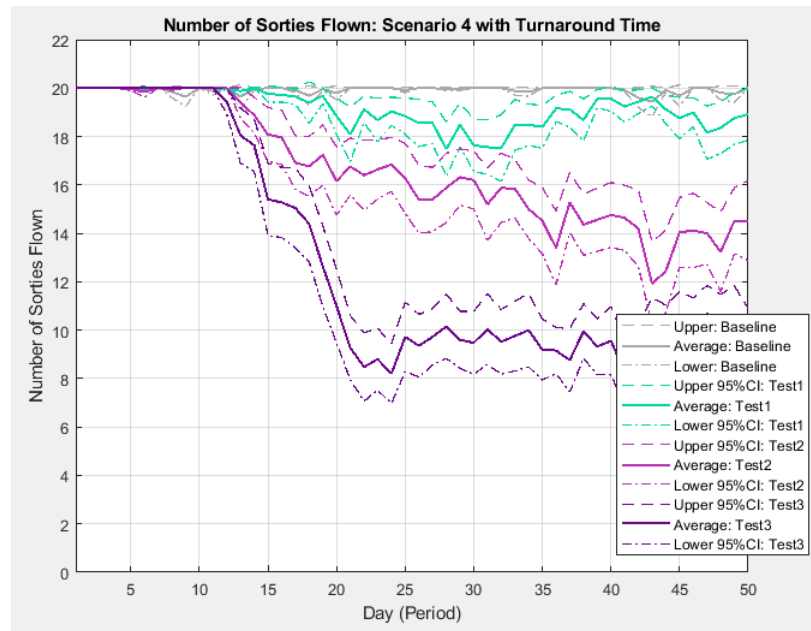


Figure 81: Operational Scenario 4 With Turnaround Time: Number of Sorties Flown

4.6.6 Scenario 5

Including a four hour turnaround time in operational scenario 5 increases the aircraft availability and slightly decreases the number of sorties flown compared to when the turnaround time is not included. This can be seen by comparing Figure 82 with Figure 64 and Figure 83 with Figure 65, respectively.

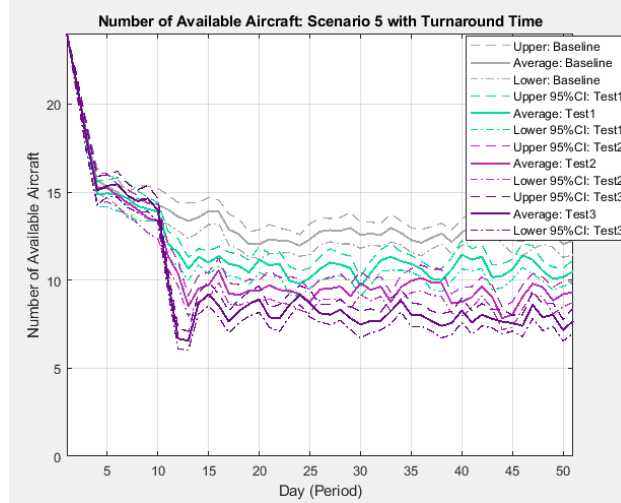


Figure 82: Operational Scenario 5 With Turnaround Time: Aircraft Availability

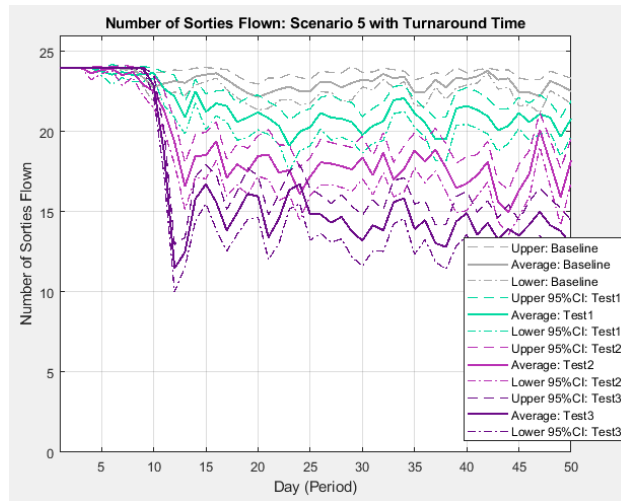


Figure 83: Operational Scenario 5 With Turnaround Time: Number of Sorties Flown

4.6.7 Scenario 6

Comparing Figure 84 to Figure 66 shows that incorporating a four hour turnaround time into operational scenario 6 increases the aircraft availability. As expected, this increase in aircraft availability is a result of flying less sorties, which can be seen by comparing Figure 85 with Figure 67, respectively.

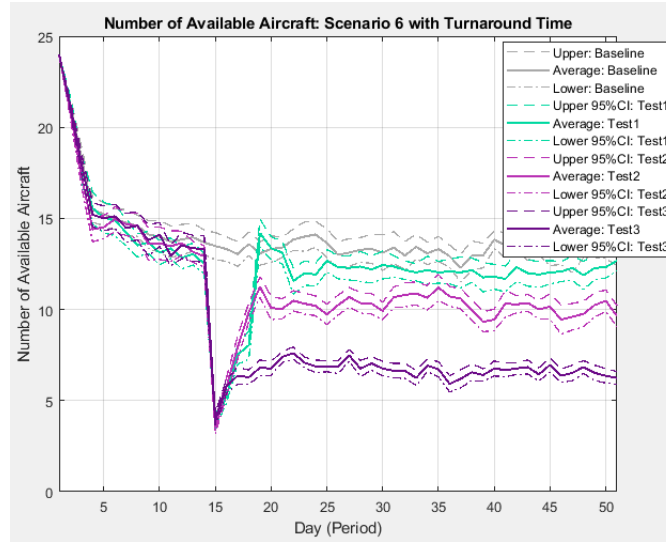


Figure 84: Operational Scenario 6 With Turnaround Time: Aircraft Availability

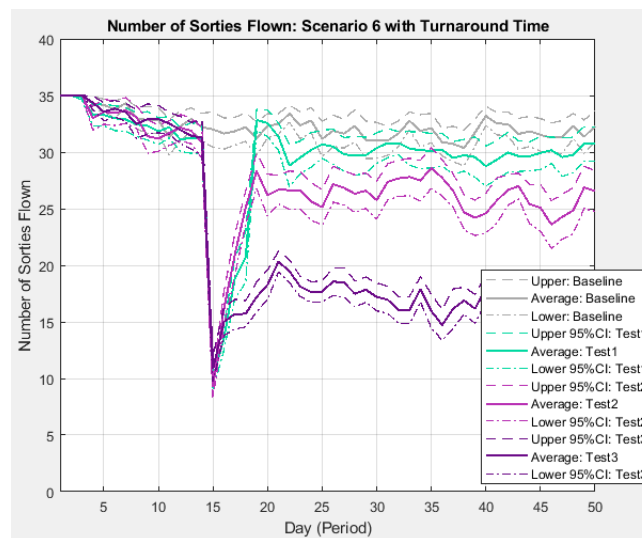


Figure 85: Operational Scenario 6 With Turnaround Time: Number of Sorties Flown

4.6.8 Scenario 7

Comparing Figure 86 to Figure 68 shows that including an eight hour turnaround time increases the aircraft availability in this scenario; similarly, comparing Figure 87 with Figure 69 shows that including this turnaround time also decreases the number of sorties that are flown. Note that the turnaround time was chosen to be very large when included in this operational scenario. While the turnaround time may be large, it shows that the impact of turnaround times may vary depending on the operational scenario. This can also be seen in this scenario since the turnaround time had a greater impact on excursion 3 of this scenario than on either excursion 1 or excursion 2 of this scenario.

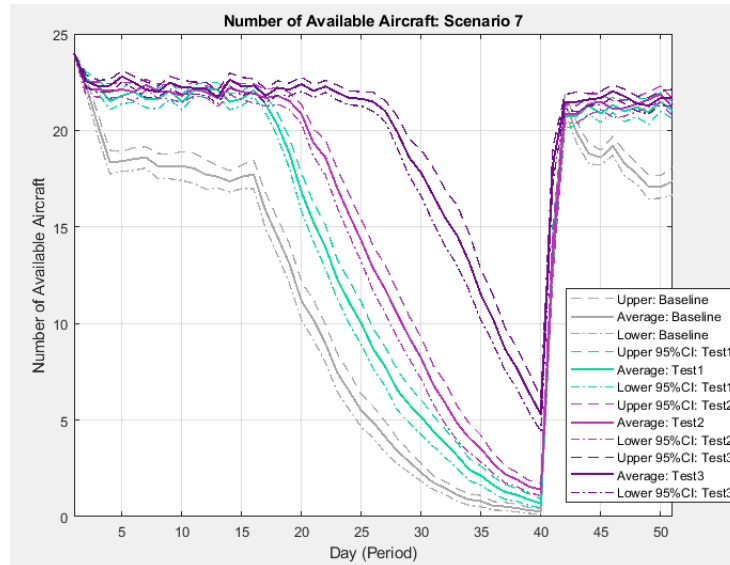


Figure 86: Operational Scenario 7 With Turnaround Time: Aircraft Availability

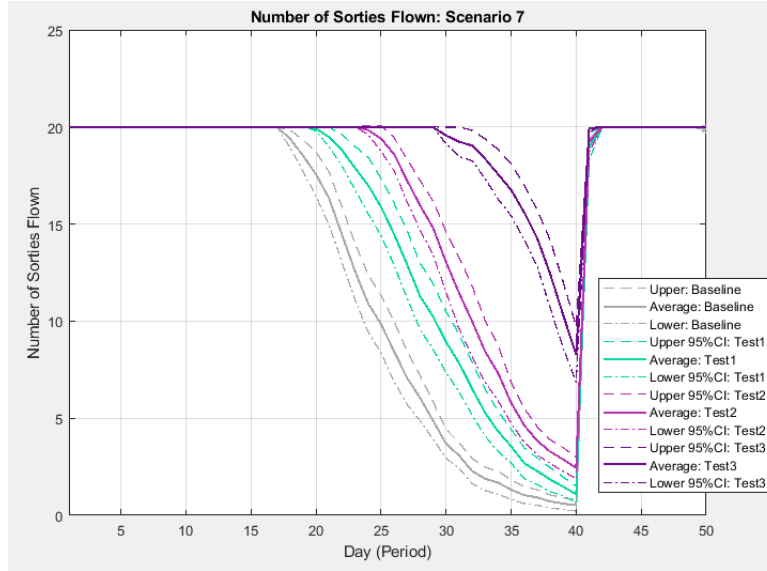


Figure 87: Operational Scenario 7 With Turnaround Time: Number of Sorties Flown

4.6.9 Summary

Rerunning the operational scenarios with turnaround times shows that turnaround times can impact the aircraft availability and the sortie generation. However, these scenarios also showed that the extent the turnaround time can have on the aircraft availability and the number of sorties flown is dependent on the operational scenario. This investigation indicates that turnaround times should be included in the future versions of ENIGMA.

4.7 Run-time Testing

For this simulation tool to be practical, it must be able to run quickly where implemented. The methodology used to test the speed of the simulation tool was to create an experimental design using a nearly-orthogonal latin hypercube design. This design is shown in Table 46 of Appendix A. The input variables included in this experimental design are the same as the experimental design used to validate that the simulation behaved as expected. However, this experimental design includes three

additional input variables. The three additional variables included in this experiment are the number of days, the number of runs, and an indicator variable that labeled "separate missions". The number of days is a variable indicating how many days (periods) will be in the simulation. The number of runs indicates the number of replications that are run. The binary indicator variable labeled "separate missions" indicates whether or not missions are separated into individual missions prior to running the simulation. Three replications were run for each of the tests in the experimental design. JMP 15.0 was used to produce a linear regression model relating the inputs of the experimental design to the run time.

The structure of the regression equation that was used to fit the model is shown in Equation (25). In order for this linear regression model to reliably represent the relationship between the inputs and the run-time of the simulation it must satisfy a few assumptions. The first assumption is that there is a linear relationship between the regressor variables and the response variables. The second assumption is that the residuals of the model are independent of one another, are well-behaved with a mean of zero. The third assumption is that the residuals have constant variance and that there is no auto-correlation. The experiment was run using MATLAB 2019b with a laptop computer with a 2.3 GHz Intel Core i5 processor and with memory of 16 GB 1600 MHz DDR3. The time that the simulation takes to run is measured in seconds.

4.7.1 Run-Time Regression Model

The adjusted- R^2 shown in the summary of fit in Figure 88 indicates that the amount of time that a simulation takes to run can be explained by the inputs to the model. The parameter estimates of the regressors shown in Figure 89 all have the expected positive and negative impact showing that the regressors impact the run time of the simulation as expected. The VIF scores of the parameter estimates are all

close to one, indicating that multicollinearity is not a concern in the model. Figure 90 shows that the three regressors that have the most impact in the model are the number of days, number of runs (replications), and whether or not the missions are separated into individual missions prior to the running the simulation. The fact that the number of days in the simulation and the number of replications have the greatest effect on the run time of the simulation makes sense because they determine how many periods and how many times the simulation must run. The observed impact of separating missions prior to running the simulation is also expected because it affects how many missions must be processes each period; the extent of its impact on the run time of the simulation will be investigated further.

Summary of Fit	
RSquare	0.958163
RSquare Adj	0.954909
Root Mean Square Error	41.1167
Mean of Response	152.52
Observations (or Sum Wgts)	195

Figure 88: Summary of Fit: Run Time

Parameter Estimates					
Term	Estimate	Std Error	t Ratio	Prob> t	VIF
Intercept	-417.134	22.39029	-18.63	<.0001*	.
Number of Daily Missions	3.8396034	0.334593	11.48	<.0001*	1.0078188
Duration	5.8255991	1.5458	3.77	0.0002*	1.0009755
MTBF	-1.492535	0.239514	-6.23	<.0001*	1.0030765
Proportion Failures Engine	776.24665	193.314	4.02	<.0001*	1.0096188
Number of Days	3.9696212	0.137413	28.89	<.0001*	1.0273685
Number of Runs	11.283767	0.345964	32.62	<.0001*	1.0017143
Separate Missions	153.61103	6.007535	25.57	<.0001*	1.040466
(Proportion Failures Engine-0.07508)*(Number of Days-38.0154)	48.388118	11.1622	4.33	<.0001*	1.1034088
(Number of Daily Missions-30.0154)*(Number of Runs-15.5077)	0.3391402	0.043731	7.76	<.0001*	1.0673751
(Number of Days-38.0154)*(Number of Runs-15.5077)	0.2850889	0.0167	17.07	<.0001*	1.3394473
(Number of Daily Missions-30.0154)*(Separate Missions-0.50769)	6.6686472	0.701501	9.51	<.0001*	1.1010793
(MTBF-29.0006)*(Separate Missions-0.50769)	2.158621	0.493648	4.37	<.0001*	1.0635499
(Number of Days-38.0154)*(Separate Missions-0.50769)	4.1721901	0.277941	15.01	<.0001*	1.0248721
(Number of Runs-15.5077)*(Separate Missions-0.50769)	8.3024196	0.796393	10.43	<.0001*	1.3259997

Figure 89: Parameter Estimates: Run Time

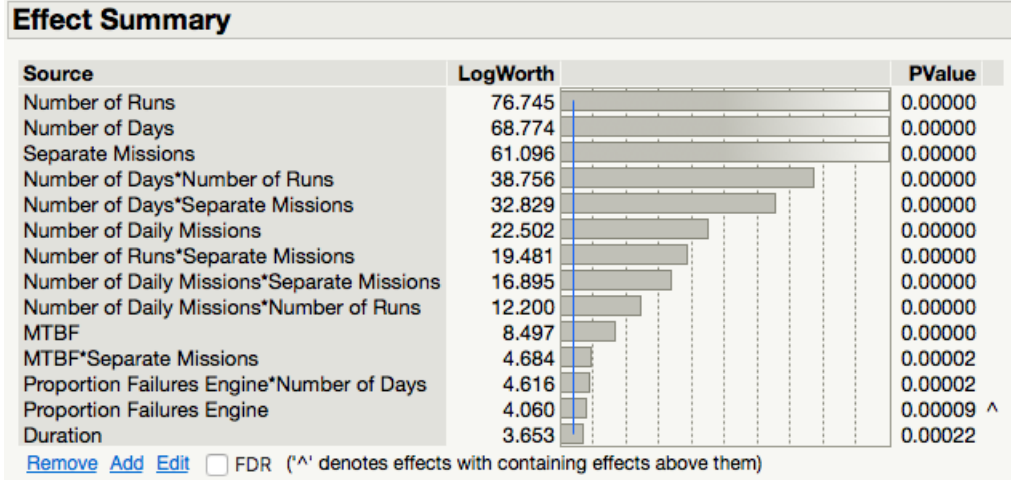


Figure 90: Effects Summary: Run Time

Although Figure 91 shows that the residuals appear to be well-distributed and have a mean close to zero, Figure 92 shows that the assumption that the residuals have constant variance may be violated. This violation raises caution that the model may be unreliable. A variance-stabilizing transformation of the response variable may improve the model describing the relationship between it and the regressors.

Transformed Run-Time Regression Model

There are many transformations of the response variable that can be used to attempt to improve the model. The Box-Cox method can be used to determine an appropriate variance-stabilizing transformation of the response variable for the model[23]. The method finds the value of $\hat{\lambda}$ that minimizes the residual sum of squares, SSE , of the regression model of the transformed response variable that is defined in Equation (27). In Equation (27), y is the response variable prior to transformation and $\dot{y}$ is the geometric mean of the observations of the response variable[23].

$$y^{(\hat{\lambda})} = \begin{cases} \frac{y^{\hat{\lambda}} - 1}{\hat{\lambda}\dot{y}^{\hat{\lambda}-1}} & \hat{\lambda} \neq 0 \\ \dot{y} \ln(y) & \hat{\lambda} = 0 \end{cases} \quad (27)$$

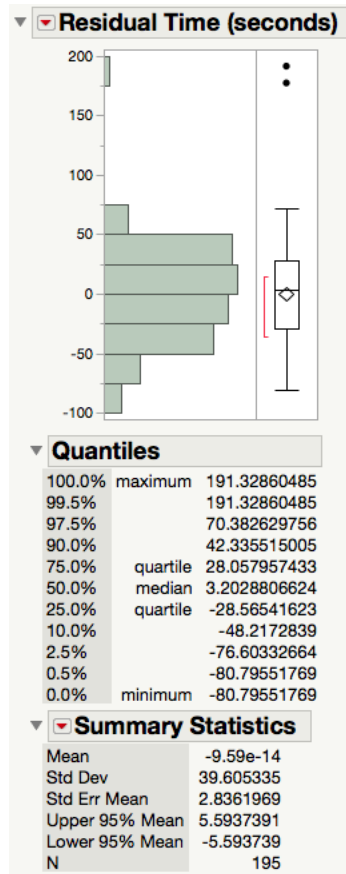


Figure 91: Distribution of Residuals

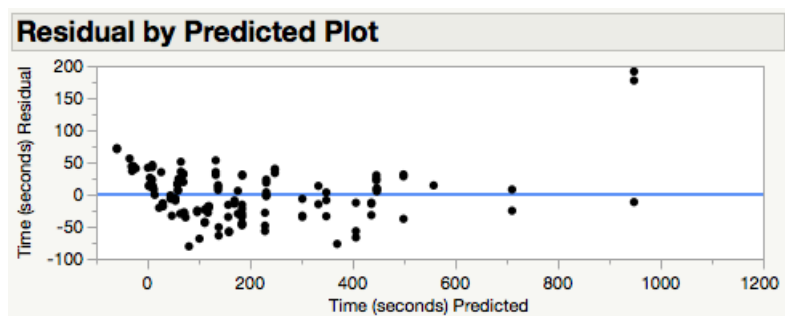


Figure 92: Residuals: Run Time

JMP 15.0.0 can calculate the optimal value for the Box-Cox transformation automatically. JMP indicates that the optimal value for the transformation of this model is $\hat{\lambda} = 0.459$. This value is very close to the value of 0.5; a $\hat{\lambda}$ of 0.5 indicates that an appropriate transformation of the response variable is the square-root function.

A linear regression model was made relating the inputs of experiment to the square-root of the time it takes to run the simulation. Figure 93 shows that the transformation improved the adjusted- R^2 value of the model. Some of the parameter estimates of this model shown in Figure 94 do not affect the run time of the simulation with the expected positive or negative signs; however, many of these parameter estimates are for regressors that are not significant to the model. These regressors include the attrition rate, the MTTR, the engine safety stock, the engine resupply time, and the proportion of failures that are engine failures. These regressors are only included in the model because they are included in interaction terms that are significant to the model.

Figure 95 also shows that several of these terms with unexpected parameter estimates do not have a large effect on the run time of the simulation. As with the regression model of the time, the three regressors that affect the run time the greatest are the number of days, the number of runs, and the indicator variable indicating whether or not the missions are separated into single aircraft missions prior to running the simulation. Additionally, the residuals of this transformed model now satisfies the assumptions needed to declare reliability of the model because there is constant variance in the residuals and the residuals follow a well-behaved distribution with a mean approximately equal to zero as shown in Figure 97 and Figure 96 respectively. Although it may be difficult to see in Figure 97, Table 43 appears to indicate that may be auto-correlation in this model; thus, this transformation may not perfectly represent of the relationship between the input variables and the run time of the simulation.

Summary of Fit	
RSquare	0.989204
RSquare Adj	0.987533
Root Mean Square Error	0.746494
Mean of Response	10.39469
Observations (or Sum Wgts)	195

Figure 93: Summary of Fit: $\sqrt{RunTime}$

Parameter Estimates					
Term	Estimate	Std Error	t Ratio	Prob> t	VIF
Intercept	-7.689042	0.744863	-10.32	<.0001*	.
Attrition Rate	-137.0627	199.5377	-0.69	0.4931	1.0804101
Number of Daily Missions	0.1059689	0.00611	17.34	<.0001*	1.0196021
Duration	0.3706723	0.028099	13.19	<.0001*	1.003407
MTBF	-0.059398	0.00436	-13.62	<.0001*	1.0082199
MTTR	-0.017492	0.022933	-0.76	0.4467	1.0122389
Num Sim Rep	0.1966173	0.043755	4.49	<.0001*	1.0300461
Engine Safety Stock	-0.010734	0.035495	-0.30	0.7627	1.0326692
Engine Resupply Time	-0.022666	0.057604	-0.39	0.6945	1.0762452
Proportion Failures Engine	4.2836537	3.544104	1.21	0.2285	1.0295048
Number of Days	0.1553789	0.002499	62.16	<.0001*	1.0312366
Number of Runs	0.4106314	0.006303	65.14	<.0001*	1.0088122
Separate Missions	6.1426855	0.115053	53.39	<.0001*	1.1577602
(MTBF-29.0006)*(MTBF-29.0006)	-0.001232	0.000506	-2.44	0.0159*	1.6431047
(Number of Daily Missions-30.0154)*(Engine Safety Stock-2.50769)	-0.018339	0.004261	-4.30	<.0001*	1.2537898
(Num Sim Rep-3.03077)*(Engine Resupply Time-10.5077)	0.5268421	0.050839	10.36	<.0001*	1.0938099
(MTTR-6.00246)*(Proportion Failures Engine-0.07508)	14.78551	2.336181	6.33	<.0001*	2.2566499
(Proportion Failures Engine-0.07508)*(Proportion Failures Engine-0.07508)	-1371.141	340.2958	-4.03	<.0001*	2.0168612
(Attrition Rate-0.00053)*(Number of Days-38.0154)	73.400247	10.23319	7.17	<.0001*	1.3555977
(Duration-4.75015)*(Number of Days-38.0154)	0.0130671	0.001404	9.31	<.0001*	1.2071218
(MTBF-29.0006)*(Number of Days-38.0154)	-0.002226	0.000198	-11.27	<.0001*	1.1712678
(MTTR-6.00246)*(Number of Days-38.0154)	0.0043644	0.001222	3.57	0.0005*	1.1438289
(Number of Days-38.0154)*(Number of Days-38.0154)	-0.001065	0.00018	-5.92	<.0001*	2.0281723
(Num Sim Rep-3.03077)*(Number of Runs-15.5077)	-0.022625	0.008059	-2.81	0.0056*	2.2645327
(Number of Days-38.0154)*(Number of Runs-15.5077)	0.0052102	0.000331	15.75	<.0001*	1.5945162
(Number of Daily Missions-30.0154)*(Separate Missions-0.50769)	0.1999991	0.014073	14.21	<.0001*	1.3444026
(Number of Runs-15.5077)*(Separate Missions-0.50769)	0.2623712	0.014998	17.49	<.0001*	1.4267846

Figure 94: Parameter Estimates: $\sqrt{RunTime}$

Effect Summary		
Source	LogWorth	PValue
Number of Runs	120.425	0.00000
Number of Days	117.144	0.00000
Separate Missions	106.575	0.00000
Number of Runs*Separate Missions	38.958	0.00000
Number of Daily Missions	38.552	0.00000
Number of Days*Number of Runs	34.184	0.00000
Number of Daily Missions*Separate Missions	29.881	0.00000
MTBF	28.226	0.00000
Duration	27.002	0.00000
MTBF*Number of Days	21.564	0.00000
Num Sim Rep*Engine Resupply Time	19.041	0.00000
Duration*Number of Days	16.151	0.00000
Attrition Rate*Number of Days	10.650	0.00000
MTTR*Proportion Failures Engine	8.665	0.00000
Number of Days*Number of Days	7.749	0.00000
Num Sim Rep	4.886	0.00001 ^
Number of Daily Missions*Engine Safety Stock	4.546	0.00003
Proportion Failures Engine*Proportion Failures Engine	4.072	0.00008
MTTR*Number of Days	3.333	0.00046
Num Sim Rep*Number of Runs	2.253	0.00558
MTBF*MTBF	1.800	0.01585
Proportion Failures Engine	0.641	0.22849 ^
MTTR	0.350	0.44668 ^
Attrition Rate	0.307	0.49309 ^
Engine Resupply Time	0.158	0.69446 ^
Engine Safety Stock	0.118	0.76272 ^

[Remove](#) [Add](#) [Edit](#) ☐ FDR (^ denotes effects with containing effects above them)

Figure 95: Effects Summary: $\sqrt{RunTime}$

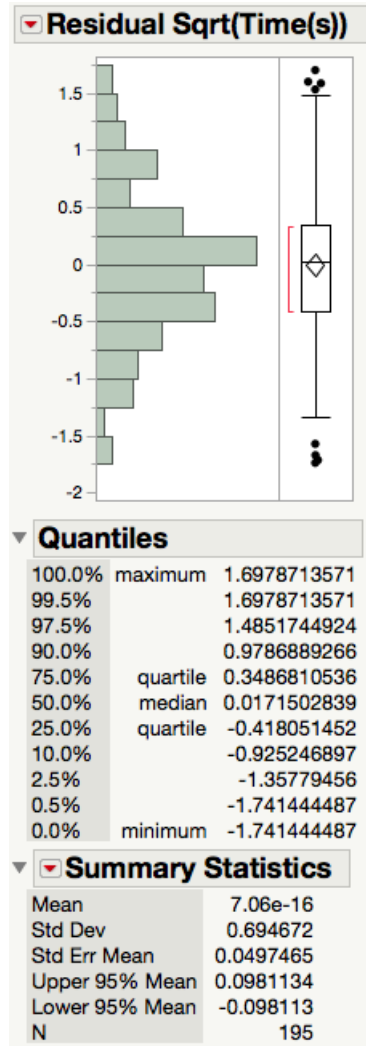


Figure 96: Distribution of Residuals: $\sqrt{RunTime}$

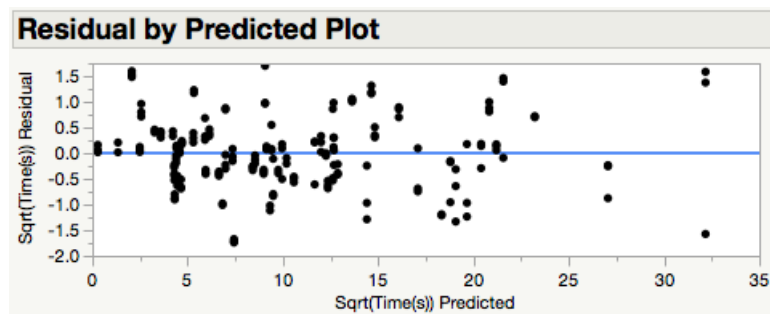


Figure 97: Residuals by Predicted: $\sqrt{RunTime}$

Durbin-Watson			
Durbin-Watson	Number of Obs.	AutoCorrelation	Prob<DW
1.0106434	195	0.4919	<.0001*

Table 43: Durbin-Watson Statistical Test Results: $\sqrt{RunTime}$

Analysis of Effect of Separate Missions Input

Interesting insights from the output data of the run time experiment can also be obtained by normalizing the run times by the respective number of days and the number of replications of each test. This normalization is done by dividing the run time by the product of the number of days and the number of replications that were designated for that specific test. This distribution may provide insight into the the run time of the simulation based on the number of days and the number of replications chosen. Figure 98 shows the distribution of the normalized run times.

Figure 98 shows that 90% of the simulation run times took less than half of a second per product of the number of days and the number of runs (replications). Both Figure 90 and Figure 95 show that separating the missions into single-aircraft missions prior to running the simulation has the third greatest effect on the run time of the simulation. To verify that this difference is present, an experiment is done to test if the run times normalized by the number of days and by the number of replications are different for the methods of separating or not separating missions into single-aircraft missions prior to running the simulation. Two experimental designs are used, which are both equivalent except that one separates missions prior to running the simulation and the other does not. These experimental designs are shown in Table 47 and Table 48 in Appendix A. Each test in each of these experiments were replicated three times. The distribution of the normalized run times of the experiment with separating missions prior to the simulation runs is shown in Figure 99; the distribution of the normalized run times of the experiment where missions were not separated prior to running the simulation is shown in Figure 100. Figure 101 allows for

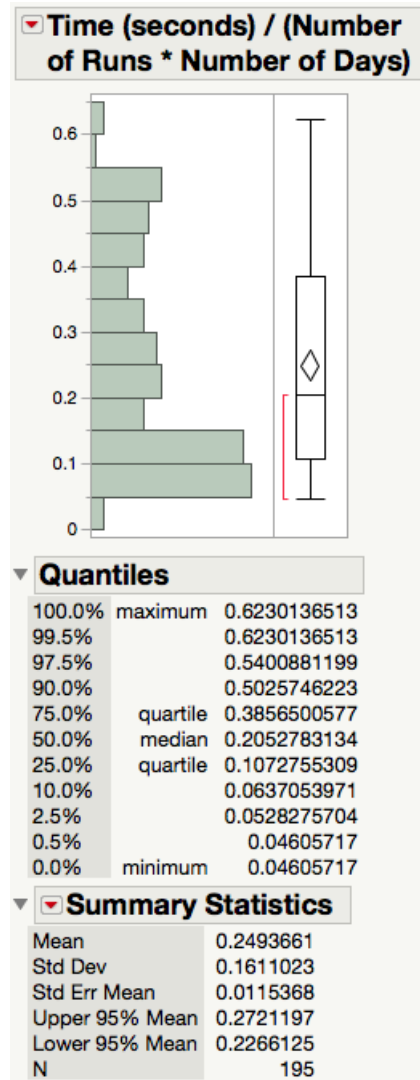


Figure 98: Distribution: $\frac{Time}{NumberofDays*NumberofRuns}$

easier visual comparison of these distributions. Since the experimental designs were equivalent, except for the indicator variable indicating whether or not to separate the missions prior to running the simulation, Figure 101 visually shows that separating the missions could have an impact on the time.

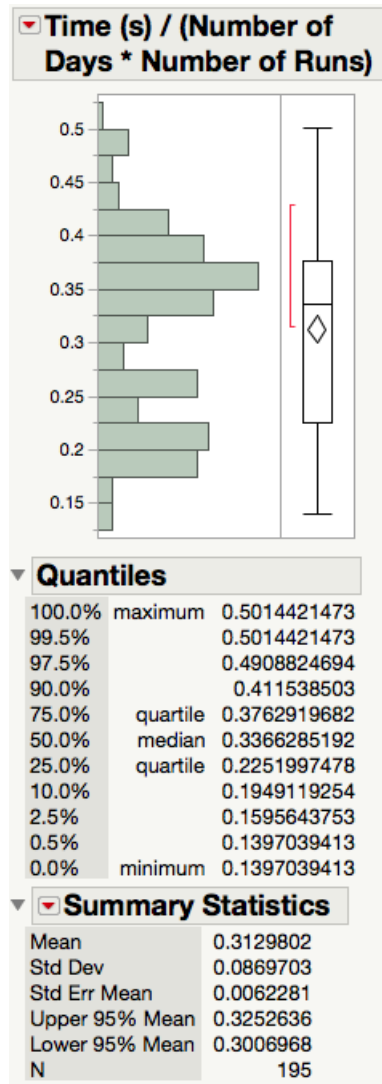


Figure 99: Distribution (Separate Missions Prior): $\frac{Time}{Number of Days * Number of Runs}$

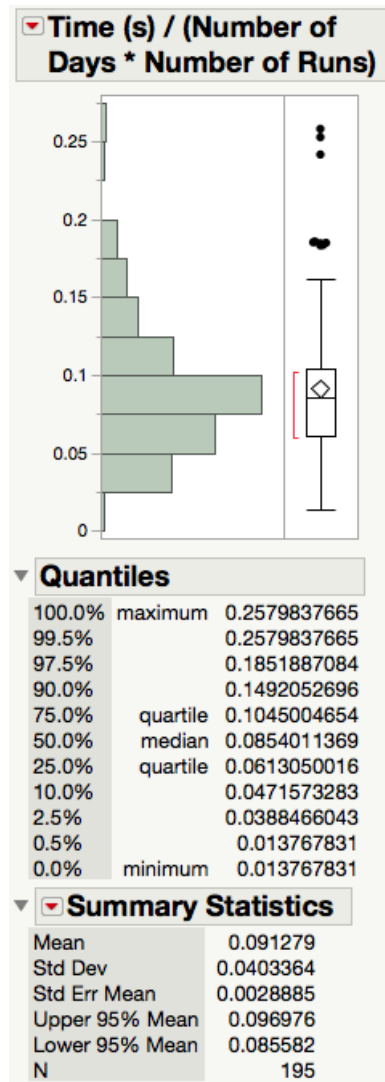


Figure 100: Distribution (Did Not Separate Missions Prior):
 $\frac{\text{Time}}{\text{Number of Days} * \text{Number of Runs}}$

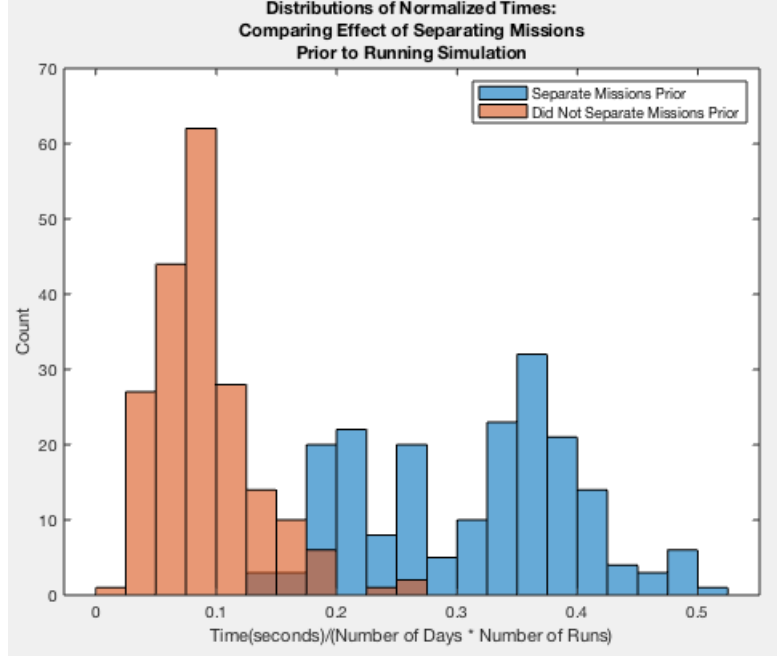


Figure 101: Comparing Distributions (Separate or Not to Separate):
 $\frac{\text{Time}}{\text{Number of Days} * \text{Number of Runs}}$

In order to make a claim that separating missions into single-aircraft missions prior to running the simulation does affect the time it takes to run the simulation, a statistical test must be done to show that the difference between the distributions is statistically significant. Since the distributions of these outputs are not known, a non-parametric test can be done to compare these two distributions. The Mann-Whitney U-Test is a non-parametric statistical test that can be used to compare two independent samples by testing the hypothesis that they are sampled from populations with equal medians[24]. The hypothesis test is as follows:

$$H_o : \zeta_1 = \zeta_2$$

$$H_1 : \zeta_1 \neq \zeta_2$$

Where ζ_1 and ζ_2 are the medians of sample 1 and sample 2 respectively. The

p-value for this test of the distributions was $p = 1.41 * 10^{-63}$; this means that the hypothesis test rejects the null hypothesis and the medians of the two distributions are not equal for an $\alpha = 0.05$. This result indicates that separating the missions into separate single-aircraft missions prior to running the simulation will significantly increase the amount of time the simulation takes to run. Even though separating the missions prior to running the simulation significantly increased the run time, Figure 99 shows that 99.5% of the data points took less than half of a second to run per the product of the number of days and the number of replications. Figure 98 shows that the average time it takes to run the simulation per product of the number of days and the number of replications is a quarter of a second. All of these run time experiments verifies that this simulation tool can run quickly on a laptop computer since the run time cost in terms of the number of days in the simulation and the number of replications is small.

V. Conclusions

This research developed a powerful stepwise simulation tool that can be used for adjudication within long-duration logistical wargames. The simulation tool is able to model many different operational scenarios and can display the expected daily aircraft availability and the expected number of daily missions accomplished. Verification was used to ensure that the model was coded properly and functions as expected. Validation of the model was done to make sure that the simulation model was well-behaved. Insights of the impact of inputs to the simulation were gleaned from analysis of several operation scenarios. The simulation tool was shown to have a short run time for a laptop computer.

The operational scenarios investigated demonstrated how some of the parameters affect the daily aircraft availability and the daily number of missions accomplished. The first scenario investigated the effect of the quantity of daily missions. The scenario showed that increasing the number of missions decreases aircraft availability and increases the number of sorties flown; however, the effect of increasing the quantity of daily missions has a limit since there is each period has a limited amount of time to fly missions. The second scenario showed that increasing the attrition rate resulted in a faster rate of loss of aircraft. The third scenario showed that reinforcing a base with additional aircraft increases the amount of available aircraft at the base. The fourth scenario showed that increasing the MTTR decreases the aircraft availability since increasing the MTTR decreases the rate of repair of damaged aircraft. The fifth scenario showed that increasing the MTBF increases the aircraft availability because it decreases the rate of failure. The sixth scenario showed that had an event that suddenly damages and destroys aircraft can significantly impact the operational capability of the base. Finally, the seventh operation scenario showed that increasing the number of available spares improves the ability of the base to maintain a high

aircraft availability, resulting in an increase in the number of missions accomplished.

5.1 Future Work

There are many directions that future research can improve on this product. Currently, the repair rates are determined by an inputted MTTR; however, it would be beneficial to determine an MTTR as a function of the maintenance personnel and equipment that are available to perform maintenance.

As shown in the *Results and Analysis* section, including a turnaround time to represent debriefing, re-arming of aircraft, and minor maintenance could improve the realism of the model. Giving the user the ability to define a turnaround time for each type of aircraft, which it will have to go through before it will be able to fly its next mission, would be beneficial to the model.

Another future development that may be interesting to investigate is adding the ability of aircraft to be disassembled for working spares that can be used to repair other aircraft. This will add much more complexity to the simulation, but would allow the user to be able to take working parts from a damaged aircraft to fix another aircraft that needs that specific part.

Another future development may be to allow for different repair rates of different parts. Currently, all parts are repaired at the same rate; however, it may be beneficial to allow the user to specify the rates of repair for individual parts. It may also be useful to allow different parts to fail at different rates. It may also be beneficial to develop a feature that allows the user to determine if the part failure is based on flight hours or based on frequency of use. For example, it may be better to model the failure rate of landing gear as a function of the number of sorties that the aircraft flies as opposed to being a function of flight hours. Additionally, future development could also include a way to allow for multiple failures to occur on a single aircraft,

which would get rid of the strong assumption that an aircraft can only have a single failure at any given time.

Another feature that would benefit the simulation tool is to create a version with a parallel computing platform. This could greatly reduce the overall computation time for simulations requiring many replications.

Appendix A. Additional Tables

Table 44: Types of Major Events

Event ID	Event Description	Required Inputs	Simulation Settings
AddNewAircraft	Adds new aircraft of the specified MDS to the specified BASE. Aircraft with a certain MDS can only be added to a base if both the MDS and BASE were properly defined in the Maintenance Data Tables.	{input 1} input 1: Number of Aircraft to Add Range: Positive integer	N/A
AdjustMTTR	Adjusts the Mean Time to Repair (MTTR) of a single aircraft of a specific MDS at the specified BASE.	{input 1} input 1: New MTTR Range: (0, inf)	N/A
AdjustNumberSimultaneousRepair	Adjusts the maximum number of simultaneous repairs of an aircraft with a certain MDS at the specified BASE.	{input 1} input 1: New Maximum Number of Simultaneous Repairs Range: Positive integer	N/A
AdjustMTBF	Adjusts the Mean Time Before Failure (MTBF) of an aircraft with a certain MDS at the specified BASE.	{input 1} input 1: New MTBF Range: (0, inf)	N/A
AdjustAFSC	N/A - This is not a valid event for this version of ENIGMA	N/A	N/A
AccessLogistics	Allows access to entering parts that will replace used spares. By default, bases have access to logistics and are able to replace used spares. This event is used to undo the event "CutOffLogistics."	{}	N/A
CutOffLogistics	Prevents access to entering parts that will replace used spares. By default, bases have access to logistics and are able to replace used spares. Access to new spares is prevented until the event "AccessLogistics" is called to counteract this event. Although new spares are unable to arrive and replaced used spares, each period will still contribute to the amount of time it takes to replace a spare; however, even if the time to replace a spare has been completed, the spare will not be able to be replaced until the logistical cut off has been removed.	{}	Simulation Settings Panel Option: Include Parts Requiring Zero Days to Replace in Cutoff. Selection Options: On: Parts that require a TotalTimeToReplaceSpare input of 0 days are included in the cutoff. Off: Parts that require a TotalTimeToReplaceSpare input of 0 days are excluded from the cutoff. (Default)
DamageAllAircraft	Damages all aircraft types that are at the specified BASE. If a damaged aircraft is selected, there is no effect on this aircraft. Aircraft are selected randomly.	{}	N/A

Table 44 continued from previous page

Event ID	Event Description	Required Inputs	Simulation Settings
DamageProportionAircraft	Damages a proportion of all aircraft types that are at the specified BASE. If a damaged aircraft is selected, there is no effect on this aircraft. Aircraft are selected randomly.	{input 1} input 1: Proportion of Aircraft to Damage Range: [0, 1]	N/A
DestroyProportionAircraft	Destroys a proportion of all aircraft types that are at the specified BASE. Both damaged and mission-capable aircraft can be selected. Aircraft are selected randomly.	{input 1} input 1: Proportion of Aircraft to Destroy Range: [0, 1]	N/A
DamageAndDestroyProportionAircraft	Simultaneously damages and destroys a proportion of all aircraft at the specified BASE. Since the order of major events that occur in a single period is undefined, this event allows aircraft to be simultaneously damaged and destroyed. Aircraft are selected randomly.	{input 1, input 2, input 3} input 1: Proportion of Aircraft to Select to damage and destroy Range: [0, 1] input 2: Damage Weight Range: [0, inf) input 3: Destroy Weight Range: [0, inf) where: $\text{sum}(\text{input 1, input 2}) > 0$	N/A
DamageFixedNumberAircraft	Damages a fixed number of all aircraft that are at the specified BASE. If the number specified is greater than the number of aircraft at the BASE, then the number of aircraft damaged will be equal to the number of aircraft that can be damaged. If a damaged aircraft is selected, there is no effect on this aircraft. Aircraft are selected randomly.	{input 1} input 1: Number of Aircraft to Damage Range: Positive integer	N/A
DestroyFixedNumberAircraft	Destroys a fixed number of all aircraft that are at the specified BASE. If the number specified is greater than the number of aircraft at the BASE, then the number of aircraft destroyed will be equal to the number of aircraft that can be destroyed. Aircraft are selected randomly.	{input 1} input 1: Number of Aircraft to Destroy Range: Positive integer	N/A

Table 44 continued from previous page

Event ID	Event Description	Required Inputs	Simulation Settings
DamageAndDestroyFixedNumberAircraft	Simultaneously damages and destroys a fixed number of all aircraft at the specified BASE. Since the order of major events that occur in a single period is undefined, this event allows aircraft to be simultaneously damaged and destroyed. If the specified number of aircraft to select is greater than the number of aircraft at the specified BASE, then the number of aircraft selected will be equal to the number of aircraft that can be selected. Aircraft are selected randomly.	{input 1, input 2, input 3} input 1: Number of Aircraft to Select to damage and destroy Range: Positive integer input 2: Damage Weight Range: [0, inf) input 3: Destroy Weight Range: [0, inf) where: sum(input 1, input2) > 0 {input 1}	N/A
DamageProportionSpecificAircraft	Damages a proportion of aircraft of a specific MDS that are at the specified BASE. If a damaged aircraft is selected, there is no effect on this aircraft. Aircraft are selected randomly.	input 1: Proportion of Aircraft to Damage Range: [0, 1]	N/A
DamageFixedNumberSpecificAircraft	Damages a fixed number of aircraft of a specific MDS that are at the specified BASE. If the number specified is greater than the number of aircraft at the BASE, then the number of aircraft damaged will be equal to the number of aircraft that can be damaged. If a damaged aircraft is selected, there is no effect on this aircraft. Aircraft are selected randomly.	{input 1} input 1: Number of Aircraft to Damage Range: Positive integer	N/A
DestroyProportionSpecificAircraft	Destroys a proportion of aircraft of a specific MDS that are at the specified BASE. Aircraft are selected randomly.	{input 1} input 1: Proportion of Aircraft to Destroy Range: [0, 1]	N/A
DestroyFixedNumberSpecificAircraft	Destroys a fixed number of aircraft of a specific MDS that are at the specified BASE. If the number specified is greater than the number of aircraft at the BASE, then the number of aircraft destroyed will be equal to the number of aircraft that can be destroyed. Aircraft are selected randomly.	{input 1} input 1: Number of Aircraft to Destroy Range: Positive integer	N/A

Table 44 continued from previous page

Event ID	Event Description	Required Inputs	Simulation Settings
DamageAndDestroyFixedNumberSpecificAircraft	Simultaneously damages and destroys a fixed number of aircraft of a specific MDS at the specified BASE. Since the order of major events that occur in a single period is undefined, this event allows aircraft to be simultaneously damaged and destroyed. If the specified number of aircraft to select is greater than the number of aircraft at the specified BASE, then the number of aircraft selected will be equal to the number of aircraft that can be selected. Aircraft are selected randomly.	{input 1, input 2, input 3} input 1: Number of Aircraft to Select to damage and destroy Range: Positive integer input 2: Damage Weight Range: [0, inf) input 3: Destroy Weight Range: [0, inf) where: $\text{sum}(\text{input 1, input 2}) > 0$	N/A
DamageAndDestroyProportionSpecificAircraft	Simultaneously damages and destroys a proportion of aircraft of a specific MDS at the specified BASE. Since the order of major events that occur in a single period is undefined, this event allows aircraft to be simultaneously damaged and destroyed. Aircraft are selected randomly.	{input 1, input 2, input 3} input 1: Proportion of Aircraft to Select to damage and destroy Range: [0, 1] input 2: Damage Weight Range: [0, inf) input 3: Destroy Weight Range: [0, inf) where: $\text{sum}(\text{input 1, input 2}) > 0$	N/A

Table 45: Experimental Design: Simulation Behavior

Property	Attrition Rate	Aircrafts per wing	Number Of Missions Each Day	Duration of each mission	MTBF	MTTR	Maximum Number of Simultaneous Repairs	Engine Safety Stock	Engine Resupply Time	Proportion of Failures that are Engine Failures
Lower Range	0.00005	18	15	1.5	8	2	1	0	7	0.05
Upper Range	0.001	24	45	8	50	10	5	5	14	0.1
Test 1	0.001	19	28	2.72	44.75	7	3	5	12	0.08
Test 2	0.000911	24	19	3.94	27.69	3.5	2	5	10	0.09
Test 3	0.000881	21	42	2.52	9.31	6.75	1	2	14	0.07
Test 4	0.000584	23	45	4.14	47.38	3.25	1	2	8	0.06
Test 5	0.000941	18	29	2.92	36.88	7.75	3	0	8	0.08
Test 6	0.00097	24	24	3.33	26.38	3.75	5	0	11	0.09
Test 7	0.000703	21	44	3.13	8	7.25	5	4	7	0.06
Test 8	0.000555	22	43	3.73	46.06	4	5	3	14	0.06
Test 9	0.000673	20	22	4.95	38.19	4.5	2	3	11	0.05
Test 10	0.000763	22	23	5.97	17.19	6.25	3	4	8	0.05
Test 11	0.000733	19	38	7.8	22.44	2.5	2	2	11	0.08
Test 12	0.000792	22	35	7.59	39.5	9.75	3	1	8	0.08
Test 13	0.000614	19	21	5.16	32.94	3	4	2	9	0.05
Test 14	0.000852	22	26	7.19	14.56	6.5	4	1	12	0.06
Test 15	0.000644	19	40	7.39	23.75	2	4	4	9	0.1
Test 16	0.000822	22	33	8	42.13	9.25	4	4	12	0.08
Test 17	0.000525	21	30	4.75	29	6	3	3	11	0.08
Test 18	0.00005	23	32	6.78	13.25	5	3	0	9	0.07
Test 19	0.000139	18	41	5.56	30.31	8.5	4	0	11	0.06
Test 20	0.000169	21	18	6.98	48.69	5.25	5	3	7	0.08
Test 21	0.000466	19	15	5.36	10.63	8.75	5	3	13	0.09
Test 22	0.000109	24	31	6.58	21.13	4.25	3	5	13	0.07
Test 23	0.00008	18	36	6.17	31.63	8.25	2	5	10	0.06
Test 24	0.000347	21	16	6.38	50	4.75	1	1	14	0.09
Test 25	0.000495	20	17	5.77	11.94	8	1	2	7	0.09
Test 26	0.000377	23	38	4.55	19.81	7.5	4	2	10	0.1
Test 27	0.000288	20	37	3.53	40.81	5.75	4	1	13	0.1
Test 28	0.000317	23	23	1.7	35.56	9.5	4	3	10	0.07

Table 45 continued from previous page

Property	Attrition Rate	Aircrafts per wing	Number Of Missions Each Day	Duration of each mission	MTBF	MTTR	Maximum Number of Simultaneous Repairs	Engine Safety Stock	Engine Resupply Time	Proportion of Failures that are Engine Failures
Test 29	0.000258	20	25	1.91	18.5	2.25	3	4	13	0.07
Test 30	0.000436	23	39	4.34	25.06	9	2	3	12	0.1
Test 31	0.000198	20	34	2.31	43.44	5.5	2	4	9	0.09
Test 32	0.000406	23	20	2.11	34.25	10	2	1	12	0.05
Test 33	0.000228	20	27	1.5	15.88	2.75	2	1	9	0.07

Table 46: Experimental Design Run Time

Property	Attrition Rate	Aircrafts per wing	Number Of Missions Each Day	Duration of each mission	MTBF	MTTR	Maximum Number of Simultaneous Repairs	Engine Safety Stock	Engine Resupply Time	Proportion of Failures that are Engine Failures	Number of Days	Number of Runs	Separate Missions (1: Yes) (0: No)
Lower Range	0.00005	18	15	1.5	8	2	1	0	9	0.05	1	1	0
Upper Range	0.001	24	45	8	50	10	5	5	12	0.1	75	30	1
Test 1	0.000733	18	26	3.63	13.25	8.13	3	5	11	0.08	70	6	1
Test 2	0.000955	22	18	4.24	22.44	4	4	4	12	0.09	37	8	0
Test 3	0.000896	20	44	2.92	20.47	8.88	3	2	11	0.09	66	15	1
Test 4	0.000659	23	37	4.45	10.63	5.38	2	1	12	0.1	47	3	0
Test 5	0.000926	21	21	1.6	11.94	3.25	3	3	10	0.05	63	20	1
Test 6	0.000555	24	22	4.65	14.56	7.25	4	4	9	0.07	59	27	0
Test 7	0.000777	19	31	1.7	18.5	4.63	3	1	10	0.07	68	29	1
Test 8	0.000822	23	43	3.53	23.75	9.38	1	1	10	0.05	48	22	0
Test 9	0.000703	18	15	6.78	25.06	6.88	1	4	10	0.09	30	11	0
Test 10	0.00097	22	30	6.48	8	4.25	3	3	9	0.08	3	13	1
Test 11	0.00054	18	44	4.95	16.53	5.5	4	0	10	0.09	15	7	0
Test 12	0.000985	21	36	7.49	15.22	2.5	4	2	10	0.08	20	14	1
Test 13	0.00057	19	25	5.66	24.41	5.88	2	5	12	0.06	4	30	0
Test 14	0.000792	21	28	7.29	19.16	9.75	1	3	11	0.06	23	16	1
Test 15	0.000599	20	38	7.7	26.38	3.75	5	1	11	0.05	33	29	0
Test 16	0.000688	21	31	6.17	13.91	9.63	3	2	11	0.07	9	21	1
Test 17	0.000866	21	27	2.31	36.22	10	5	3	11	0.07	22	13	1
Test 18	0.000584	23	23	3.73	32.28	5.63	4	2	11	0.06	1	1	0
Test 19	0.000748	20	32	3.43	40.81	9.13	3	3	11	0.07	7	7	1
Test 20	0.000629	22	41	1.91	30.97	3.38	2	4	12	0.05	32	6	0
Test 21	0.000837	19	27	2.11	49.34	5	4	1	9	0.07	14	19	1
Test 22	0.000807	23	15	2.52	29.66	7.63	5	1	10	0.1	24	22	0
Test 23	0.001	20	39	3.13	48.69	3	2	3	10	0.08	21	17	1
Test 24	0.000614	24	40	3.94	36.88	6.25	2	5	9	0.09	16	26	0
Test 25	0.000644	20	18	5.36	42.13	7.88	2	0	9	0.06	50	5	0
Test 26	0.000763	22	20	8	40.16	3.5	2	2	10	0.05	65	11	1
Test 27	0.000852	19	38	6.68	30.31	9.25	5	4	10	0.06	45	10	0
Test 28	0.000911	23	34	6.88	46.72	4.5	4	4	10	0.07	74	3	1

Table 46 continued from previous page

Property	Attrition Rate	Aircrafts per wing	Number Of Missions Each Day	Duration of each mission	MTBF	MTTR	Maximum Number of Simultaneous Repairs	Engine Safety Stock	Engine Resupply Time	Proportion of Failures that are Engine Failures	Number of Days	Number of Runs	Separate Missions (1: Yes) (0: No)
Test 29	0.000941	20	19	5.46	34.91	3.63	1	1	12	0.09	41	27	0
Test 30	0.000718	24	25	6.27	45.41	9.88	3	0	11	0.08	51	25	1
Test 31	0.000673	19	36	5.16	48.03	5.25	4	5	12	0.09	40	23	0
Test 32	0.000881	22	43	7.09	38.19	7.13	4	3	11	0.09	58	19	1
Test 33	0.000525	21	30	4.75	29	6	3	3	11	0.08	38	16	1
Test 34	0.000317	24	34	5.87	44.75	3.88	3	0	10	0.07	6	25	0
Test 35	0.000095	20	42	5.26	35.56	8	2	1	9	0.06	39	23	1
Test 36	0.000154	22	16	6.58	37.53	3.13	3	3	10	0.06	10	16	0
Test 37	0.000391	19	23	5.05	47.38	6.63	4	4	9	0.05	29	28	1
Test 38	0.000124	21	39	7.9	46.06	8.75	3	2	11	0.1	13	11	0
Test 39	0.000495	18	38	4.85	43.44	4.75	2	1	12	0.08	17	4	1
Test 40	0.000273	23	29	7.8	39.5	7.38	3	4	11	0.08	8	2	0
Test 41	0.000228	19	17	5.97	34.25	2.63	5	4	11	0.1	28	9	1
Test 42	0.000347	24	45	2.72	32.94	5.13	5	1	11	0.06	46	20	1
Test 43	0.00008	20	30	3.02	50	7.75	4	2	12	0.07	73	18	0
Test 44	0.00051	24	16	4.55	41.47	6.5	2	5	11	0.06	61	24	1
Test 45	0.000065	21	24	2.01	42.78	9.5	2	3	11	0.07	57	17	0
Test 46	0.00048	23	35	3.84	33.59	6.13	4	0	9	0.09	72	1	1
Test 47	0.000258	21	32	2.21	38.84	2.25	5	2	10	0.09	53	15	0
Test 48	0.000451	22	22	1.8	31.63	8.25	1	4	10	0.1	43	2	1
Test 49	0.000362	21	29	3.33	44.09	2.38	3	3	10	0.08	67	10	0
Test 50	0.000184	21	33	7.19	21.78	2	1	2	10	0.08	54	18	0
Test 51	0.000466	19	37	5.77	25.72	6.38	2	3	10	0.09	75	30	1
Test 52	0.000302	22	28	6.07	17.19	2.88	3	2	10	0.08	69	24	0
Test 53	0.000421	20	19	7.59	27.03	8.63	4	1	9	0.1	44	25	1
Test 54	0.000213	23	33	7.39	8.66	7	2	4	12	0.08	62	12	0
Test 55	0.000243	19	45	6.98	28.34	4.38	1	4	11	0.05	52	9	1
Test 56	0.00005	22	21	6.38	9.31	9	5	2	11	0.07	55	14	0
Test 57	0.000436	18	20	5.56	21.13	5.75	4	0	12	0.06	60	5	1
Test 58	0.000406	23	42	4.14	15.88	4.13	4	5	12	0.09	26	26	1
Test 59	0.000288	20	40	1.5	17.84	8.5	4	3	11	0.1	11	20	0

Table 46 continued from previous page

Property	Attrition Rate	Aircrafts per wing	Number Of Missions Each Day	Duration of each mission	MTBF	MTTR	Maximum Number of Simultaneous Repairs	Engine Safety Stock	Engine Resupply Time	Proportion of Failures that are Engine Failures	Number of Days	Number of Runs	Separate Missions (1: Yes) (0: No)
Test 60	0.000198	23	23	2.82	27.69	2.75	1	1	11	0.09	31	21	1
Test 61	0.000139	19	26	2.62	11.28	7.5	2	1	11	0.08	2	28	0
Test 62	0.000109	22	41	4.04	23.09	8.38	5	4	9	0.06	35	4	1
Test 63	0.000332	18	35	3.23	12.59	2.13	3	5	10	0.07	25	6	0
Test 64	0.000377	23	24	4.34	9.97	6.75	2	0	9	0.06	36	8	1
Test 65	0.000169	20	17	2.41	19.81	4.88	2	2	10	0.06	18	12	0

Table 47: Experimental Design Run Time (Separate Missions Prior to Running Simulation)

Property	Attrition Rate	Aircrafts per wing	Number Of Missions Each Day	Duration of each mission	MTBF	MTTR	Maximum Number of Simultaneous Repairs	Engine Safety Stock	Engine Resupply Time	Proportion of Failures that are Engine Failures	Number of Days	Number of Runs	Separate Missions (1: Yes) (0: No)
Lower Range	0.00005	18	15	1.5	8	2	1	0	9	0.05	1	1	1
Upper Range	0.001	24	45	8	50	10	5	5	12	0.1	75	30	1
Test 1	0.000733	18	26	3.63	13.25	8.13	3	5	11	0.08	70	6	1
Test 2	0.000955	22	18	4.24	22.44	4	4	4	12	0.09	37	8	1
Test 3	0.000896	20	44	2.92	20.47	8.88	3	2	11	0.09	66	15	1
Test 4	0.000659	23	37	4.45	10.63	5.38	2	1	12	0.1	47	3	1
Test 5	0.000926	21	21	1.6	11.94	3.25	3	3	10	0.05	63	20	1
Test 6	0.000555	24	22	4.65	14.56	7.25	4	4	9	0.07	59	27	1
Test 7	0.000777	19	31	1.7	18.5	4.63	3	1	10	0.07	68	29	1
Test 8	0.000822	23	43	3.53	23.75	9.38	1	1	10	0.05	48	22	1
Test 9	0.000703	18	15	6.78	25.06	6.88	1	4	10	0.09	30	11	1
Test 10	0.00097	22	30	6.48	8	4.25	3	3	9	0.08	3	13	1
Test 11	0.00054	18	44	4.95	16.53	5.5	4	0	10	0.09	15	7	1
Test 12	0.000985	21	36	7.49	15.22	2.5	4	2	10	0.08	20	14	1
Test 13	0.00057	19	25	5.66	24.41	5.88	2	5	12	0.06	4	30	1
Test 14	0.000792	21	28	7.29	19.16	9.75	1	3	11	0.06	23	16	1
Test 15	0.000599	20	38	7.7	26.38	3.75	5	1	11	0.05	33	29	1
Test 16	0.000688	21	31	6.17	13.91	9.63	3	2	11	0.07	9	21	1
Test 17	0.000866	21	27	2.31	36.22	10	5	3	11	0.07	22	13	1
Test 18	0.000584	23	23	3.73	32.28	5.63	4	2	11	0.06	1	1	1
Test 19	0.000748	20	32	3.43	40.81	9.13	3	3	11	0.07	7	7	1
Test 20	0.000629	22	41	1.91	30.97	3.38	2	4	12	0.05	32	6	1
Test 21	0.000837	19	27	2.11	49.34	5	4	1	9	0.07	14	19	1
Test 22	0.000807	23	15	2.52	29.66	7.63	5	1	10	0.1	24	22	1
Test 23	0.001	20	39	3.13	48.69	3	2	3	10	0.08	21	17	1
Test 24	0.000614	24	40	3.94	36.88	6.25	2	5	9	0.09	16	26	1
Test 25	0.000644	20	18	5.36	42.13	7.88	2	0	9	0.06	50	5	1
Test 26	0.000763	22	20	8	40.16	3.5	2	2	10	0.05	65	11	1
Test 27	0.000852	19	38	6.68	30.31	9.25	5	4	10	0.06	45	10	1
Test 28	0.000911	23	34	6.88	46.72	4.5	4	4	10	0.07	74	3	1

Table 47 continued from previous page

Property	Attrition Rate	Aircrafts per wing	Number Of Missions Each Day	Duration of each mission	MTBF	MTTR	Maximum Number of Simultaneous Repairs	Engine Safety Stock	Engine Resupply Time	Proportion of Failures that are Engine Failures	Number of Days	Number of Runs	Separate Missions (1: Yes) (0: No)
Test 29	0.000941	20	19	5.46	34.91	3.63	1	1	12	0.09	41	27	1
Test 30	0.000718	24	25	6.27	45.41	9.88	3	0	11	0.08	51	25	1
Test 31	0.000673	19	36	5.16	48.03	5.25	4	5	12	0.09	40	23	1
Test 32	0.000881	22	43	7.09	38.19	7.13	4	3	11	0.09	58	19	1
Test 33	0.000525	21	30	4.75	29	6	3	3	11	0.08	38	16	1
Test 34	0.000317	24	34	5.87	44.75	3.88	3	0	10	0.07	6	25	1
Test 35	0.000095	20	42	5.26	35.56	8	2	1	9	0.06	39	23	1
Test 36	0.000154	22	16	6.58	37.53	3.13	3	3	10	0.06	10	16	1
Test 37	0.000391	19	23	5.05	47.38	6.63	4	4	9	0.05	29	28	1
Test 38	0.000124	21	39	7.9	46.06	8.75	3	2	11	0.1	13	11	1
Test 39	0.000495	18	38	4.85	43.44	4.75	2	1	12	0.08	17	4	1
Test 40	0.000273	23	29	7.8	39.5	7.38	3	4	11	0.08	8	2	1
Test 41	0.000228	19	17	5.97	34.25	2.63	5	4	11	0.1	28	9	1
Test 42	0.000347	24	45	2.72	32.94	5.13	5	1	11	0.06	46	20	1
Test 43	0.00008	20	30	3.02	50	7.75	4	2	12	0.07	73	18	1
Test 44	0.00051	24	16	4.55	41.47	6.5	2	5	11	0.06	61	24	1
Test 45	0.000065	21	24	2.01	42.78	9.5	2	3	11	0.07	57	17	1
Test 46	0.00048	23	35	3.84	33.59	6.13	4	0	9	0.09	72	1	1
Test 47	0.000258	21	32	2.21	38.84	2.25	5	2	10	0.09	53	15	1
Test 48	0.000451	22	22	1.8	31.63	8.25	1	4	10	0.1	43	2	1
Test 49	0.000362	21	29	3.33	44.09	2.38	3	3	10	0.08	67	10	1
Test 50	0.000184	21	33	7.19	21.78	2	1	2	10	0.08	54	18	1
Test 51	0.000466	19	37	5.77	25.72	6.38	2	3	10	0.09	75	30	1
Test 52	0.000302	22	28	6.07	17.19	2.88	3	2	10	0.08	69	24	1
Test 53	0.000421	20	19	7.59	27.03	8.63	4	1	9	0.1	44	25	1
Test 54	0.000213	23	33	7.39	8.66	7	2	4	12	0.08	62	12	1
Test 55	0.000243	19	45	6.98	28.34	4.38	1	4	11	0.05	52	9	1
Test 56	0.00005	22	21	6.38	9.31	9	5	2	11	0.07	55	14	1
Test 57	0.000436	18	20	5.56	21.13	5.75	4	0	12	0.06	60	5	1
Test 58	0.000406	23	42	4.14	15.88	4.13	4	5	12	0.09	26	26	1
Test 59	0.000288	20	40	1.5	17.84	8.5	4	3	11	0.1	11	20	1

Table 47 continued from previous page

Property	Attrition Rate	Aircrafts per wing	Number Of Missions Each Day	Duration of each mission	MTBF	MTTR	Maximum Number of Simultaneous Repairs	Engine Safety Stock	Engine Resupply Time	Proportion of Failures that are Engine Failures	Number of Days	Number of Runs	Separate Missions (1: Yes) (0: No)
Test 60	0.000198	23	23	2.82	27.69	2.75	1	1	11	0.09	31	21	1
Test 61	0.000139	19	26	2.62	11.28	7.5	2	1	11	0.08	2	28	1
Test 62	0.000109	22	41	4.04	23.09	8.38	5	4	9	0.06	35	4	1
Test 63	0.000332	18	35	3.23	12.59	2.13	3	5	10	0.07	25	6	1
Test 64	0.000377	23	24	4.34	9.97	6.75	2	0	9	0.06	36	8	1
Test 65	0.000169	20	17	2.41	19.81	4.88	2	2	10	0.06	18	12	1

Table 48: Experimental Design Run Time (Does Not Separate Missions Prior to Running Simulation)

Property	Attrition Rate	Aircrafts per wing	Number Of Missions Each Day	Duration of each mission	MTBF	MTTR	Maximum Number of Simultaneous Repairs	Engine Safety Stock	Engine Resupply Time	Proportion of Failures that are Engine Failures	Number of Days	Number of Runs	Separate Missions (1: Yes) (0: No)
Lower Range	0.00005	18	15	1.5	8	2	1	0	9	0.05	1	1	0
Upper Range	0.001	24	45	8	50	10	5	5	12	0.1	75	30	0
Test 1	0.000733	18	26	3.63	13.25	8.13	3	5	11	0.08	70	6	0
Test 2	0.000955	22	18	4.24	22.44	4	4	4	12	0.09	37	8	0
Test 3	0.000896	20	44	2.92	20.47	8.88	3	2	11	0.09	66	15	0
Test 4	0.000659	23	37	4.45	10.63	5.38	2	1	12	0.1	47	3	0
Test 5	0.000926	21	21	1.6	11.94	3.25	3	3	10	0.05	63	20	0
Test 6	0.000555	24	22	4.65	14.56	7.25	4	4	9	0.07	59	27	0
Test 7	0.000777	19	31	1.7	18.5	4.63	3	1	10	0.07	68	29	0
Test 8	0.000822	23	43	3.53	23.75	9.38	1	1	10	0.05	48	22	0
Test 9	0.000703	18	15	6.78	25.06	6.88	1	4	10	0.09	30	11	0
Test 10	0.00097	22	30	6.48	8	4.25	3	3	9	0.08	3	13	0
Test 11	0.00054	18	44	4.95	16.53	5.5	4	0	10	0.09	15	7	0
Test 12	0.00085	21	36	7.49	15.22	2.5	4	2	10	0.08	20	14	0
Test 13	0.00057	19	25	5.66	24.41	5.88	2	5	12	0.06	4	30	0
Test 14	0.000792	21	28	7.29	19.16	9.75	1	3	11	0.06	23	16	0
Test 15	0.000599	20	38	7.7	26.38	3.75	5	1	11	0.05	33	29	0
Test 16	0.000688	21	31	6.17	13.91	9.63	3	2	11	0.07	9	21	0
Test 17	0.000866	21	27	2.31	36.22	10	5	3	11	0.07	22	13	0
Test 18	0.000584	23	23	3.73	32.28	5.63	4	2	11	0.06	1	1	0
Test 19	0.000748	20	32	3.43	40.81	9.13	3	3	11	0.07	7	7	0
Test 20	0.000629	22	41	1.91	30.97	3.38	2	4	12	0.05	32	6	0
Test 21	0.000837	19	27	2.11	49.34	5	4	1	9	0.07	14	19	0
Test 22	0.000807	23	15	2.52	29.66	7.63	5	1	10	0.1	24	22	0
Test 23	0.001	20	39	3.13	48.69	3	2	3	10	0.08	21	17	0
Test 24	0.000614	24	40	3.94	36.88	6.25	2	5	9	0.09	16	26	0
Test 25	0.000644	20	18	5.36	42.13	7.88	2	0	9	0.06	50	5	0
Test 26	0.000763	22	20	8	40.16	3.5	2	2	10	0.05	65	11	0
Test 27	0.000852	19	38	6.68	30.31	9.25	5	4	10	0.06	45	10	0

Table 48 continued from previous page

Property	Attrition Rate	Aircrafts per wing	Number Of Missions Each Day	Duration of each mission	MTBF	MTTR	Maximum Number of Simultaneous Repairs	Engine Safety Stock	Engine Resupply Time	Proportion of Failures that are Engine Failures	Number of Days	Number of Runs	Separate Missions (1: Yes) (0: No)
Test 28	0.000911	23	34	6.88	46.72	4.5	4	4	10	0.07	74	3	0
Test 29	0.000941	20	19	5.46	34.91	3.63	1	1	12	0.09	41	27	0
Test 30	0.000718	24	25	6.27	45.41	9.88	3	0	11	0.08	51	25	0
Test 31	0.000673	19	36	5.16	48.03	5.25	4	5	12	0.09	40	23	0
Test 32	0.000881	22	43	7.09	38.19	7.13	4	3	11	0.09	58	19	0
Test 33	0.000525	21	30	4.75	29	6	3	3	11	0.08	38	16	0
Test 34	0.000317	24	34	5.87	44.75	3.88	3	0	10	0.07	6	25	0
Test 35	0.000095	20	42	5.26	35.56	8	2	1	9	0.06	39	23	0
Test 36	0.000154	22	16	6.58	37.53	3.13	3	3	10	0.06	10	16	0
Test 37	0.000391	19	23	5.05	47.38	6.63	4	4	9	0.05	29	28	0
Test 38	0.000124	21	39	7.9	46.06	8.75	3	2	11	0.1	13	11	0
Test 39	0.000495	18	38	4.85	43.44	4.75	2	1	12	0.08	17	4	0
Test 40	0.000273	23	29	7.8	39.5	7.38	3	4	11	0.08	8	2	0
Test 41	0.000228	19	17	5.97	34.25	2.63	5	4	11	0.1	28	9	0
Test 42	0.000347	24	45	2.72	32.94	5.13	5	1	11	0.06	46	20	0
Test 43	0.00008	20	30	3.02	50	7.75	4	2	12	0.07	73	18	0
Test 44	0.00051	24	16	4.55	41.47	6.5	2	5	11	0.06	61	24	0
Test 45	0.000065	21	24	2.01	42.78	9.5	2	3	11	0.07	57	17	0
Test 46	0.00048	23	35	3.84	33.59	6.13	4	0	9	0.09	72	1	0
Test 47	0.000258	21	32	2.21	38.84	2.25	5	2	10	0.09	53	15	0
Test 48	0.000451	22	22	1.8	31.63	8.25	1	4	10	0.1	43	2	0
Test 49	0.000362	21	29	3.33	44.09	2.38	3	3	10	0.08	67	10	0
Test 50	0.000184	21	33	7.19	21.78	2	1	2	10	0.08	54	18	0
Test 51	0.000466	19	37	5.77	25.72	6.38	2	3	10	0.09	75	30	0
Test 52	0.000302	22	28	6.07	17.19	2.88	3	2	10	0.08	69	24	0
Test 53	0.000421	20	19	7.59	27.03	8.63	4	1	9	0.1	44	25	0
Test 54	0.000213	23	33	7.39	8.66	7	2	4	12	0.08	62	12	0
Test 55	0.000243	19	45	6.98	28.34	4.38	1	4	11	0.05	52	9	0
Test 56	0.00005	22	21	6.38	9.31	9	5	2	11	0.07	55	14	0
Test 57	0.000436	18	20	5.56	21.13	5.75	4	0	12	0.06	60	5	0
Test 58	0.000406	23	42	4.14	15.88	4.13	4	5	12	0.09	26	26	0

Table 48 continued from previous page

Property	Attrition Rate	Aircrafts per wing	Number Of Missions Each Day	Duration of each mission	MTBF	MTTR	Maximum Number of Simultaneous Repairs	Engine Safety Stock	Engine Resupply Time	Proportion of Failures that are Engine Failures	Number of Days	Number of Runs	Separate Missions (1: Yes) (0: No)
Test 59	0.000288	20	40	1.5	17.84	8.5	4	3	11	0.1	11	20	0
Test 60	0.000198	23	23	2.82	27.69	2.75	1	1	11	0.09	31	21	0
Test 61	0.000139	19	26	2.62	11.28	7.5	2	1	11	0.08	2	28	0
Test 62	0.000109	22	41	4.04	23.09	8.38	5	4	9	0.06	35	4	0
Test 63	0.000332	18	35	3.23	12.59	2.13	3	5	10	0.07	25	6	0
Test 64	0.000377	23	24	4.34	9.97	6.75	2	0	9	0.06	36	8	0
Test 65	0.000169	20	17	2.41	19.81	4.88	2	2	10	0.06	18	12	0

Bibliography

1. Harold S Balaban, Robert T Brigantic, Samuel A Wright, and Anthony F Papatyi. A simulation approach to estimating aircraft mission capable rates for the united states air force. In *2000 Winter Simulation Conference Proceedings (Cat. No. 00CH37165)*, volume 1, pages 1035–1042. IEEE, 2000.
2. Adam MacKenzie, John O Miller, Raymond R Hill, and Stephen P Chambal. Application of agent based modelling to aircraft maintenance manning and sortie generation. *Simulation Modelling Practice and Theory*, 20(1):89–98, 2012.
3. Paul D Faas and JO Miller. Impact of an autonomic logistics system (als) on the sortie generation process. In *Winter Simulation Conference*, volume 1, pages 1021–1025, 2003.
4. Bahadir Aykiri. Simulation of modeling sortie generation process in turaf. *Theses and Dissertations*, 2016.
5. Adam MacKenzie, John O Miller, and Raymond Hill. An exploration of the effects of maintenance manning on combat mission readiness utilizing agent based modeling. In *Proceedings of the 2010 Winter Simulation Conference*, pages 1376–1382. IEEE, 2010.
6. Dennis C Dietz and Richard C Jenkins. Analysis of aircraft sortie generation with the use of a fork-join queueing network model. *Naval Research Logistics (NRL)*, 44(2):153–164, 1997.
7. Adem Okal. Simulation modeling and analysis of f-16 pilot training squadron. *Theses and Dissertations*, 2008.

8. Hamed Jalali and Inneke Van Nieuwenhuyse. Simulation optimization in inventory replenishment: A classification. *IEE Transactions*, 47(11):1217–1235, 2015.
9. LL Goldman. Crystal ball professional introductory tutorial. In *Proceedings of the Winter Simulation Conference*, volume 2, pages 1539–1545. IEEE, 2002.
10. Thomas R O’Neal. Sortie-based aircraft component demand rate to predict requirements. *Theses and Dissertations*, 2020.
11. James Waugh Harris. The sortie generation rate model. In *Proceedings of the Winter Simulation Conference*, volume 1, pages 864–868. IEEE, 2002.
12. Changsung Kim. Simulation modeling and analysis of air force depot engine repair during normal and increased operational tempos. 2016.
13. Jerry Banks, John S. Carson II, Barry L. Nelson, and David M. Nicol. *Discrete-Event System Simulation Fifth Edition*. Pearson Education Inc., 2010.
14. Georgiy V Bobashev, D Michael Goedecke, Feng Yu, and Joshua M Epstein. A hybrid epidemic model: Combining the advantages of agent-based and equation-based approaches. In *2007 Winter Simulation Conference*, pages 1532–1537. IEEE, 2007.
15. Pankaj Sharma, Makarand S Kulkarni, and Vikas Yadav. A simulation based optimization approach for spare parts forecasting and selective maintenance. *Reliability Engineering & System Safety*, 168:274–289, 2017.
16. Abdullah Alrabghi and Ashutosh Tiwari. A novel approach for modelling complex maintenance systems using discrete event simulation. *Reliability Engineering & System Safety*, 154:160–170, 2016.

17. Paul D Faas. Simulation of autonomic logistics system (als) sortie generation. Technical report, Air Force Inst. of Tech Wright-Patterson AFB OH School of Engineering and Management, 2003.
18. Neil J Gunther. *Analyzing Computer System Performance with Perl:: PDQ*. Springer Science & Business Media, 2011.
19. Russell R Barton. Tutorial: Simulation metamodeling. In *2015 Winter Simulation Conference (WSC)*, pages 1765–1779. IEEE, 2015.
20. S. M. Sanchez and H. Wan. Work smarter, not harder: A tutorial on designing and conducting simulation experiments. In *2015 Winter Simulation Conference (WSC)*, pages 1795–1809, 2015.
21. Thomas M Cioppa and Thomas W Lucas. Efficient nearly orthogonal and space-filling latin hypercubes. *Technometrics*, 49(1):45–55, 2007.
22. S.M. Sanchez. NOLH designs spreadsheet. <http://harvestnps.edu/>, 2011. [online; accessed 08/24/2020].
23. Douglas C Montgomery, Elizabeth A Peck, and G Geoffrey Vining. *Introduction to linear regression analysis*, volume 821. John Wiley & Sons, 2012.
24. *Comparing Two Unrelated Samples: The Mann–Whitney U-Test*, chapter 4, pages 57–78. John Wiley Sons, Ltd, 2011.

REPORT DOCUMENTATION PAGE					<i>Form Approved</i> 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) 24-12-2020		2. REPORT TYPE Master's Thesis			3. DATES COVERED (From — To) Oct 2019 — Dec 2020							
4. TITLE AND SUBTITLE The Effects of Aircraft Use and Available Repair Spares on Aircraft Sortie Generation: A Long-Duration Logistical Wargaming Simulation Tool					5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER 5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER 							
6. AUTHOR(S) Nathaniel M. Choo					8. PERFORMING ORGANIZATION REPORT NUMBER AFIT-ENS-MS-20-D-069							
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					10. SPONSOR/MONITOR'S ACRONYM(S) HQ AFMC/A5R							
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) HQ AFMC/A5R 4225 Logistics Ave #S205 WPAFB OH 45433-7765 937.656.3938 (DSN 986), cell: 937.974.1999, email: david.farrell.8@us.af.mil Mr. David Farrell, ISWAT Program Manager					11. SPONSOR/MONITOR'S REPORT NUMBER(S)							
12. DISTRIBUTION / AVAILABILITY STATEMENT DISTRIBUTION STATEMENT A: APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.												
13. SUPPLEMENTARY NOTES This material is declared a work of the U.S. Government and is not subject to copyright protection in the United States.												
14. ABSTRACT A long-duration logistical wargame simulation tool that can provide quick insights into the daily aircraft availability and the daily number of missions accomplished for a variety of operational scenarios is developed. This simulation tool is designed to be a stepwise wargaming support tool for adjudication within long-duration logistical wargames and provides the user many capabilities including, but not limited to, the ability to have multiple bases and types of aircraft. Additionally, the user has the ability to control types of part failures, control parts availability, control maintenance capabilities, and control number of mission scheduled. Finally, the user can account for the possibility of attrition along with the effects of numerous major events present in real-life scenarios.												
15. SUBJECT TERMS subject terms here												
16. SECURITY CLASSIFICATION OF: <table border="1" style="width: 100%; border-collapse: collapse; font-size: x-small;"> <tr> <td style="width: 33%;">a. REPORT</td> <td style="width: 33%;">b. ABSTRACT</td> <td style="width: 33%;">c. THIS PAGE</td> </tr> <tr> <td style="text-align: center;">U</td> <td style="text-align: center;">U</td> <td style="text-align: center;">U</td> </tr> </table>			a. REPORT	b. ABSTRACT	c. THIS PAGE	U	U	U	17. LIMITATION OF ABSTRACT UU		18. NUMBER OF PAGES 176	
a. REPORT	b. ABSTRACT	c. THIS PAGE										
U	U	U										
19a. NAME OF RESPONSIBLE PERSON Dr. Darryl Ahner, AFIT/ENS			19b. TELEPHONE NUMBER (include area code) (937) 255-6565, ext 4708; darryl.ahner@afit.edu									