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THESIS

MARCH 2016

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LOGISTICS SIMULATION FOR LONG DURATION LOGISTICS WARGAMES

THESIS

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in Partial Fulfillment of the Requirements for the
Degree of Master of Science in Operations Research

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Abstract

Wargames were originally created to test wartime strategies against opposing forces within a short time frame. Due to the short duration design of these wargames, logistics were deemed irrelevant and it was incorrectly assumed that the warfighter would be logistically supported for the entire duration of the wargame. The purpose of this thesis is to provide insight to the value of capturing logistics within a wargame and to better model the increased requirement for Agile Combat Support. This research utilizes a logistics simulation tool and its outputs to conduct statistical analyses comparing a baseline scenario created to mirror the Joint Strike Fighter key performance parameters and a modified model with increased operations tempo. Additionally, an experimental design provides key insight to the primary factors contributing to the changes in essential measures of effectiveness. This research identifies statistically significant differences between the baseline and modified models and finds the most essential components for Agile Combat Support are the number of spares, the number of maintenance personnel, and sortie duration. Incorporating logistics in wargames provides a more holistic view of a war and can be the crucial addition to wargames that helps the USAF maintain dominance in air, space, and cyberspace.

To Mom and Dad

Acknowledgements

I would like to express my sincere appreciation to my faculty advisor, Dr. J.O. Miller, for his guidance and support throughout the course of this thesis effort. I would also like to thank Dr. D.K. Ahner for his invaluable insight throughout our research.

Kevin R. Cardenas

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LOGISTICS SIMULATION FOR LONG DURATION LOGISTICS WARGAMES

I. Introduction

This thesis provides insight to the value of modeling the effects of logistics within a combat model or wargame. Wargaming encapsulates the concept of simulating reality in order to assess a unit's strength or impact on a war and to provide an alternative for battle commanders to enhance the quality of their decisions made during war time. Wargames have been used throughout the history of warfare. From games created by the early Chinese military General Sun Tzu to current super computer warfare simulations, wargames and warfare strategies have substantially progressed. Despite the evolution of the types and complexity of wartime simulations, an omnipresent flaw in wargames is the omission of logistics from these warfare models. Neglecting logistics can be catastrophic to the warfighter. Especially with current budgetary constraints, battle commanders are not only required to be cognizant of the logistical ramifications of war time decisions, but also account for the supplies necessary to maintain the United States Air Force's (USAF) dominance in air, space, and cyberspace.

1.1 Problem Background

Historically, wargames consistently overestimate the capabilities of Blue Forces, United States Forces, and underestimate the constraints limiting the Blue Force. This problem is even more inflated when considering logistics within a wargame. With an exception to a few models specifically created for logistics support, wargames do not consider logistic demands and constraints for either Blue or Red (Enemy) Forces. The assumption that logistics will support the warfighter might hold true for a quick and easy war, but recent history proved that this is not the case. Historically, most wars require logistics support over a long duration of time. As a result, Air Force Material Command (AFMC) Logistics, Engineering and Force Protection (A4) is seeking a way to properly or more realistically model logistics within a wargame to gain more accurate insight to the Blue Force capability.

1.2 Research Objectives

The objective for this research is to answer the following questions:

1. How do prolonged surge operations impact the supply of parts, maintenance personnel utilization and the number of aircraft that are not mission capable due to supply (NMCS)?
2. What impact on sortie operations do the number of spare JSF engine modules and maintenance personnel have?

This research uses a logistics simulation tool, the Logistics Composite Model (LCOM) Analysis Tool Kit (ATK), to compare multiple models, specifically focusing on sortie rate, manpower utilization and the failure of missions due to unscheduled maintenance. Analysis is conducted to distinguish the differences between a baseline model and a modified model with a higher OPSTEMPO. The baseline model is derived from the key performance parameters (KPP) for the Joint Strike Fighter (JSF) program and the modified model alters the length and intensity of surge operations. Furthermore, this research performs a design of experiments to analyze different allocation levels of spare parts and maintenance personnel under different demands in sortie length. The goal of this research is to provide some measures of the difference in logistical requirements between the current accepted surge period and the longer surge operation. In addition, this research aims to provide insight on reasonable levels of spare modules and maintenance personnel to adequately sustain the JSF mission over a sustained period of time.

1.3 Research Scope

This research is not directed at a specific approach to incorporate logistics into wargames, but rather focuses on and explores the potential impact of a more restricted logistics supply over a prolonged period with higher OPSTEMPO. This thesis is not attempting to establish a new definition for surge operations and their intensity, but rather explore the possibility of more prolonged and intense surge and sustainment operations. Additionally, a more detailed look at the JSF engine and its spare parts are analyzed to provide a more comprehensive analysis of the logistic support of a fighter squadron. This research not only enlightens readers about the complete disregard for incorporating logistics into wargames, but also provides essential insight to a more realistic look at logistics and the true capabilities of the Blue Force.

1.4 Thesis Outline

The remainder of this paper is organized as follows. Chapter 2 provides background to wargames and logistics and reviews relevant research in the field that influences our examination of the problem. Chapter 3 presents the methodologies applied in this research. Chapter 4 presents the results and analysis of our simulations, as well as analysis on the outputs from the simulations. Chapter 5 summarizes the contributions of this research and proposes directions for further studies.

II. Literature Review

2.1 Introduction

The purpose of this literature review is to introduce and outline key points of several pieces of literature in relation to the incorporation of logistics into or alongside wargames. This literature review begins by outlining and summarizing wargames and their application to the United States Air Force (USAF). Secondly, this literature review highlights the absence of logistics in current wargames, as well as how the lack of logistics impacts decision making. Additionally, the necessity for Repair Network Integration (RNI) is addressed along with past attempts to integrate repair networks in simulation. Finally, this literature review covers the Logistics Composite Model (LCOM) Analysis Tool Kit (ATK), its utility and its applicability to this topic.

2.2 Wargames

History of Wargames.

Wargames have been used throughout history, dating all the way back to ancient China. More than five thousand years ago Sun Tzu created a game called Wei Hai which was a board game designed to allow players to practice encircling or outflanking their opponent [1]. Although Wei Hai is a simplified version of a wargame, the development of wargames did not stop there. Some people believe the next evolution of wargames which gained larger interest was the ancient Indian game of war in which the pieces represented various components of armies on the battlefield [2]. Others believe it was the Koenigspel which was invented in a German town in 1664 and involved more pieces and a larger board than modern chess.

These types of wargames were very simplistic in which the pieces represent individual actors in a wargame, where it wasn't until 1781 until wargames employed the concepts of aggregating a large number of people into one piece [1]. In late 1781, John Clerk, a Scotsman, developed a method for using model ships to gain tactical insights [2]. The continuation of modifications to wargames did not stop here. In 1811, the birth of modern wargaming appeared with the creativity of a Prussian Army Lieutenant by the name Georg Leopold von Reisswitz. He constructed a table model of the actual terrain and used blocks to represent units of soldiers. There were two players in this wargame with one umpire or official. The umpire would update the table and inform the players the ramifications of the previous decision. The umpire would use complex tables of data to determine casualties and would even use the roll of a dice to model the uncertainties of the battlefield [3]. Over the next two hundred years these umpires often turned into computers and more aspects of the battlefield were able to be modeled and more uncertainty was able to be entered into the model. As seen in the examples above, wargaming was used throughout history as a fundamental tool in developing and practicing military strategy.

Defining Wargames.

The United States Air Force defines wargames as "a simulation, by whatever means, of a military operation involving two or more opposing forces, using rules, data, and procedures designed to depict an actual or assumed real life situation" [4]. Wargames are very similar to simulations and are, in fact, just a specific type of simulation where there are actors or players making real time decisions which ultimately alter the outcomes of the simulation. "A simulation is an operating representation of selected features of real-world or hypothetical events and processes. It is conducted in accordance with known or assumed procedures and data, and with the aid of methods and equipment ranging from the simplest to the most sophisticated" [4]. A simulation has inputs and outputs and provides similar results every time depending on the randomness of the events occurring within a stochastic simulation.

Wargames utilize simulations to investigate or train the interactions between two opposing decision makers. This decision making is what distinguishes a wargame from a simulation. Having these decision makers present produces unique unrepeatable simulations. The human in the loop allows wargames to be unpredictable and deviate from the mundane rules and algorithms utilized by computer simulations [5]. "Good wargames must be structured to help human players make decisions and allow them to learn about the effects of those decisions" [2]. Wargames are extremely useful to train or test strategies which would allocate real forces, weapons or other resources which are expensive or irreplaceable. Another utility wargames provide is the ability to simulate real life scenarios without any ramifications, damage or even loss of life these scenarios induce. This opportunity afforded to the decision makers provides priceless information and training which would not be received any other way other than a real life situation. "When it works, wargaming can appear almost magical in its power to inform and instruct" [6] and it doesnt expend the resources necessary for the game.

Modern Wargames.

"[T]he Goldwater Nichols Act of 1986 gave the service chiefs responsibility under U.S. Code Title 10 to train, man, and equip their individual forces" [7]. "Title 10 wargames can be defined as a series of major service-sponsored wargames that address future concepts and capabilities in the context of Title 10 responsibilities to organize, train, and equip its forces to carry out its roles and functions as a component of the national instrument of power" [7]. The Air Force began conducting Title 10 wargames in 1995 by creating two types of wargames: Unified Engagement (UE) and Future Capabilities Game [7]. UE wargames are completed on even years with Future

Capabilities Games being held on odd years. UE is conducted at alternating locations between the European and Pacific theaters. There are three teams or forces involved with these wargames: white, blue and red. The white team consists of the judges; the Blue Force represents the United States forces while the Red Force represents a generalized opponent force [3]. Similar to wargames throughout history, the players during these wargames are the decision makers. These players use history, culture and doctrine to develop strategies for the tactical level [3].

Future Games are conducted in odd years at Air Force Wargaming Institute (AFWI) at Maxwell AFB [5]. While UE is focused to address military challenges and concept exploration, AF Future Games are focused to address future concepts and force structure alternatives (SECAF, 2012). The Air Force Future Games explore future capabilities as far as 20 years into the future. The Air Force Research Lab (AFRL) assists the design and analysis of the highly analytical game. Compared to Unified Engagement, Air Force Future Games create a balance between educational and analytical purposes [7]. One of the downfalls of Title 10 wargames is designing a game for all purposes would require an enormous amount of resources. The size, cost and complexity all inhibit the accuracy and computation time of the wargame. That may be why the Global games of old used to have hundreds of players and adjudicators and last multiple weeks [7].

2.3 Incorporation of Logistics, Or Lack Thereof

One of the main issues of UE is a failure to evaluate the logistic operations [8]. This statement holds true for any wargame currently being used by the United States Department of Defense. Typically logistics is regarded as an operational constraint in wargames and, as a result, wargames tend to avoid how incorporating logistics impacts campaign planning [9]. Other reasons that logistics has failed to be captured in wargames is largely due to logisticians and warfighters being excluded from the wargames [9]. Without the insight and information provided by logisticians, wargames were oblivious to combat consumption, transportation, industrial base, maintenance, and regeneration of ordnance, as well as command and control [9].

Wargames are a critical asset for training and executing command-level decisions. Wargames are extremely valuable and useful tools, but the necessity of incorporating logistics into these wargames is equally important. The role of logistics is to further define a mirrored representation of Blue Force capabilities by providing limitations and constraints to the wargames[5]. Wargames are a pertinent tool for the Department of Defense, but without these limitations and constraints provided by logistics, wargames depreciate in value and may provide inaccurate insight.

Fortunately, over the past decade, logisticians were considered during wargames. However, despite the addition of these logisticians, logistics is still not being simulated in wargames. “Blue Forces overestimate their effectiveness level and completely disregard the logistics involved in supporting their campaign” [5]. For example, the kill rates included in the wargame simulations require that munitions be provided for each of the weapon systems. However, the amount of ammunition available is limitless and consumption is not tracked [8]. “This in turn over predicts the effectiveness of US forces, under predicts the red forces, underestimates the budget, and provides less insightful results to a large number of policies and doctrine” [5]. The primary reason this is continually happening refers back to Ducharme: the size, cost and complexity of wargames is too great to evolve the current wargames and incorporate another large aspect of the war simulation, logistics. “But what senior leaders fail to understand is that funding a project to develop and maintain logistics within a wargame simulation model is far less expensive than underestimating the budget for a war in the Pacific” [5].

Past.

John Long (1993) wrote a thesis focusing on the Surge and Sustainment Simulation (S3) which was an initial push to address the complication of incorporating logistics in wargame. The Wargames Department at Naval War College needed a computer model to simulate “theater level logistics to generate wargame ‘ground truth’ and to aid players in simple planning” [10]. As a response, S3 fulfilled the required characteristics to allow the Naval War College to add logistical constraints to their wargames. Like all wargames over the course of history, there is always room for improvement.

Curtis Plunk (1995) wrote a thesis focusing on The Logistics Wargaming Simulation (LogWarS). LogWarS was “a computer program designed to facilitate the incorporation of logistics considerations and constraints into wargames played at the Wargaming Department of the Naval War College” [1]. Very similar to S3, LogWarS allows an umpire of a wargame to create a scenario with forces and operating bases with the logistical constraints for their supply and transportation of assets. The simulation has the ability to pause, collect user input or modifications to the scenario, and resume the wargame simulation. The largest improvement to S3 which LogWarS contributed was a new graphical interface to follow the supply status of forces and bases [1]. Despite these modifications and alterations to the computer program, logistics still was not being fully incorporated into command-level decision making.

Present.

In 2014, Daniel Krievs addressed the failure of incorporating logistics into wargames, specifically Title 10 wargames. With the use of a stochastic discrete-event simulation tool, LCOM ATK, Krievs was able to “design, analyze and demonstrate that logistics can and should be incorporated into wargames” [5]. Statistical analysis was used to evaluate the effectiveness of sortie missions under logistical constraints. This analysis could be conducted prior to, or upon completion of, the wargame. Unfortunately, the aforementioned restraints such as size, cost and complexity inhibit the use of a more realistic, complex LCOM ATK model during wargames. The decision makers need timely results from the logistics model in order to keep up with the time frame of the wargame and complete it in a timely manner. In order to accomplish this, multivariate analysis techniques were used to develop a meta-model simply using four metrics to successfully predict measures of effectiveness [5]. This meta-model could then be run during a wargame to provide more timely results while incorporating logistics.

The S3 and LogWarS were separate logistics simulation programs which were completed at the conclusion of a wargame. There was minimal success with this approach because feasibility results are provided several days after the wargame is completed. This approach doesn't allow Blue Force commanders to alter their approach and retest their updated strategies in the wargame scenario [5]. However, the simulation programs highlighted interesting results by omitting logistics from wargames which drew attention to the incorporation of logistics within wargames. Their main contribution to wargames was disproving that unlimited resources provides a feasible solution. While these are great results and help advance this field of study, it still leaves the fundamental issue with running a separate logistics simulation model after the wargame has concluded [5].

Up to this point, the most applicable approach to incorporate logistics into wargames would be to run a logistics simulation prior to a wargame. "This allows for ACS to provide further representation of Blue Forces and provide more meaningful insights from wargames by allowing commanders to alter their strategies during the wargame" [5]. Additionally, it is possible for multiple various scenarios to be run through the logistics simulations to try to consider the possible decisions made by commanders during wargames. Ultimately, running a logistics simulation model prior to a wargame provides plenty of time to modify, complete and analyze the separate logistics models and inform the decision makers in a timely manner [5].

Future.

Idealistically, the best approach would be to run the wargame and a logistics simulation model simultaneously or in the same model. However, this is not an easy task because of the conflicting aggregation levels between logistic simulations and combat models. “This conflict comes down to a difference in metrics and processes that might not have the ability to communicate with each other within a single simulation platform” [5]. Despite these large obstacles, the massive benefit of providing instantaneous results to decision makers is extremely coveted. Being able to view supply levels, system failures, aircraft availability, and more during a wargame is extremely more realistic.

In addition, running logistics within a wargame would require commanders to provide near real-time decisions with a larger amount of constraints or restrictions.

> For example, during a large-scale real-world disaster, decision makers will face emotional and psychological stresses as well as operational challenges. Strictly intellectual exercises, including simple, scenario-based planning, seldom create emotional or psychological stress. Indeed, no planning system or training tool can cover every possible contingency or produce the same stresses experienced in reality. Real people do not die in wargames. Nevertheless, effective high-engagement games can equip leaders better to confront whatever contingency they must actually face, regardless of its similarity in detail to the game actually played. Leaders responsible for making crisis decisions and living with their consequences will benefit from the synthetic experience derived from playing high-engagement games–as well as from the additional mental tools they can develop through that experience–to help ready themselves for confronting those challenges. [6]

Running a model which includes logistics into the wargame would be monumental, but this still leaves the issue of long run times. Constructing a single wargame model that captures attrition, decision making, and logistics is currently not feasible due to these and other constraining factors [5].

2.4 Repair Network Integration

The Deputy Chief of Staff for Logistics, Installations and Mission Support, Lt. Gen. Judith Fedder, declares in AFI20-117 “The Repair Network will accomplish the Intermediate-level and Depot-level maintenance and repair of aircraft and reparable assets required to fulfill operational needs outside the capability and/or capacity of the Mission Generation Network” [11]. This AFI concentrates on the implementation of repair networks through the use of a new management specifically created to organize the RNI management process. A Repair Network (RN) provides a centralized management for aircraft repairs. The RN is comprised of globally distributed repair facilities (or nodes) to enable quick and versatile response to meet the demands of the sortie generation process. The primary goal for the RN is to support the warfighter and deliver optimized aircraft/weapons system availability at the same or reduced cost. In order to do so, Lt. Gen. Fedder tasked the Air Force Material Command Director of Logistics (AFMC/A4) to lead, coordinate, and plan RNI implementation of standard processes, reporting processes, management plans, systems, training and most importantly tools related to Repair Network Management [11].

In response to the Expeditionary Logistics for the 21st Century (eLog21), RAND conducted analysis of a repair network in 2010. Their primary focus was to analyze the efficiency of establishing Central Repair Facilities (CRFs) and how it would save the Air Force time, money and personnel. RAND enumerated the current process for Air Force Maintenance, determined the weapon-system requirements and workload, analyzed the optimal allocations of workloads between a unit and repair network and evaluated the efficiency of consolidating maintenance facilities specifically for the F-16, KC-135, and C-130 platforms. In order to do so, RAND utilized the capabilities of LCOM ATK to define the unit-repair capabilities, the distribution of each center's workload personnel utilization, and personnel levels. As a result of their analysis, RAND concluded that consolidated wing-level scheduled inspections and component back-shop maintenance capabilities were far more efficient than the current layout of Air Force maintenance operations [12].

The principal objective for RNI is to transform the current maintenance management process to improve efficiency while meeting the requirements of the warfighter. Lt. Gen. Fedder concentrates part of the AFI to the management of a RN, but aspects of RN to be considered in the field of analysis is component repair, depot-level reparables (DLRs), and modifications. Metrics such as availability, performance, and affordability should be considered and used as a diagnostic tool to aid decision making. In order to support the initiative of the Chief of Staff of the Air Force, through the tasking of Lt. Gen. Fedder, a tool should be built to collect these metrics, provide insight, conduct analysis and present significant results to better the decision making process. The most widely used logistics simulation tool across the Air Force that can be used to provide this analysis and insight is LCOM ATK.

2.5 LCOM ATK Model

LCOM ATK is a detailed simulation model that identifies the effect of logistics resources (primarily maintenance personnel, equipment, facilities, and spare parts) on sortie generation [12]. Another, more technical, definition for the LCOM ATK model is "a stochastic, discrete-event simulation that relies on probabilities and random number generators to model scenarios,(LCOM) is one of the Air Forces primary tools for determining optimal logistics and maintenance manpower levels" [13]. "LCOM

ATK supports and integrates the many complex tasks required to run LCOM into a single suite of tools" [14]. This model can be extremely powerful for the fight to incorporate logistics into wargames. The following chapter discusses our use of LCOM ATK as the primary tool in our methodology for incorporating logistics in wargames.

III. Methodology

3.1 Introduction

Past research indicates a superseding necessity for logistics and provides awareness to its impact on the feasibility of decisions made during wargames. This research not only continues to illustrate the necessity for logistics in relevant wargames, but also explores the possibility of tighter constraints on resources, as well as a higher and more prolonged OPSTEMPO within a Long Duration Logistics Wargame (LDLW) through use of a separate logistics simulation.

3.2 LDLW Overview

AFMC/A4F and Frontier Technologies Inc. sponsored the first LDLW workshop in order to examine, validate and quantify logistics and sustainment gaps and shortfalls within Agile Combat Support (ACS). As a research focus of AFMC/A4F, LDLW provides the ability to analyze the logistics incorporated with decisions made in wargames over a long period of time. Typically wargames span a 7-10 day period of time, but LDLW is designed to cover upwards of 180 days. This longer duration wargame not only provides logistics feedback for the initial surge and establishment of air superiority, but also considers the required logistics to maintain air superiority and sustain air operations throughout an extended period of conflict.

Booz Allen Hamilton conducted the first LDLW workshop in September 2015 at the Simulation and Analysis Facility at Wright Patterson Air Force Base. This workshop combined the superior intellect of the maintenance community, pilots, contractors and other personnel. Each member of the workshop had a unique background which enabled them to provide opinions other members may have never considered. The discussions during this workshop provided valuable opinions about the key contributing logistics factors to consider during a wargame. More details on this workshop can be found in the after action report[15].

3.3 RNI Overview

The Repair Network Integration (RNI) concept provides a centralized management and location for aircraft repairs beyond the existing Air Logistic Centers (ALC). Additionally, RNI focuses on Intermediate and Depot level maintenance done at a central repair facility (CRF), as opposed to Organizational level maintenance which is typically done on the flight line (Fedder, 2013). The concept of RNI and CRFs was developed to provide a more efficient allocation of resources by consolidating the depots and repair facilities, along with their management and maintenance personnel, to reduce cost and time for repairs. Due primarily to software limitations, we do not consider RNI for our study.

3.4 LCOM ATK Overview

This research utilizes a preexisting logistics model in order to significantly reduce the cost, complexity and knowledge of incorporating logistics into a wargame model. This research requires an operational level logistics model to conduct constructive analysis while considering maintenance personnel and equipment required to capture Agile Combat Support. LCOM ATK accomplishes all of these requirements and has been used throughout the logistics community for decades.

The logistics model constructed for this research uses LCOM ATK version 4.2. AFLCMC/EZJS altered and enhanced the LCOM software tool into LCOM ATK with support from Frontier Technology Incorporated (FTI). LCOM ATK is a collection of modules written in SIMSCRIPT II, each with the capability of communicating with other modules to function as a unit (Erdman, 2014:13). The three models are:

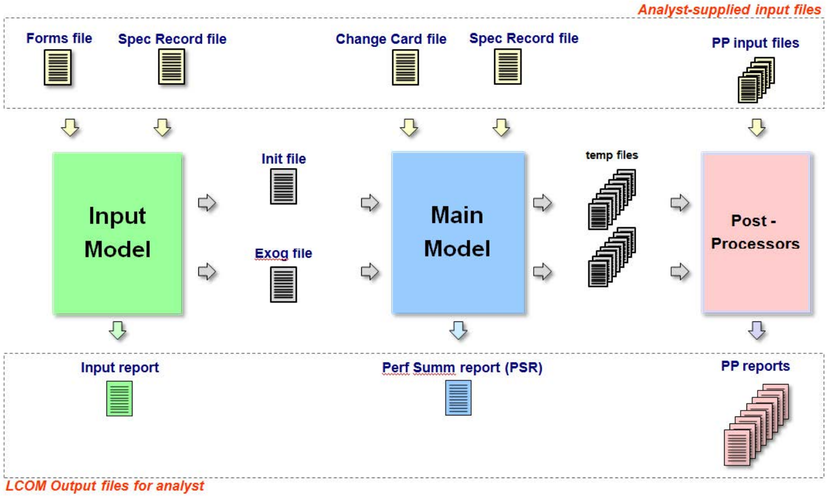

Figure 1. LCOM Process

the Input Model which preprocesses the data, the Main Model which runs the simulation, and the Post Processor Model which analyzes post simulation data (Erdman, 2014:27). The software tool is utilized across the USAF to simulate studies concerning AF base level functions like maintenance and supply.

LCOM ATK is an extremely flexible software tool which allows the user to define the level of detail of the simulation. This flexibility in a tool is extremely beneficial for logistics simulations because of the conflicting aggregation levels of wargames and constructive logistics models used for analysis. The LCOM ATK model is designed to process spares or other similar entities to capture the maintenance or support system throughout the entirety of a war (AFLCMC/EZJS, 2014). This allows LCOM ATK users to alter the model to capture a wide range of different types of logistics processes and resources while maintaining a manageable level of understanding and complexity. The interaction and order of the three models is shown in Figure 1.

The output of LCOM ATK is consolidated into reports which consist of various statistics grouped together by type. The three important groups this research focused on were groups C, D and F which represent key aircraft statistics, manpower statistics, and key supply statistics, respectfully. The most important statistics from each of those groups were selected to form a subset of metrics used for analysis. This subset of statistics are organized into groups shown in Table 1.

Table 1. LCOM ATK Output Statistics

Stat	Description
C3	Percent Sorties
C4	Percent Unscheduled Maintenance
C6	Percent NMCS
C15	Achieved Sorties / Aircraft / Day
C16	Flying Hours
C17	Average Flying Hours / Aircraft / Day
D3	Manhours Used
F3	Number of Backorder Days
F4	Number of Units Demanded
F11	NMCS Indicator

3.5 Logistics Simulation Scenario

This research builds on previous studies and lessons learned from the LDLW workshop efforts involving longer wargame scenarios with added logistics capabilities and constraints. AFMC desires logistics analysis and insight on decisions made for the “Pivot to the Pacific”. This idea indicates the US shifting focus from the Middle East and/or the European theater to the Pacific region. Due to security concerns, the scenario for our wargame is completely fictional. The simulation does not contain any real opposing forces, the sortie times/rates are not real, and the locations of both Blue and Red Forces are representative of a notational conflict in the Pacific region. This research aims to provide a proof of concept that a stand-alone logistics simulation can effectively capture a more accurate and realistic representation of logistics supply during a high OPSTEMPO war that lasts longer than the traditional wargame's seven to ten day time period.

The scenario takes place in the Pacific with two Blue Force units. These forces are captured in LCOM ATK with two Blue forward operating bases (FOB) each conducting F-35 sorties. The two Blue FOBs each contain twenty-four Joint Strike Fighters (JSF), three maintenance facilities, a minimum of thirty-eight maintenance crew members, and an extensive amount of parts to repair the JSF. This wargame scenario is illustrated in Figure 2. For supply processes we focus only on the JSF engine and its modules, similar to the approach used in the September 2015 LDLW workshop. JSF engines within LCOM ATK comprise thousands of parts which are susceptible to fail, but this research focuses specifically on five critical modules: nozzle, augmenter, fan, power, and gear box.

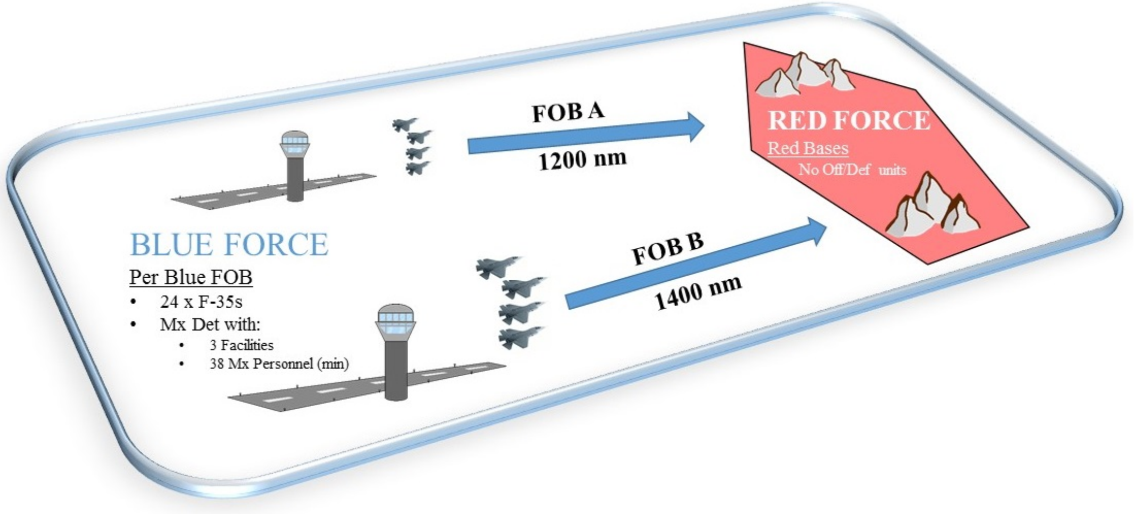

Figure 2. Wargame Scenario

This wargame model does not incorporate the interaction between Blue and Red Forces, but focuses on the predetermined sortie rate and schedule, similar to that used in the LDLW workshop. The simulation contains a predefined set of Blue Force strategies to conduct air operations over a 180 day period. Figure 3 illustrates the sortie operations modeled within LCOM ATK. The Red Forces are not able to attrit

Blue Forces, however, this could be easily modified within LCOM ATK. This aspect does not impact the overall objective for this thesis, which is to capture a more realistic observation of the logistics support for a wargame scenario.

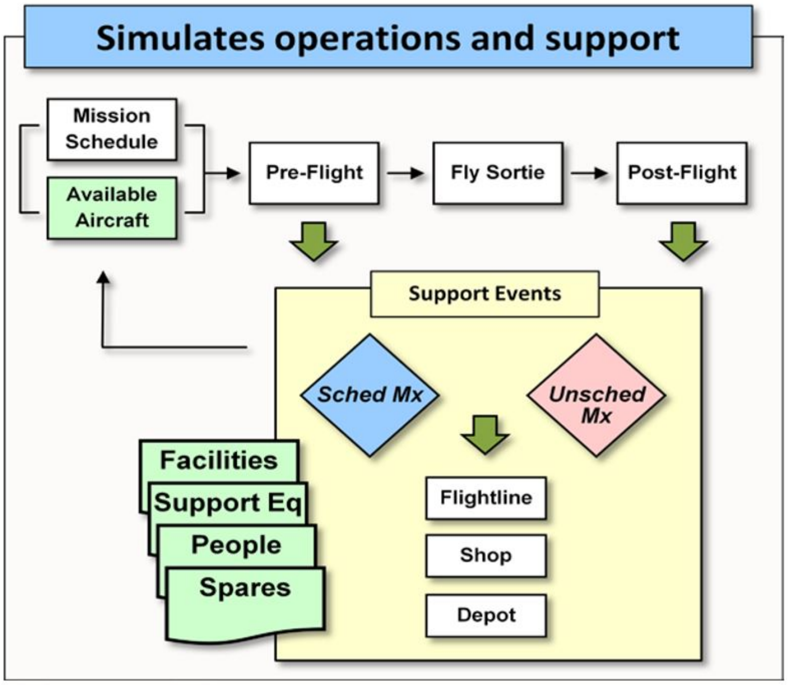

Figure 3. Simulation Operations and Support

This research uses a preexisting JSF logistics model in LCOM ATK that was created by Lockheed Martin in order to mirror the requirements laid out in alignment with key performance parameters (KPP). This research takes advantage of the immense amount of detail this model provides and merely alters small details to tune the model to accurately represent the aforementioned scenario. In order to create a baseline scenario for this research, an additional FOB was added to the preexisting model, but the majority of the logic in the model was left unchanged. A part of the model logic was modified in the change card to incorporate the use of the five pertinent modules and their spares in the repair process, instead of only considering whole engines. Originally, the model designated three spare JSF engines to aid the repair process, but after our changes, the model was able to represent three spare parts for each of the five JSF engine modules. We believe incorporating three spare parts for each of the modules is equivalent, but more descriptive than the original design which included three whole JSF engines.

Typically, a war is seen in two phases, the surge phase and the sustainment phase. Surge operations consist of a higher OPSTEMPO in order to take advantage of battlefield opportunities, whereas sustainment operations slow the tempo down to a sustainable level where maintenance, manpower and logistics can keep up. The baseline scenario is programmed for the JSF to fly surge operation sorties for seven days, seize operation sorties for twenty-three days, and sustainment operation sorties for 150 days. In LCOM ATK, sorties are flown in accordance with a flight schedule and the logistics and maintenance support of the JSF is monitored. During surge operations in LCOM ATK sorties are flown every forty minutes for a total of twenty sorties per day at each FOB. Seize operations consist of fourteen sorties per day starting every hour and sustainment operations allow two hours between sorties for a total of seven sorties per day at each FOB. A slight modification to this baseline model was made in the change card by increasing the duration of the surge and seize periods. The modified model uses thirty days for both the surge and seize periods and 120 days for sustainment operations. Instead of flying twenty sorties per day for seven days and fourteen sorties per day for twenty-three days–a total of 462 sorties per FOB–the extended surge operation will fly 600 sorties per FOB during the same thirty day period. These two models comprise the baseline and modified models compared in our analysis.

The simulation steps 24 hours at a time for a total of 180 days. The 24 hour time step is used because it is customarily the length for logistic models and similar to how real world metrics are gathered. This analysis gathers 30 replications worth of data in order to provide a reasonable ninety-five percent half width for various statistics. The baseline model created by Lockheed Martin, with our slight amendments, and our modified model with prolonged surge and seize periods are compared for statistical differences in order to answer questions about how successful the Blue Forces would be with increased sortie rates and duration throughout the surge and seize periods of a war.

The original idea for the next step of analysis was supposed to include RNI into a further modified model. Due to the limited amount of time available, as well as the complexity of incorporating RNI into our existing model, this step was deemed infeasible. Hopefully with ongoing enhancements, LCOM ATK will soon include an RNI capability. Instead of an RNI extension to our analysis, we explore the impact of our newly modeled engine modules.

Knowing the number of spare engine module parts necessary to sustain higher sortie rates during wartime operations is an extremely valuable piece of information. Additionally, allocation of military personnel is a critical part of a war. Our research develops a design of experiments (DOE) with varying levels of number of spare module parts, number of maintenance personnel, and sortie duration. This DOE not only answers our imperative questions, but provides information on how the length of sorties impact key statistics. The next chapter of this thesis analyzes the comparison of aircraft, manpower and spare part statistics between the baseline model and the modified model, as well as a DOE using the modified model as described.

IV. Analysis and Results

In this analysis section we assert the importance of our model to a continual logistics problem of interest to the U.S. military and the wargames it uses. This section of our research is organized into two sub-categories for the two parts of analysis we outlined in Chapter 3. Both parts of this analysis help address the omnipresent issue of Blue Force logistics constraints being underestimated. The first sub-category focuses on comparing the mean outputs from the baseline and modified models to portray the differences in key statistics between a model created by Lockheed Martin to meet the required JSF KPPs (baseline) and a long duration wargame (modified) model over the first 30 days of surge operations. The second sub-category further analyzes the modified model with an experimental design, specifically focusing on the number of accessible spare JSF engine modules, the number of maintenance personnel available at both of the FOBs, and the length of sorties flown over the full duration of the 180 day logistics wargame. We examine key measures of effectiveness (MOE) output by LCOM ATK by varying the levels of these factors, high and low, in order to gather a broader insight to the modified model and the Blue Force logistical limitations.

4.1 Comparison Analysis

LCOM ATK has the ability to output hundreds of metrics, but this research focuses on eight metrics that we consider the most important for the analysis we are conducting. These eight metrics we chosen after observing the LDLW workshop and talking to subject matter experts (SME) about metrics which encapsulate the results of the JSF mission and its maintenance and supply support. The simulations were run thirty times and the data for the eight statistics was saved in a comma delimited text file, which was easily imported into Microsoft Excel. We chose to use Microsoft Excel because the LCOM ATK data output was manageable in size after we eliminated a significant amount of metrics. Additionally, Microsoft Excel provides an easy to use interface for organizing data, conducting statistical analysis, and creating graphical outputs of the data and results of the analysis. Once the data was imported into Microsoft Excel, we organized the outputs by group, C-Statistics (Aircraft), D-Statistics (Manpower), and F-Statistics (Supply).

The metrics for the three groups are summarized in Tables 2, 3, and 4. The data is filtered to include the first thirty days of the simulation, as opposed to the full 180 day output used in the experimental design. The most important comparisons for the metrics occur within the first thirty days because this analysis focuses on the extended surge operation from the KPP-based seven days to the LDLW thirty days. This research compares the combined seven days of surge operations and the twenty-three day seize period in the baseline model to the thirty day surge period in the modified model.

The tables are sorted by metric and then further broken down into columns for the baseline model, modified model and the differences between the two models. The means and standard deviations are output from LCOM ATK and the half-widths and two sample confidence intervals seen in the tables were calculated in Microsoft Excel using a t-distribution with an alpha of 0.05 and twenty-nine degrees of freedom.

The C-Statistics shown in Table 2 are organized with metrics related to the aircraft. The table is sorted by the metrics: C3 - Percent Sorties, C4 - Percent Unscheduled Maintenance, C6 - Percent Not Mission Capable due to Supply (NMCS), C15 - Achieved Sorties / Day / AC, C16 - Flying Hours, and C17 - Average Flying Hours / AC / Day.

The two sample confidence intervals for the C-Statistics for the baseline and modified models were plotted next to each other to perform a visual test to see if there

Table 2. **C-Statistics: Aircraft Statistics**

DESCRIPTION	**ITEM**	**BASE AVG ± HW**	**MOD AVG ± HW**	**DIFF AVG ± HW**
PCT SORTIES	JSF at A	24.469 ± 0.185	27.421 ± 0.366	2.952 ± 0.409
PCT SORTIES	JSF at B	25.367 ± 0.239	28.057 ± 0.37	2.69 ± 0.44
PCT UNSCHED MAINTENANCE	JSF at A	19.777 ± 0.309	21.363 ± 0.339	1.586 ± 0.458
PCT UNSCHED MAINTENANCE	JSF at B	20.121 ± 0.316	21.625 ± 0.379	1.504 ± 0.493
PCT NMCS	JSF at A	4.503 ± 1.114	6.136 ± 1.072	1.633 ± 1.544
PCT NMCS	JSF at B	5.906 ± 1.353	6.629 ± 1.103	0.723 ± 1.743
ACHIEVED SORTIES / AC / DAY	JSF at A	2.347 ± 0.018	2.63 ± 0.035	0.283 ± 0.039
ACHIEVED SORTIES / AC / DAY	JSF at B	2.286 ± 0.022	2.529 ± 0.034	0.243 ± 0.04
FLYING HOURS	JSF at A	4228.182 ± 31.999	4738.319 ± 63.172	510.137 ± 70.712
FLYING HOURS	JSF at B	4383.431 ± 41.26	4848.256 ± 63.971	464.825 ± 76.012
AVG. FLYING HOURS / AC / DAY	JSF at A	5.872 ± 0.044	6.581 ± 0.088	0.709 ± 0.098
AVG. FLYING HOURS / AC / DAY	JSF at B	6.088 ± 0.057	6.734 ± 0.089	0.646 ± 0.105

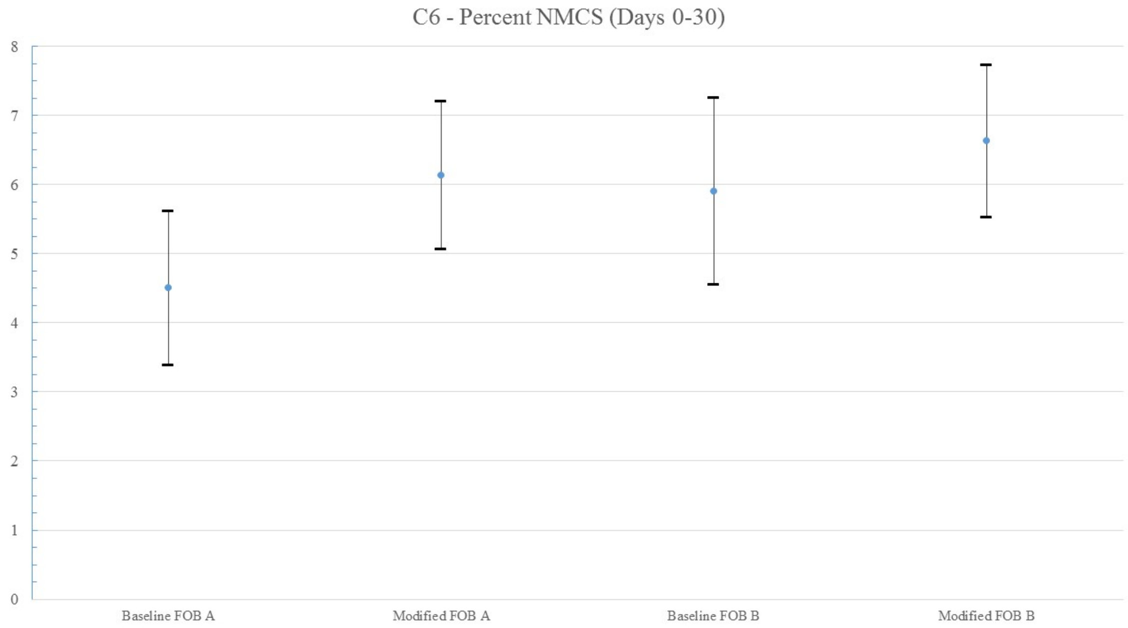

Figure 4. **C6 - Percent NMCS**

was a difference between the two models at each FOB. As illustrated in Figure 4, the confidence interval bounds for the C6 metric had overlapping confidence interval bounds, but for the remaining C-Statistics, the baseline model did not overlap the modified models. So, we can say the the models are statistically different at both locations for C3, C4, C15, C16 and C17. However, based solely on a visual test of the confidence interval plots, we cannot conclude the C6 metric shows significant or insignificant differences at both locations. Therefore, we conducted a two sample t-test to compare the difference in means; the mean and halfwidth can be found in the last column in Table 2.

The results from the t-tests conclude a significant difference in the means for the C6 metric at FOB A, but not at FOB B. This result could be attributed to the difference in sortie lengths between location A and B due to their different distances from the opposing force. The longer duration of sorties at FOB B causes a larger mean and variance for NMCS, as well as the other C-Statistics. Table 2 displays these larger values at FOB B when compared to FOB A.

If the confidence intervals for the difference of means in the last column of Table 2 included zero, such as C6 at location B, there would not be sufficient information to prove the models are statistically different. However, we can confidently say that differences in means of the remaining eleven metrics between these two models is statistically significant.

Although a majority of the C-Statistics are statistically significant, the next questions is if a practical difference exists. The difference between the baseline and modified models for the percent of time aircraft spent flying sortie tasks (C3) was 2.952 and 2.69 for FOBs A and B, respectively. This equates to an extra 21.25 flying hours per aircraft at FOB A and 19.37 flying hours per aircraft at FOB B during the first 30 day period of surge operations. This result can also be found by changing the units for the C15, C16 and C17 metrics. Within the baseline total flying hours per aircraft during surge operations, it is expected that three JSF parts fail per aircraft at both

FOB A and B. To clarify, these are three parts failing out of the list of JSF parts modeled in LCOM ATK, not just the JSF engine and its modules. This data was found from the failure clocks within the LCOM ATK code in the scenario created by Lockheed Martin. With the increase of approximately 20 flying hours per aircraft at each location throughout the first 30 days, the number of JSF parts expected to fail increases to 5 JSF parts; once again, not to be confused with the JSF engine modules. The expected number of part failures increases by two parts for each of the 24 aircraft at both locations, so a total of 96 additional JSF parts would be required just during the first 30 day surge period. This increase in percent sorties and flying hours causes ramifications on sortie operations and can significantly increase the amount of parts required for this JSF scenario. Note that the JSF data provided only models to the line-replaceable unit (LRU) level of total JSF parts within LCOM ATK.

In addition to the extra flying hours, the increase of more than 1.5% of unscheduled maintenance for both locations results in an increase of almost 11 hours of additional time aircraft spend in maintenance. This averages to an additional thirty minutes of unscheduled maintenance per aircraft for the duration of the 30 day surge operation. As an average, the additional thirty minutes does not seem detrimental, but it is possible that an aircraft spends an hour or more for unscheduled maintenance in a single day. This could significantly affect sortie operations on that day. Additionally, this extra 11 hours of unscheduled maintenance causes more stress on the maintenance squadrons with a possible need for members to work overtime.

Table 3. D-Statistics: Personnel Statistics

DESCRIPTION	**ITEM**	**BASE AVG ± HW**	**MOD AVG ± HW**	**DIFF AVG ± HW**
MANHOURS USED	AVG at A	227.698 ± 1.391	251.301 ± 2.759	23.604 ± 3.085
MANHOURS USED	AVG at B	229.216 ± 1.670	249.122 ± 3.227	19.906 ± 3.628

The data for the metrics pertaining to the maintenance personnel is displayed in

Table 3. The table contains data for the metric D3 - Manhours Used. This statistic consists of the outputs for the maintenance members across the eleven different Air Force Specialty Codes (AFSC), which were averaged to consolidate the data. In order to find this total average, the average number of manhours used was first found by taking the total manhours used at each FOB and dividing it by 70, the number of scheduled maintenance personnel during the first month. This average number of manhours used was then averaged across the thirty replications and the grand mean and standard deviation was computed from those thirty averages.

Similar to the C-Statistics, the means and halfwidths were calculated for the two models and the difference in means. It is apparent there is a statistical difference in the baseline and modified models because the difference in means two sample confidence intervals do not contain zero at both FOB A and FOB B. We observed a slightly larger increase at location A compared to location B and we can attribute this to the extra ten minute sortie length at location B. This causes the aircraft at FOB B to be on the ground ten minutes less per aircraft per sortie which decreases the amount of time available for maintenance to spend working on aircraft at FOB B.

The additional 24 manhour increase at FOB A and 20 manhour increase at FOB B can impact the moral and effectiveness of a maintenance unit. This increase averages to roughly 40 minutes extra work per day for each maintenance member for the first 30 days of surge operations. The 40 minute increase per day is just an average across the AFSCs, but some AFSCs might be impacted more than others. We found the maximum increase to be an hour and a half of additional work per day for the 2A3W3 AFSC (wheel and tire maintenance) throughout the first month of surge operations.

Table 4 displays all of the spare JSF engine parts for the F4 metric which represents the number of units demanded for the entire duration of the 180 day logistics simulation. Initially, the number of spares demanded was observed for the first thirty days similar to the other statistics. However, there weren't enough JSF module failures within the first thirty days to compare the baseline and modified models. Therefore, we decided to evaluate the JSF module failures and their demanded spare parts over the entire 180 day scenario. For reference, the JSF engine module parts and their related part number designators in the code are displayed in Table 5.

Table 4. F-Statistics: Supply Statistics

DESCRIPTION	ITEM	BASE AVG ± HW	MOD AVG ± HW	DIFF AVG ± HW
NUMBER OF UNITS DEMANDED	Nozzle at A	0.9 ± 0.42	1.233 ± 0.487	0.333 ± 0.642
NUMBER OF UNITS DEMANDED	Augmenter at A	1.833 ± 0.597	2.4 ± 0.434	0.567 ± 0.737
NUMBER OF UNITS DEMANDED	Fan at A	2.433 ± 0.516	3.267 ± 0.596	0.833 ± 0.787
NUMBER OF UNITS DEMANDED	Power at A	3.733 ± 0.877	4.633 ± 0.743	0.9 ± 1.148
NUMBER OF UNITS DEMANDED	Gear Box at A	0.267 ± 0.194	0.367 ± 0.23	0.1 ± 0.3
NUMBER OF UNITS DEMANDED	Nozzle at B	0.933 ± 0.339	1.2 ± 0.397	0.267 ± 0.521
NUMBER OF UNITS DEMANDED	Augmenter at B	1.9 ± 0.474	2.5 ± 0.634	0.6 ± 0.79
NUMBER OF UNITS DEMANDED	Fan at B	2.4 ± 0.677	2.733 ± 0.74	0.333 ± 1.001
NUMBER OF UNITS DEMANDED	Power at B	3.3 ± 0.673	4.9 ± 0.947	1.6 ± 1.161
NUMBER OF UNITS DEMANDED	Gear Box at B	0.3 ± 0.223	0.067 ± 0.095	-0.233 ± 0.242

Table 5. JSF Engine Modules

Item Designator	Reference Number	Module Name
C7810010	1	Nozzle
C7851010	2	Augmenter
P7220010	3	Fan
P7230010	4	Power
P7260010	5	Gear Box

Each FOB was supplied with three spares for each of the five JSF engine modules.

The ability to track JSF engine modules was not included in the original model created by Lockheed Martin (which tracked complete JSF engines), but we modified the model to incorporate and track the individual JSF engine module parts. Note that the three spares for each of the engine modules corresponds to the three spare full engines in the original JSF KPP data. The results from Table 4 indicate there is a lack of evidence to prove a statistical difference for a majority of the nozzles, augmenters, gear boxes, fans, and power modules demanded between the baseline and modified models at both locations. However, there are two modules that were statistically significant; the fan at FOB A and the power module at FOB B. On average the modified model required 0.833 more fans at location A and 1.6 more power modules at location B.

Although there is a statistical significance for the fan at FOB A and the power module at FOB B, an additional part or two would not significantly impact the JSF mission in this scenario nor vastly increase the amount of spares required at each location.

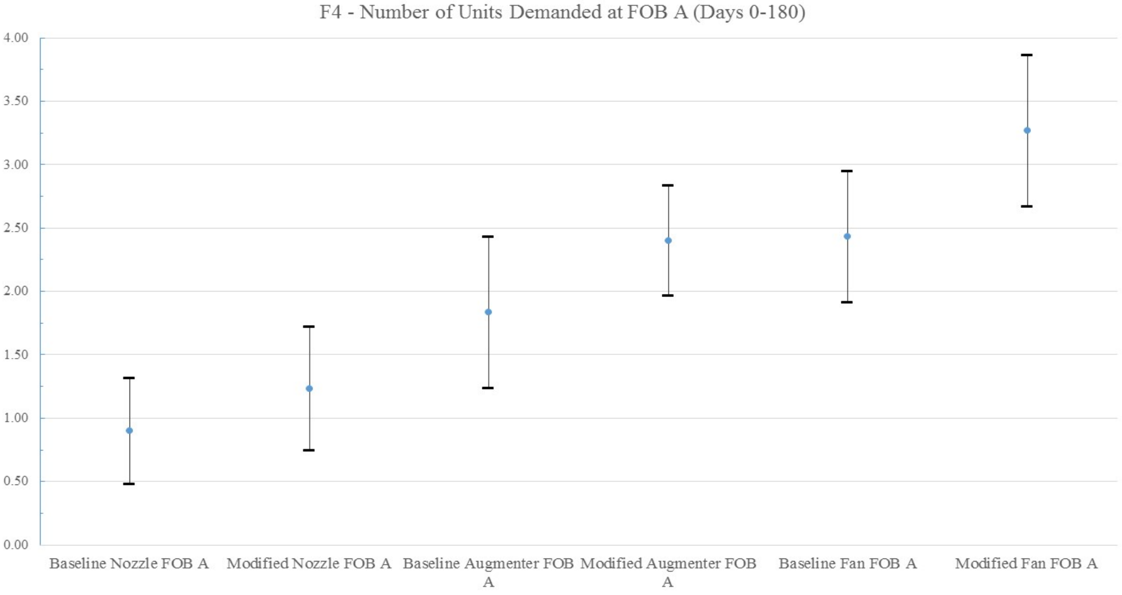

Figure 5. F4 - Number of Units Demanded at FOB A (Modules 1-3)

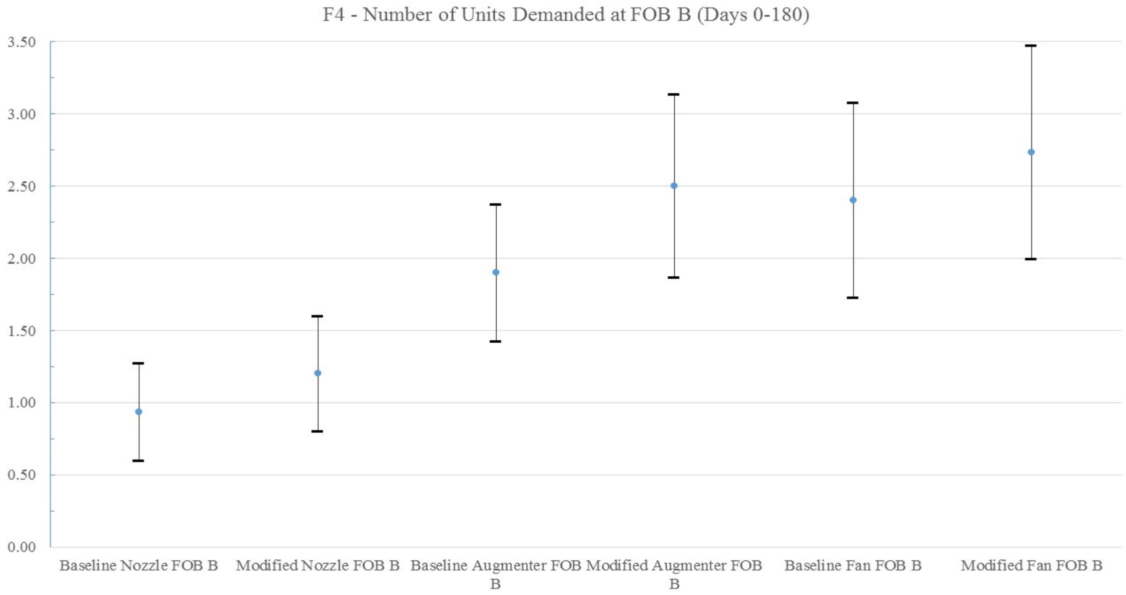

Figure 6. F4 - Number of Units Demanded at FOB B (Modules 1-3)

Figures 5 and 6 illustrate the overlapping confidence intervals for the nozzles, augmenters, and fans. Despite the overlap of confidence intervals, two sample t-tests with an alpha of 0.05 must be conducted in order to determine the statistical significance of the difference between the baseline and modified models. For example, even though the confidence intervals overlap for the fan module at FOB A, there is a statistically significant difference between the two models.

Additionally, Figures 7 and 8 show the overlapping confidence intervals for the power modules and gear boxes. Once again, the overlapping confidence intervals for the JSF engine modules cannot statistically conclude a lack of evidence for a significant difference between the two models. However, we can find the 95% confidence intervals for the difference in means in the last column in Table 4 and see that they include zero for all of the modules except the fan at FOB A and the power module at FOB B.

Figures 9 and 10 display the confidence intervals for the five JSF engine modules for the baseline and modified models by FOB. These plots help identify the differ-

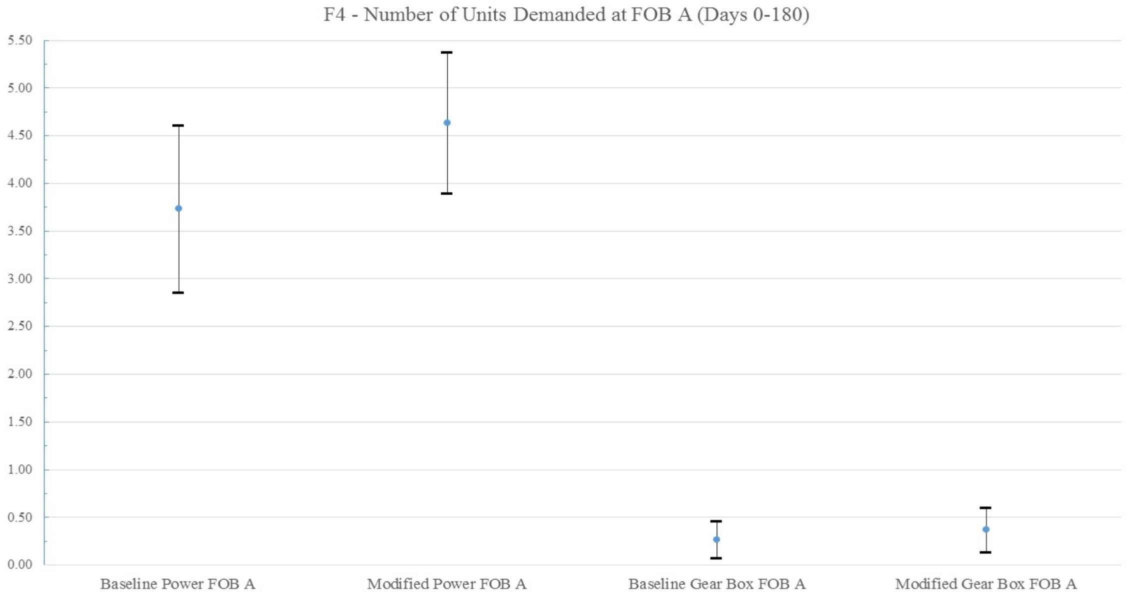

Figure 7. F4 - Number of Units Demanded at FOB A (Modules 4-5)

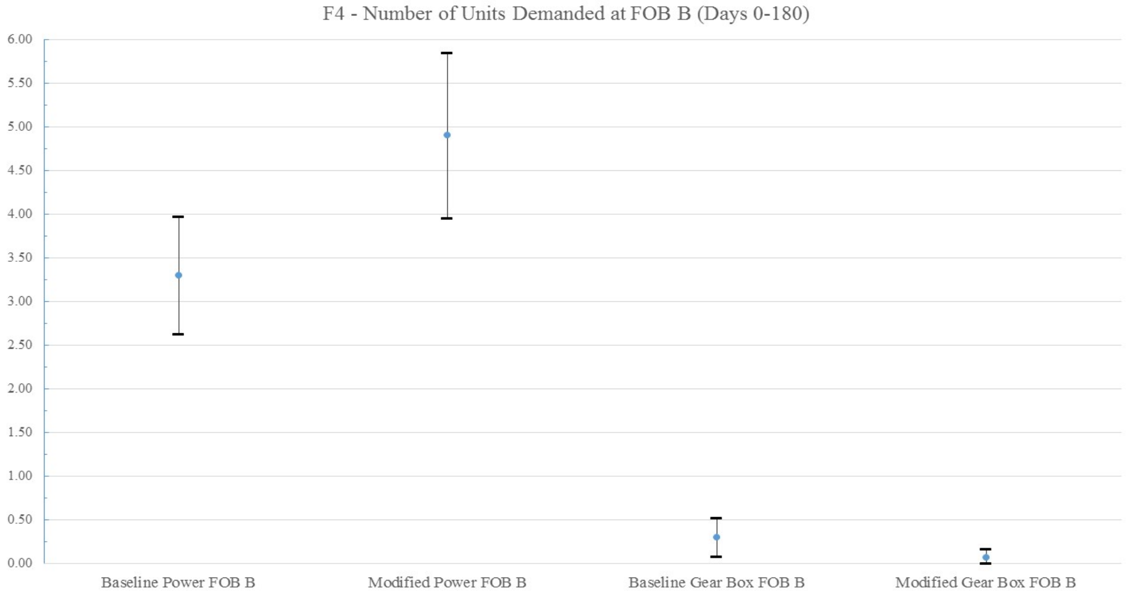

Figure 8. F4 - Number of Units Demanded at FOB B (Modules 4-5)

ences in mean and variance between the different JSF engine modules at each FOB. Additionally, these plots show that the nozzle and gear box modules have the smallest variance at both locations compared to the confidence interval widths for the augmenter, fan and power modules. This information provides insight to maintenance commanders about which JSF engine modules are more volatile and which fluctuate less. The spares with less variance provide more confidence for a commander when buying spare parts. Alternatively, wider confidence intervals portray a potential for an increased number of spares parts necessary for the JSF mission.

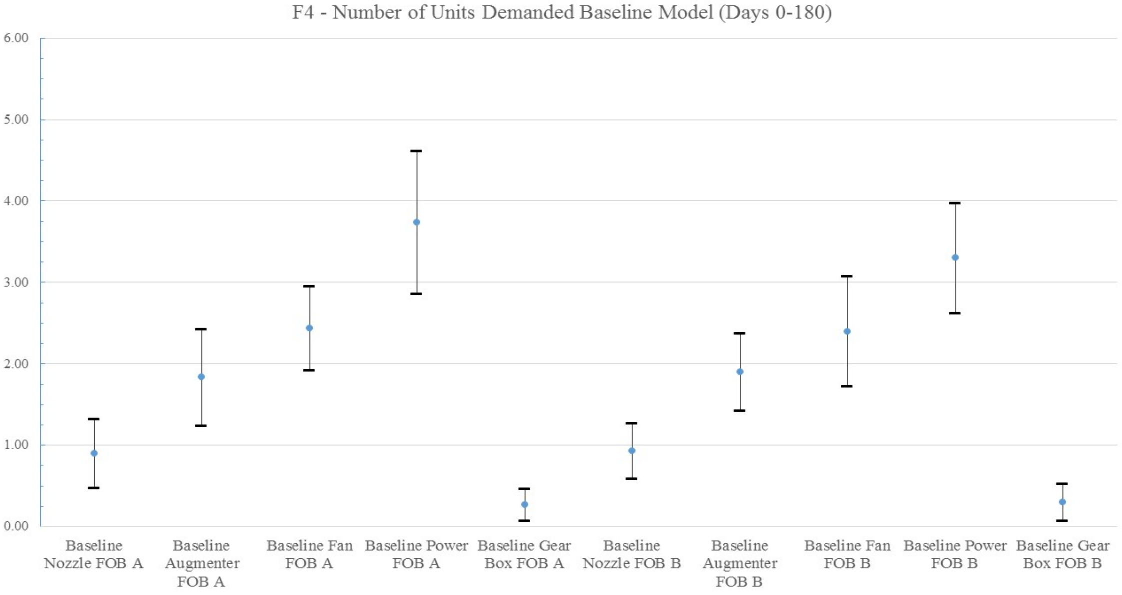

Figure 9. F4 - Number of Units Demanded (Baseline Model)

Originally, we looked at multiple supply metrics to include with our first analysis to help understand the entire JSF spare engine module process and see the potential impacts of increased OPSTEMPO on spare parts. However, we chose not to include information about the F3 metric (Number of Backorder Days) and other supply statistics because the LCOM ATK model scenario did not fully include logic to track the number of backorder days for the individual JSF engine module parts. Despite only having one supply statistics to analyze, the effects of the F3 metric can be related to observed changes with the C6 statistic (Not Mission Capable due to Supply).

Another insight gained from this part of the analysis were the differences between location A and B. As mentioned in Chapter 3, FOB B is further away from the Red

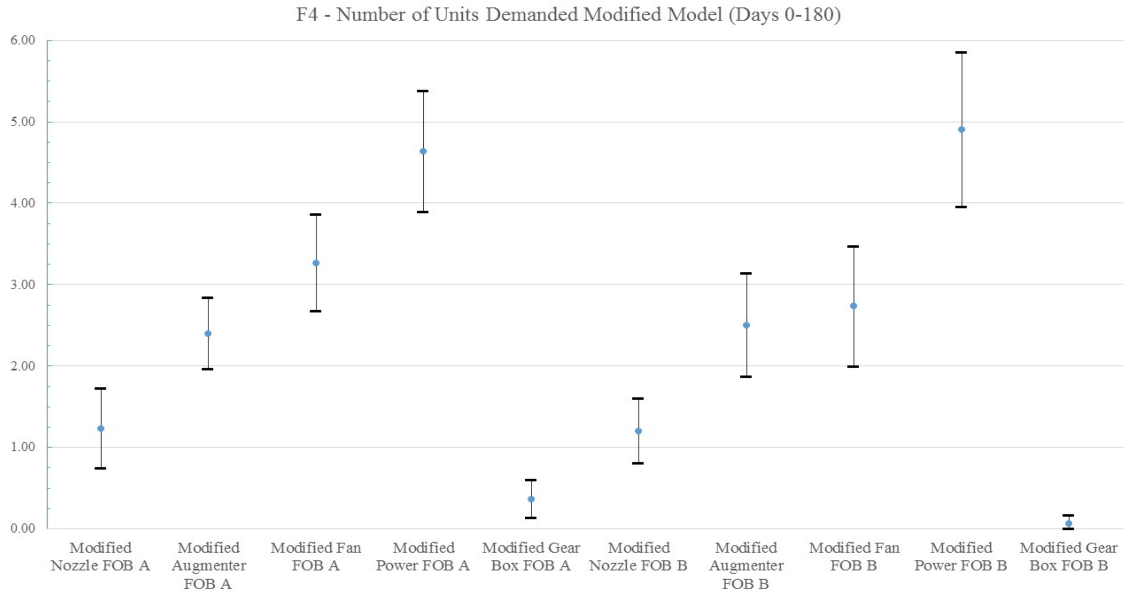

Figure 10. F4 - Number of Units Demanded (Modified Model)

Force location, so the sorties flown from FOB B follow a uniform distribution that is ten minutes longer than the uniform distribution for FOB A. With longer sorties at location B, we expected there to be higher outputs in the C-Statistics for the percent of time sorties are being flown (C3), percent unscheduled maintenance (C4), percent of aircraft not mission capable due to supply (C6), flying hours (C16), and the average flying hours per aircraft per day (C17). Due to longer sortie durations, we expected lower observed values for the number of achieved sorties per aircraft per day (C15). Table 2 is consistent with our expectations with higher numbers for C3, C4, C6, C16 and C17, in addition to lower outputs for C15.

For the D and F-Statistics we expected relatively similar outputs for location A and B, with a slight increase in the outputs for location B. The observed values in Table 3 show very similar outputs for locations A and B, as expected. In the modified model it is interesting to see less manhours used in location B compared to location A. We attribute that to the increased amount of time a JSF spends in the air compared to their time on the ground. The results in Table 4 confirm our expectations of similar results for both FOB A and B.

From the results of our first analysis, we deemed the following statistics the most interesting for further exploration: C4 - Percent Unscheduled Maintenance, C6 - Percent NMCS, C17 - Average Flying Hours / AC / Day, and D3 - Manhours Used.

4.2 Experimental Design

We created a full factorial set of experiments to assess the way three factors impacted key MOEs over the full 180 day simulation period. For the design of experiments we chose three factors: the number of spare JSF engine module parts, number of maintenance personnel, and the sortie duration. We chose two levels for each factor, high and low settings.

The number of spare JSF engine module parts for the high level (baseline) consists of three spare parts and the low setting drops these spares to one part. Due to a lower than expected use of JSF spare module parts in our baseline model, we use this lower setting design point for spare JSF engine modules. For the low level (baseline), the number of maintenance personnel follows the first analysis with the scheduled number of members assigned to the eleven different AFSC positions. The high level schedules an additional member to each of the AFSCs, allowing for eleven more maintenance personnel to work on aircraft. Finally, for the low level (baseline), the sortie duration is selected by a uniform distribution between 142.5 minutes and 157.5 minutes for aircraft at FOB A and a uniform distribution between 152.5 minutes and 167.5 minutes for aircraft at FOB B. The high level increases the distribution for the sortie duration by twenty percent for aircraft at both locations.

A design matrix was created to show all possible combinations of high and low levels for each input factor. These high and low levels can be generically coded as +1 and -1, respectively. This design matrix, as well as the responses to each of the settings, can be found in Table 6. C4 - Percent Unscheduled Maintenance, C6 - Percent NMCS, C17 - Average Flying Hours / AC / Day, and D3 - Manhours Used were the chosen MOEs for this part of our analysis. The results for each of the responses was found by running LCOM ATK for each of the eight settings or design points shown in Table 6, with the baseline settings in bold. These baseline results are not equivalent to the results from the modified model in the first study because the first study analyzes the 30 day surge operation where the experimental design explores the effects over the entire 180 day surge, seize and sustainment periods.

Table 6. DOE Results

# Spares	# MX	Sortie Duration	PCT UNSCHED MAINTENANCE	PCT NMCS	AVG. FLYING HRS/AC/DAY	MANHOURS USED
1	1	-1	11.36 ± 0.08	9.85 ± 0.29	2.823 ± 0.013	139273 ± 612
-1	1	-1	11.29 ± 0.09	10.29 ± 0.31	2.808 ± 0.013	138400 ± 668
1	**-1**	**-1**	**11.72 ± 0.06**	**9.39 ± 0.28**	**2.793 ± 0.012**	**137002 ± 543**
1	1	1	12.55 ± 0.1	11.31 ± 0.33	3.134 ± 0.01	145051 ± 571
-1	-1	-1	11.68 ± 0.08	9.99 ± 0.3	2.782 ± 0.011	136852 ± 542
-1	1	1	12.55 ± 0.09	12.14 ± 0.32	3.118 ± 0.013	144650 ± 592
1	-1	1	12.96 ± 0.08	11.05 ± 0.34	3.082 ± 0.011	140673 ± 558
-1	-1	1	12.86 ± 0.1	11.41 ± 0.35	3.068 ± 0.012	140031 ± 701

As a result of using the entire 180 days for the second analysis, there are large differences between baseline design point in the third line of Table 6 and the modified model's outputs from the 30 day analysis back in Table 2 and 3 (column 3) from the first analysis. When comparing the two analyses, the percent of unscheduled maintenance decreases by about 50%. The JSF mission flies surge operations for 30 days and flies seize and sustainment operations for 150 days. Due to the lower sortie rates and the larger percent of time in the sustainment period, the average percent of unscheduled maintenance decreases. The percent NMCS increases after the initial 30 days causing the total percent NMCS for the 180 days to increase by roughly 3-4%. This inflation of percent NMCS is caused by more JSF parts failing because of the cumulative hours flown on each JSF. The average flying hours per aircraft per day remained fairly constant between the two time periods, but the number of manhours changed drastically between the two tables. This is attributed mainly to the combination of the two locations manhours and the the additional 150 days of manhours added to the initial 30 day surge period. Despite the differences between the two analyses, we believe the different chosen time periods help answer the primary questions for this research.

The LCOM ATK scenarios were run for thirty replications at each design point, resulting in a total of 240 runs. Similar to the first analysis, the data from LCOM ATK was output into a comma delimited text file. This text file was imported into a workbook in Microsoft Excel to organize the data for a clean import to JMP, a computer program created as a tool to be used for expert data analysis, design of experiments, and Six Sigma implementation. In order to find the effects of the three factors on the four response variables, a model was created in JMP for each MOE. The goal of this part of our analysis is to gain insight on how the factors impact the responses, not to find the best factor level setting. For each of the models, a response consisting of values from the 240 runs was used for y-variable and the x-variable consisted of the first order factors and their interaction terms.

The Adjusted R-Square values from two of the four models were not as high as we would expect and the residuals were not normally distributed. The low Adjusted R-Square value suggests there are other factors that were not included in those two models that are also important to the responses. However, we were able to draw insight from the models and answer our primary focus question for this analysis that was “which factors significantly impacted the responses?”. We are not using the parameter estimates provided by the outputs from the JMP models to indicate or predict the amount each significant factor affects the responses. Rather, we use the parameter estimates to draw insight to which direction, positive or negative, the significant factors influence the MOEs and on what order of magnitude the response changes in comparison to other significant factors in the model.

Tables 7 and 8 summarize the results from the first model (Adjusted R-square of 0.89) which analyzes the percent unscheduled maintenance response. The results from the ANOVA table suggest that the model explains a significant amount of the variation in the data. The number of maintenance personnel and sortie duration were significant factors for the first model.

Table 7. C4 Analysis of Variance

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Model	7	96.12	13.7321	265.2645
Error	232	12.01	0.0518	**Prob >F**
Total	239	108.13		<.0001*

The number of maintenance personnel decreased the unscheduled maintenance response, but the sortie duration increased the unscheduled maintenance more than the magnitude of # MX, as shown in Table 8. Compared to the number of available maintenance personnel, sortie duration caused more than triple the change in response and resulted in the most significant impact on the percent of unscheduled maintenance. Intuitively, this makes sense because as sortie durations increase, the number of unexpected maintenance requirements to include JSF engine failures is expected to rise as well.

Table 8. C4 Parameter Estimates

Term	**Estimate**	**Std Error**	**t Ratio**	**Prob >|t|**
Intercept	12.12	0.015	825.22	<.0001*
# Spares	0.03	0.015	1.84	0.068
# MX	-0.18	0.015	-12.33	<.0001*
# Spares* # MX	-0.01	0.015	-0.65	0.513
Sortie Duration	0.61	0.015	41.23	<.0001*
# Spares*Sortie Duration	-0.001	0.015	-0.06	0.950
# MX*Sortie Duration	0.003	0.015	0.24	0.812
# Spares*# MX*Sortie Duration	-0.02	0.015	-1.16	0.248

The results from the second model, which analyzes the percent NMCS, are organized in Tables 9 and 10. This is one of the two models with lower Adjusted R-Square values (R-square of 0.5134), due to the random error's large contribution to the total sum of squares. However, from our mean squares and the F-Ratio, this model has a p-value of <0.0001 which suggests the model explains a significant amount of the variation in the data.

Table 9. C6 Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	7	187.96	26.8521	37.0278
Error	232	168.24	0.7252	**Prob >F**
Total	239	356.21		<.0001*

The number of JSF engine spare modules, the number of maintenance teams and sortie duration were significant factors that affected the percent NMCS, as shown in Table 10. The number of available spares at the FOBs decreased the percent NMCS, but an increase in sortie duration increased the percent NMCS almost four times more than the negative effect from increasing the number of JSF spares.

Table 10. C6 Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob >|t|
Intercept	10.69	0.055	194.41	<.0001*
# Spares	-0.28	0.055	-5.17	<.0001*
# MX	0.21	0.055	3.87	0.0001*
# Spares* # MX	-0.03	0.055	-0.62	0.539
Sortie Duration	0.81	0.055	14.66	<.0001*
# Spares*Sortie Duration	-0.03	0.055	-0.47	0.642
# MX*Sortie Duration	0.02	0.055	0.39	0.698
# Spares*# MX*Sortie Duration	-0.07	0.055	-1.31	0.192

As the sortie duration increases, we expect the number of total JSF failures to increase as well, causing the percent NMCS to increase. It also makes sense that the percent NMCS decreases if we allocate more spare JSF engine modules to the FOBs, because aircraft are repaired more quickly (but only for engine module failures). However, its isn't obvious why adding one member to each of the AFSCs causes an increase in the percent NMCS at roughly the same magnitude as the number of spares. We believe this is due to the decrease in not mission capable due to maintenance (NMCM), which causes the total percent not mission capable to consist of more NMCS. In other words, some of the NMCM shifted to the NMCS.

The third model presents results with how we expected the three factors to affect average flying hours per aircraft per day. These JMP outputs are organized in Tables 11 and 12. The results found in Table 11 suggest that the model explains a statistically significant amount of the variation in the data with an Adjusted R-square value of 0.9574.

Table 11. C17 Repsonse: Analysis of Variance

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Ratio**
Model	7	5.481	0.783	768.789
Error	232	0.236	0.001	**Prob >F**
Total	239	5.7168410		<.0001*

As shown in Table 12, the number of spare JSF parts, number of maintenance personnel and sortie duration were significant factors that positively affected the C17 response. The number of spares and maintenance personnel affected the response roughly the same, but the parameter estimate associated with sortie duration was twenty-one times that of the number of spares and almost eight times the coefficient for number of maintenance personnel. This is exactly what we expect because, as the number of spares and maintenance personnel increase, maintenance on aircraft take less time allowing for more sorties to be flown. This would also increase the ratio of time in the air versus time on the ground. It is intuitive to the casual observer that sortie duration is highly correlated with the number of flying hours, so if the sortie length was increased by twenty percent there should be a significant impact to the average flying hours per aircraft per day. Another significant variable is the interaction term between # MX and sortie duration. This result suggests a greater increase in average flying hours per aircraft per day if both # MX and sortie duration are at their high levels compared to the increase with only one high level factor.

Table 12. C17 Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob >|t|
Intercept	2.95	0.002	1432.5	<.0001*
# Spares	0.007	0.002	3.39	0.0008*
# MX	0.02	0.002	9.69	<.0001*
# Spares* # MX	0.0007	0.002	0.35	0.724
Sortie Duration	0.15	0.002	72.58	<.0001*
# Spares*Sortie Duration	0.0005	0.002	0.24	0.807
# MX*Sortie Duration	0.006	0.002	2.91	0.0039*
# Spares*# MX*Sortie Duration	-0.0004	0.002	-0.20	0.842

The last model analyzed the effects of the factors on the number of manhours and the results are displayed in Tables 13 and 14. From the sum of squares, we calculate the Adjusted R-square value to be 0.7686. With a p-value less than 0.0001 in Table 13, we can conclude that this model explains a statistically significant amount of the variation in the data. D3 is the output statistic for the number of manhours used, so we assume more maintenance personnel would show the most prominent increase in manhours used and an increase in sortie duration would also result in a higher number of manhours used.

Table 13. D3 Repsonse: Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	7	2073965405	296280772	114.416
Error	232	600764578	2589502.5	**Prob >F**
Total	239	2674729984		<.0001*

Table 14 confirms these assumptions with significant estimates for both the number of maintenance personnel and sortie duration. The number of spares was also a significant factor, but it did not impact this MOE nearly as much as the other two factors. The last significant variable is the interaction term between # MX and sortie duration. This indicates that there is an even more significant increase in manhours used if both # MX and sortie duration are increased together.

Table 14. D3 Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob >|t|
Intercept	140233.85	103.87	1350.1	<.0001*
# Spares	266.05	103.87	2.56	0.0111*
# MX	1609.49	103.87	15.49	<.0001*
# Spares* # MX	52.62	103.87	0.51	0.613
Sortie Duration	2352.08	103.87	22.64	<.0001*
# Spares*Sortie Duration	10.13	103.87	0.10	0.922
# MX*Sortie Duration	654.76	103.87	6.30	<.0001*
# Spares*# MX*Sortie Duration	-128.20	103.87	-1.23	0.218

In all of the four models, the first order terms were the most significant factors in the model. This can be explained by the sparsity of effects principle which states that systems are usually dominated by main effects and low-order interactions. From this analysis we were able to identify the significant factors that influenced the four different MOEs we chose to analyze.

4.3 Summary

This analysis provides insight to realistic capabilities and limitations of Blue Forces and can be used by a commander before a wargame begins to help them make more informed decisions during a wargame. The first sub-section of our research uses statistical analysis with plots, two sample t-tests, and 95% confidence intervals to show that there was statistically more strain on the JSF mission in the modified model when compared to the baseline model. The modified model resulted in higher percentages for unscheduled maintenance and NMCS, as well as a large increase in the number of manhours used. Our second analysis conducted an experimental design to pinpoint important factors that impact key MOEs. We found the statistically significant factors were the number of spares, number of maintenance personnel, and the length of sorties. This analysis provides essential insight to these factors that are key in capturing ACS through our selected MOEs. Both of these analyses contributed to a proof of concept that it is plausible for a logistics simulation to be run before a wargame and that a logistics simulation is vital for a more realistic and holistic view of Blue Force capabilities during a wargame.

V. Conclusions and Recommendations

5.1 Conclusions of Research

This thesis utilized a preexisting model created in LCOM ATK as a basis for analysis. With modifications to the scenario created by Lockheed Martin, a baseline scenario was created with two FOBs that conducted JSF sorties for 180 days to simulate a long duration wargame. The sorties followed a flight schedule that captured a seven day surge period, a twenty three day seize period and 150 days of sustainment operations. This flight schedule was created to mirror the expectations in the JSF KPPs. This research explored a more prolonged wargame scenario by examining the effects of elongating the surge operation to thirty days. This heightened OPSTEMPO strained the JSF mission and its maintenance support. We found statistically significant increases in the percent of time flying sorties, percent unscheduled maintenance, the amount of flying hours and sorties per aircraft, and the number of manhours required to maintain the JSF squadrons. We do not track fuel or ammunition in our study as opposed to the research done by Captain Daniel Krievs [5], but clearly there would be more demand for both in this JSF scenario. The results of this study clearly show a need for increased levels of ACS during even a relatively short extension of surge operations. The significantly different aircraft statistics are illustrated in Figures 11, 12, and the significantly different manpower statistic in Figure 13.

The increase in the percent of time aircraft fly sorties with our heightened OPSTEMPO adds about twenty flying hours per aircraft over the first thirty days. This increase is illustrated in Figure 11. The average achieved sorties per aircraft per day for the baseline scenario was a little more than two sorties per day and the modified model showed an increase to 2.6 sorties per day. This increase in sorties for twenty-four aircraft at two locations requires an additional twelve to thirteen sorties

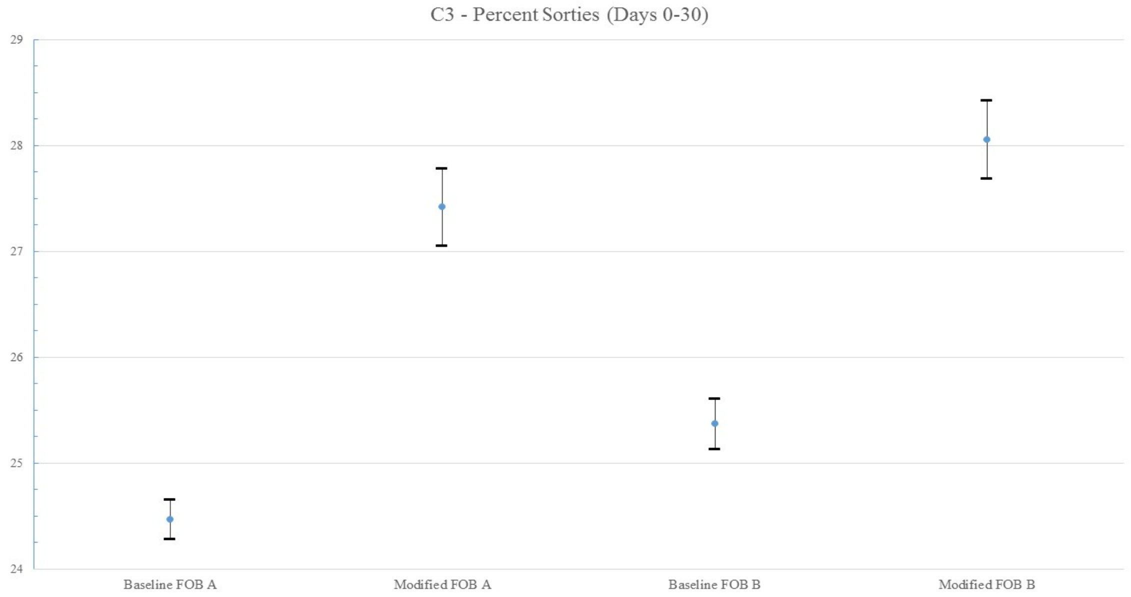

Figure 11. C3 - Percent Time Flying Sorties

per day. That equates to almost 400 more sorties between the two locations just within the first 30 days of the wargame scenario. This vast increase in the number of sorties and flying hours places a significant amount of stress on JSF parts and results in more failures and unscheduled maintenance. The increase in percent unscheduled maintenance is illustrated by the confidence intervals in Figure 12.

The increase in the total number of manhours adds about 150 manhours with our modified scenario at each FOB over the first thirty days. This increase requires an additional five hours of work on average per day across the eleven AFSCs. This large increase in the number of manhours required at the two FOBs places a significant amount of stress on maintenance personnel and could possibly result in degraded job performance and squadron moral. The increase in maintenance manhours is illustrated by the confidence intervals in Figure 13.

In order to mitigate the potential issues with constraints on Blue Forces, this research found significant factors which impact the aforementioned increased responses. The number of available spare JSF parts, number of maintenance personnel scheduled

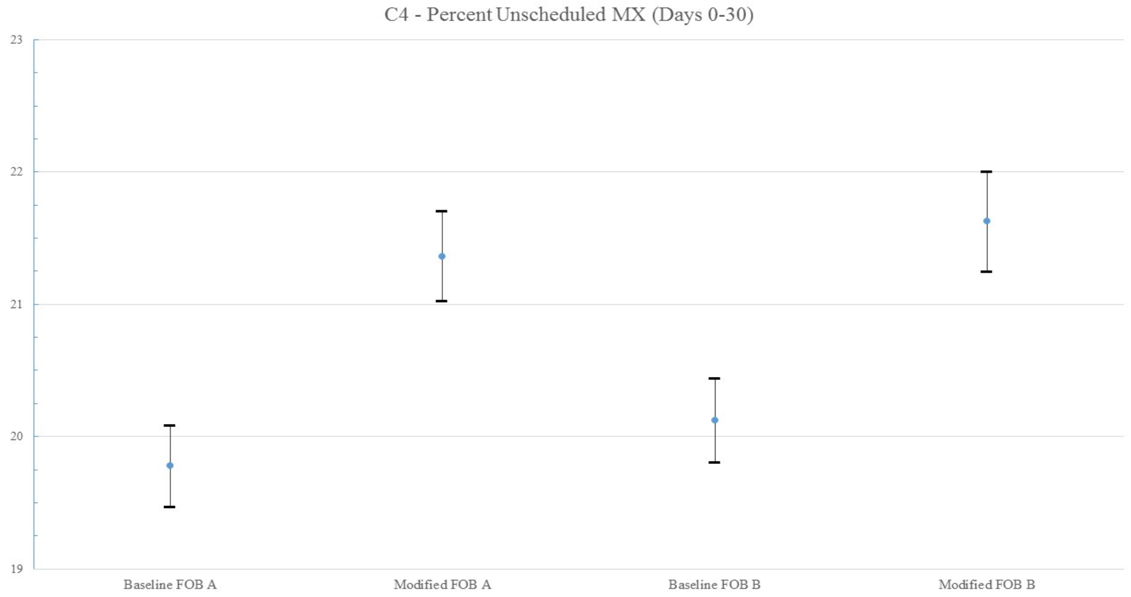

Figure 12. C4 - Percent Unscheduled Maintenance

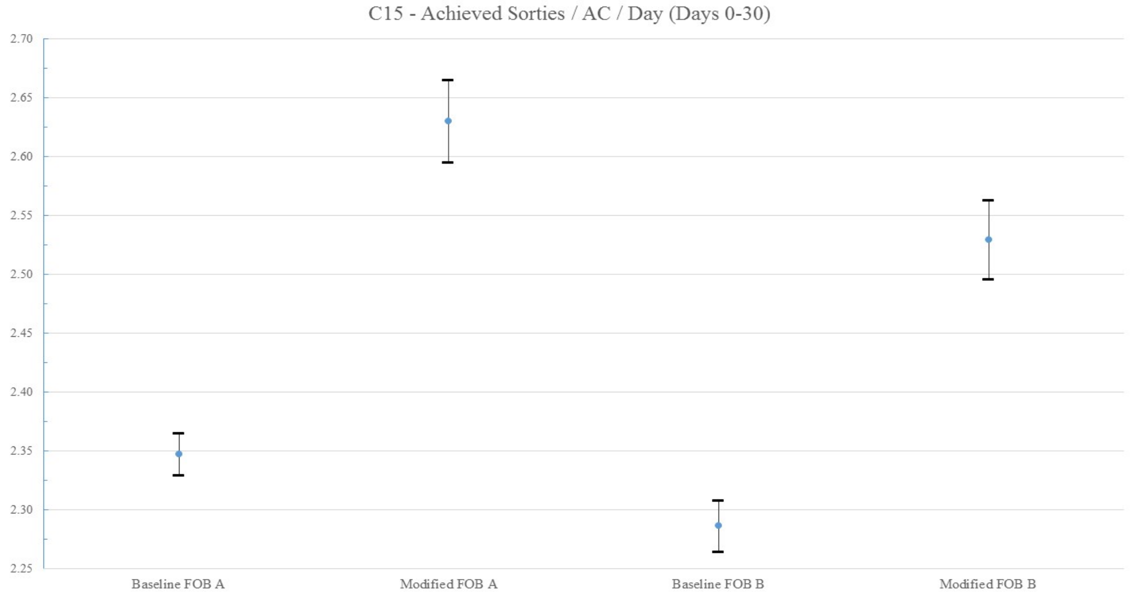

Figure 13. D3 - Manhours Used

at the FOBs, and the length of the sorties were significant factors which effected these responses. There are definitely other factors which influence the responses, but our analysis provided insight on how the factors modeled influence operation in a LDLW.

This research found that increasing the number of spare JSF parts available at the FOBs significantly decreased the percent of aircraft NCMS and allowed the aircraft to fly more hours per day, on average. Increasing the number of maintenance personnel scheduled to be working at each location significantly decreased the percent of aircraft requiring unscheduled maintenance and allowed the aircraft to fly more hours each day, on average. Additionally, if there are sorties that require a higher level of engagement with opposing forces or are scheduled for missions further away from the FOBs, we saw a significant increase in the percent of unscheduled maintenance, the percent of aircraft NMCS, the average flying hours per aircraft per day, and the number of manhours required to maintain the JSF squadrons. Sortie duration was the most influential parameter in each of the four models, so in a more prolonged war with a higher OPSTEMPO we would expect a significant increase in the amount of JSF spares required and the amount of time our airmen spend maintaining the JSF engines to enable the sustainment rate of sorties for the JSF mission.

These results are starkly similar to those of Captain Krievs who found, through multivariate analysis, that the keys to capturing ACS are the number of spares, number of maintenance crews, ammunition, and fuel [5]. This study did not incorporate fuel or ammunition, but clearly they would be significant parameters that affect the MOEs.

5.2 Recommendations for Future Research

The Deputy Chief of Staff for Logistics proposed an idea that a repair network should accomplish the Intermediate-level and Depot-level maintenance and repair of aircraft. RAND conducted analysis of a repair network in 2010 to address this issue. They analyzed the efficiency of establishing Central Repair Facilities (CRFs) within a repair network, particularly concentrating on manpower utilization. Additionally, the LDLW workshop conducted by AFMC/A4F did include RNI and contributed to the initial foundation of incorporating RNI into logistics simulations. The studies conducted by RAND, the LDLW workshop, and the results from this thesis provide an opportunity for future work with RNI in LCOM ATK. The conclusions of this research pave a pathway to discovering the impact of RNI compared to traditionally modeled repairs. Introducing RNI to LCOM ATK would open many doors to further analyze the maintenance procedure and its impact on a long duration logistics wargame.

In addition to introducing RNI to a logistics wargame, future work could focus on the logic within LCOM ATK with respect to individual spare JSF engine module parts, similar to the LDLW workshop conducted by AFMC/A4F and FTI.

5.3 Summary

Wargames were originally created to test war time strategies against opposing forces within a short time frame. Due to the short duration design of these wargames, logistics were deemed irrelevant and it was incorrectly assumed that the warfighter would be logistically supported for the entire duration of the wargame. The purpose of this thesis is to provide insight to the value of capturing logistics within a combat model or wargame and to better quantify and model a scenario with an increased requirement for ACS. An imperative piece to wargames is logistics because it provides a more accurate representation of Blue Force capabilities and constraints and yields key insight to the logistical ramifications of war time decisions for commanders. Incorporating logistics in wargames provides a more holistic view of a war and can be the crucial addition to wargames that helps the USAF maintain dominance in air, space, and cyberspace.

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14. ABSTRACT

Wargames were originally created to test wartime strategies against opposing forces within a short time frame. Due to the short duration design of these wargames, logistics were deemed irrelevant and it was incorrectly assumed that the warfighter would be logistically supported for the entire duration of the wargame. The purpose of this thesis is to provide insight to the value of capturing logistics within a wargame and to better model the increased requirement for Agile Combat Support. This research utilizes a logistics simulation tool and its outputs to conduct statistical analyses comparing a baseline scenario created to mirror the Joint Strike Fighter key performance parameters and a modified model with increased operations tempo. Additionally, an experimental design provides key insight to the primary factors contributing to the changes in essential measures of effectiveness. This research identifies statistically significant differences between the baseline and modified models and finds the most essential components for Agile Combat Support are the number of spares, the number of maintenance personnel, and sortie duration. Incorporating logistics in wargames provides a more holistic view of a war and can be the crucial addition to wargames that helps the USAF maintain dominance in air, space, and cyberspace.

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