A SIMULATION BASED METHODOLOGY TO EXAMINE THE B-1B's AN/ALQ-161 MAINTENANCE PROCESS

THESIS

Ricardo R. Garza, Captain, USAF

AFIT-LSCM-ENS-10-04

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY
AIR FORCE INSTITUTE OF TECHNOLOGY
Wright-Patterson Air Force Base, Ohio

AFIT-LSCM-ENS-10-04

A SIMULATION BASED METHODOLOGY TO EXAMINE THE B-1B's AN/ALQ-161 MAINTENANCE PROCESS

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 Logistics Management

Ricardo R. Garza, BS

Captain, USAF

March 2010

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

AFIT-LSCM-ENS-10-04

A SIMULATION BASED METHODOLOGY TO EXAMINE THE B-1B'S AN/ALQ-161 MAINTENACE PROCESS

Ricardo R. Garza, BS
Captain, USAF

Approved:

Dr. Raymond R. Hill (Chairman) date

Daniel D. Mattioda, Maj, USAF (Member) date

AFIT-LSCM-ENS-10-04

Abstract

The B-1 Bomber is the Air Force's only supersonic, conventional-only strike platform. This thesis looks at the maintenance procedures associated with the defensive electronic counter measure (ECM) system on the B-1B, designated the AN/ALQ-161. Computer simulation of the current line-replaceable-unit maintenance network for Ellsworth AFB and Dyess AFB is modeled. In addition, two hypothetical repair networks are proposed and analyzed. This research considers the applicability of this type of computer simulation, using ARENA software to study the AN/ALQ-161 repair system.

The contribution of this research is a discrete simulation methodology specific to the AN/ALQ-161 LRU repair line. Two response variables of interest were addressed, work-in-process and machine utilization. A total of 20 different repair scenarios were analyzed for the three different LRU networks simulated. A best-case scenario is selected from each model and the results are compared to one another.

AFIT-LSCM-ENS-10-04

To Mom & Dad

Acknowledgments

I would like to express my sincere appreciation to Dr. Raymond Hill and Maj. Dan Mattioda for their guidance, support and encouragement throughout the course of this thesis effort. I am also indebted to MSgt Richard C. Diamond, ACC/A4FI, who spent much of his valuable time and exhibited a great deal of patience trying to explain the B-1B’s AN/ALQ-161 maintenance process to a “loggie.” In addition, I would like to thank my previous commander, Lt Col Travis Condon for his mentorship. Put simply, I would have never been accepted to AFIT without his help.

Most important, I would like to thank my wife and two beautiful daughters for their constant love and support throughout my entire time in the Air Force. Their unselfishness is truly amazing. I couldn’t imagine doing any of this without them by my side.

Rick Garza

Table of Contents

Page

List of Figures

List of Tables

Page

A SIMULATION BASED ANALYSIS OF THE B-1B's AN/ALQ-161 MAINTENANCE PROCESS

I. Introduction

Background

Today's U.S. Air Force (USAF) bomber structure is a remnant of the Cold War and the Nuclear Triad. Large numbers of widely dispersed aircraft were required to maintain nuclear alert and deter aggression. "Bombers play a unique and versatile role in National strategic policy and doctrine. American bombers support USAF doctrine by performing several basic Aerospace Power functions and roles listed in Air Force Basic Doctrine, Air Force Doctrine Document (AFDD-1) and delineated in Air Warfare, Air Force Doctrine Document 2-1 (AFDD 2-1)" (U.S. Air Force Long-Range Strike Airstrike White Paper, 2001: 22). "While the current Air Force bomber inventory retains a nuclear mission the emphasis has shifted to conventional operations, small scale contingencies, and defeating global terrorism" (U.S. Air Force Long-Range Strike Airstrike White Paper, 2001: 2). Today the USAF bomber inventory consists of three platforms. Each brings unique capabilities and strengths to the USAF mission while sharing common characteristics of long range, large payload and flexibility (U.S. Air Force Long-Range Strike Airstrike White Paper, 2001). "The Air Force does not think of, or advertise, bombers as interchangeable. The B-1, B-2 and B-52 all have a specific mission area and each fills a particular combat niche" (U.S. Air Force Long-Range Strike Airstrike White Paper, 2001:v).

B-1 Bomber

Nicknamed "The Lancer", the B-1 is the Air Force's only supersonic and conventional-only strike platform. It weighs approximately 55,000 pounds, has a range of 7,500 nautical miles and is capable of speeds of approximately 1.2 mach (sea level). It requires a crew of four to operate and "with three internal weapons bays, the B-1 has the largest and most flexible payload capability of the three bombers" (U.S. Air Force Long-Range Strike Airstrike White Paper, 2001:19). The original production estimates for the B-1 called for approximately 100 aircraft to be produced (Roark, 1983). The last B-1 was delivered to McConnell AFB, KS in 1998. In 2002, the B-1 inventory peaked to its highest level at 93 bombers. The B-1 is an extremely expensive platform to operate and maintain. By the end of 2002, in order to address major cost overruns, the USAF approved a reduction in the B-1 inventory (U.S. Air Force Long-Range Strike Airstrike White Paper). The idea was "to provide America with a smaller, more lethal, more survivable long-range strike force, by retiring 33 B-1's and reducing the B-1 main operating bases from five to two" (U.S. Air Force Long-Range Strike Airstrike White Paper:2). The savings from this retirement and consolidation of resources were then reinvested in the remaining B-1 inventory to support maintenance and operations. As of 2007, there were 66 supersonic B-1's in the USAF inventory, 51 of which were deemed combat ready. Furthermore, there are three main operating bases (MOBs) and squadrons for the B-1 in the continental United States (CONUS). Two are active-duty squadrons, located at Dyess AFB, TX and Ellsworth AFB, SD. The Georgia Air National Guard operates the remaining squadron.

Upgrades.

As with most Air Force weapons systems, the B-1 has been upgraded well beyond its original programmed life cycle to extend its operational capability and life span. As such, it has seen numerous upgrades: to its avionics, small diameter bomb (SDB) integration, mobility readiness spares package (MRSP) kits added, and the incorporation of synthetic aperture radar (SAR) capability and SNIPER targeting acquisition pods. Recent block upgrades gave battlefield commanders an even more flexible and lethal platform to use. Today, the B-1 is a high demand asset that supports two simultaneous combat operations, one in Iraq and another in Afghanistan. “The B-1’s speed and maneuverability allow responsiveness and seamless integration with composite strike packages” (U.S. Air Force Long-Range Strike Airstrike White Paper, 2001:19). In addition, the B-1 “provides the Joint Force Commander massive firepower potential coupled with a significant loiter capability perfectly suited for the inconsistent tempo of today’s ongoing operations” (Gertler, 2009:38). The B-1 has enjoyed tremendous success with the adaptation to “allow the delivery of the latest cluster bombs, Joint Direct Attack Munitions (JDAM), and other precision-guided conventional weapons” (CRS, 2009:14). However, the trade-off for this high demand and constant use is evidenced in the added cost of maintenance and upkeep. “The non-stop overseas contingency operations are taking a toll on the overall fleet” (Gertler, 2009:34). Keeping this bomber fully mission capable is directly related to the maintenance of its myriad of different avionics systems. Modern aircraft, such as the B-1, have complex systems requiring frequent unscheduled maintenance.

AN/ALQ-161

"The B-1's avionics consist of offensive, defensive and miscellaneous avionics associated with other systems" (Roark, 1983:16). This thesis looks specifically at the maintenance procedures associated with the defensive electronic counter measure (ECM) system on the B-1B. Consisting of over 100 units and weighing approximately 5,200 pounds, it is designated the AN/ALQ-161. Built by Eaton Corporation, "the AN/ALQ-161 defensive avionics suite provides jamming against early warning radars and the fire control radars of missiles and anti-air guns. The system also incorporates Northrop Grumman jamming transmitters, Raytheon phased array antennas and a tail warning pulse Doppler radar, which gives rear-facing hemispherical coverage. A single AN/ALQ-161 system contains and controls a large quantity of jamming transmitters and antennas and is capable of jamming multiple threats simultaneously" (B-1's defensive avionics getting new guts, 2007). Its primary function is to protect the B-1 from the threat of adversarial integrated air defense systems (IADS). This system detects and identifies the full spectrum of threats, then applies the appropriate jamming technique, either automatically or manually, while recognizing when it might be dangerous to use ECM and limiting its jamming to specific directions for some minimum time (Gertler, 2009). In a wartime environment, this defensive system is absolutely critical to the B-1's mission effectiveness. If the AN/ALQ-161 is down, the mission does not happen.

Repair Process.

The B-1 has an integrated avionics system totaling over 424 installed line-replaceable-units (LRUs) of which there are approximately 212 repairable LRUs. Tentatively, 109 LRUs have been designated for base level repair on B-1 automatic test equipment (ATE) (Roark, 1983). Other repairable LRUs are designated for base level repair on other support equipment or for depot level repair. The AN/ALQ-161 ECM suite consists of roughly 33 LRUs and over 900 single-replaceable-units (SRUs).

The overall USAF maintenance concept for aircraft repair is a hierarchical system of main and sub-components. "Avionics components, called LRUs, are removed from aircraft when a malfunction is detected" (Roark 1983:17). This removal allows the technician to quickly troubleshoot and isolate the problem. Furthermore, modularity of the part provides the ability to pull a LRU and replace it immediately should the repair take longer than anticipated. Each LRU is made up of components called single-replaceable-units (SRUs). In order to maintain this weapon system, a fine balance must be reached between inventory on-hand and cost. Currently, the average organic (base-level) LRU repair capability of the AN/ALQ-161 is approximately 80%. This means approximately 20% of LRU repair cannot be handled by intermediate repair and must be repaired through other means (either sent to depot or to a contractor). Note that the term back-shop, intermediate repair and organic repair all mean the same thing and are used interchangeably. Due to the hierarchical system architecture, the LRU repair capability is only as good as the availability of SRUs on-hand. Currently, organic repair of SRUs is approximately 33%. This thesis does not address SRU repair, but it is vital to note that on-hand inventory of SRUs is pivotal to any successful intermediate LRU repair capability.

Problem Statement

The specific purpose of this study is to understand and describe the effect resource collaboration and a centralized repair facility has on the current AN/ALQ-161 LRU maintenance processes. The readiness of the B-1B weapon system is directly tied to the parts availability for the AN/ALQ-161 ECM suite. Using computer modeling and simulation makes it possible to model the current LRU maintenance repair process for the ECM and compare it to other proposed repair system configurations. This systematic and logical approach allows for easy identification of the best system enhancements for each representative model.

Research Objectives

The primary objective of this research is to apply simulation modeling techniques to examine the impacts various maintenance strategies, such as repair queuing policy, consolidated resource sharing, and centralized intermediate repair facilities (CIRF), might have on the repair cycle for the AN/ALQ-161. Additionally, research will focus on ways to reduce total time in system, work in process (WIP) and automatic test equipment (ATE) utilization. The goal of this study is to identify what repair network design provides the optimum balance between what exists today and what is possible tomorrow. The study also provides a model-based methodology useful for more detailed future analyses given problem-specific scenarios and data.

Research Questions

Specific research questions are listed below:

1. What are the advantages and disadvantages associated with resource sharing between the Ellsworth AFB and Dyess AFB maintenance processes?
2. What are the advantages and disadvantages associated with implementing a Centralized Intermediate Repair Facility for all ALQ-161 LRU repair activities?
3. Does the prototype simulation model realistically represent the empirical data employed and the repair systems in place?
4. What is the best process configuration for each model scenario employed or examined?

Research Focus

The primary tool used for this research is discrete event simulation modeling. Simulation is quite appropriate for describing and examining complex systems or processes. Three repair models of the AN/ALQ-161 LRU repair process at Ellsworth AFB, SD and Dyess AFB, TX were compared. The results are analyzed using traditional statistical techniques to determine significant performance differences using work-in-progress (WIP) and machine utilization as the primary independent, or response, variables.

Methodology.

The methodology used in this research involved the following steps:

1. Conducted a literature search of theses, journals, briefings, white papers, Congressional reviews, current Air Force Instructions and other associative resources.

2. Coordinated with ACC/A4F1 Command B-1 Electronic Warfare Systems Manager. Discussed current issues, practices, and collected data on current material flows for the AN/ALQ-161.

3. Considered commercial software packages for simulation and modeling analysis.

4. Prepared a baseline assessment, and documented the LRU repair process at Ellsworth and Dyess AFB respectively. (Model 1-Independent Ops).

5. Identified measures of performance and performance criteria (WIP and machine utilization were selected).

6. Modeled the repair process and conducted simulation experiments.

7. Evaluated baseline model results with actual performance. (Compared Model 1 to the empirical data obtained from step 2).

8. Prepared a comparative analysis. (Compared Model 1 to Model(s) 2 & 3).

Assumptions.

Various assumptions were made to complete this effort. These assumptions helped scope the effort and overcome deficiencies in specific scenario details (e.g., processes, data, etc.).

1. Continuous maintenance operations are conducted.

2. Bases are identical in terms of resources (same number of machines and personnel to carry out tasks).

3. Three-level maintenance is in place for all LRU repairs.

4. All LRUs removed from an aircraft are replaced immediately.

5. Probabilities of LRU failure are based upon serviceability rates and are identical for each base. LRUs can be sent to depot at any point in the intermediate repair cycle.

6. Mean repair times used for both bases and the depot are identical for each respective LRU.

7. Automatic Test Equipment (ATE) set-up and inspection times for both bases are equal.

8. Inter-arrival times follow a Poisson process (Roark, 1983). A stochastic process $\{N(t),\ t \geq 0\}$ is said to be a Poisson process if: (Law & Kelton, 2007:376; Banks et al., 2005:186)

   a. Arrivals occur one at a time

   b. $N(t + s)$ - $\mathrm{N}(t)$ (the number of arrivals in the time interval $(t,\ t + s)$ is independent of $\{N(u),\ 0 \leq u \leq t\}$

   c. The distribution of $N(t + s)$ - $N(t)$ is independent of t for all $t,\ s \geq 0$

9. Each base has approximately 80% LRU organic repair capability.

10. WIP time is equal to the interval between a LRUs removal and its return to base supply and/or depot

11. Each base has an unlimited supply of SRUs on-hand at the base or available from the depot.

12. The current system applies the first-in-first-out (FIFO) as the generic queuing policy; LRUs already repaired and requiring re-inspection take precedence over non-repaired LRUs currently in a repair queue.

13. Balking rates (repairs getting removed from the queue) are arbitrary in nature and established in model(s) 2 and 3.

14. Static inspection times are used across all 8 LRUs considered in detail. For simplicity, LRUs already repaired used a shorter inspection time and received precedence over other LRUs in system.

15. The model simulates only the repair process from base(s) to depot and does not consider the inventory level at either location.

16. Transportation (i.e. routing times), internal to each base, are equal, while times between base and depot were established as 2 days from Dyess AFB to Warner Robbins (depot) and 3 days from Ellsworth AFB to Warner Robbins.

Scope and Limitations.

There are numerous limitations when trying to model the complex maintenance procedures of the AN/ALQ-161 suite for the B-1B. First, there were limits with regard to the data obtained. This was overcome by using a previous thesis by Roark (1983) detailing the B-1B repair process and arrival rate distributions. Roark noted "the avionics LRUs are assumed to arrive to the organizational maintenance squadron queue according to a (homogeneous) Poisson process" (Roark, 1983:60). Furthermore, the current model was scoped to only consider LRU repair processes for the AN/ALQ-161. Of the 33 LRUs for this system, only 8 were modeled in detail. Their selection was based on a recommendation from ACC/A4F1; these LRUs are the "problem children" based upon historical evidence. There was a constraint associated with the respective repair times for each LRU. System average repair times were given, but not the times separated by each of the two bases studied. Triangular distribution rates were used for automatic test equipment (ATE) set-up, test, and repair times in all models used in this research.

Implications.

Air Combat Command (ACC/A4F1) recently proposed implementing a CIRF concept for all AN/ALQ-161 LRU repairs at the existing MOBs. The concept was unanimously rejected, as organic repair capability is presently good (80%). This study analyzes the current AN/ALQ-161 LRU repair process and recommends alternatives to the current maintenance structure should intermediate repair rates diminish or resources become constrained in the future.

Preview

The remainder of this thesis is organized as follows. In Chapter II, a review of applicable research is presented. Studies dealing specifically with differing levels of maintenance (organizational and intermediate level), a CIRF concept and queuing theory are reviewed to clarify the extent of the problem. Chapter III provides the foundation of the simulation experiment and the methodology employed. A detailed description of the simulation models and experimental design is presented, as well as a description of the data collection methods employed. The plan for analyzing the data and formulating the results is presented. Chapter IV presents the data output from the simulation experiment, the statistical analysis of the data, and the results of the experiment. Finally, in Chapter V, overall conclusions are presented. Results are examined, and suggestions for implementation and procedural guidance are offered as well as areas for potential future research.

II. Literature Review

Introduction

This chapter summarizes some of the past work supporting the methodology used and conclusions drawn in this research. Some key background information regarding the AN/ALQ-161 ECM suite is first discussed. Next, the measures of effectiveness of WIP and machine utilization are addressed as the primary focus in all three simulation models. The goal of this research is to identify LRU repair system configurations that increase both measures and to highlight any inefficiency in the repair network. Next, a review of two-level and three-level maintenance is provided and the concept of a CIRF is discussed. Finally, modeling and simulation, the research tool selected, is discussed.

Level of Maintenance

"The overall mission of Air Force maintenance is to provide aerospace systems ready to fly, fight, and sustain mission-ready equipment at the time and place it is needed" (DAF, 1998: 3). All USAF maintenance tasks are preventive or corrective in nature and are divided into two categories: on-equipment and off-equipment. On-equipment means the maintenance task is performed directly on the aircraft, while off-equipment maintenance is carried out on a removed component (DAF, 1998). Maintenance is performed at three different levels (3LM): organizational (on-equipment), intermediate (off-equipment), and depot. Most Air Force weapon systems are currently repaired at these three levels (DAF, 1998). In 1998, the Air Force mandated a shift towards a two-level maintenance (2LM) approach where applicable. Essentially, in a

2LM system, the middleman (i.e. intermediate repair) is removed from the process. The rationale behind this is to reduce unit-level manning requirements and maintenance costs by leveraging "state of the art communications, item visibility, and fast transportation systems, thus unserviceable parts move rapidly through a regional, depot or contractor repair process. A regional repair center is a "hybrid of 3LM and 2LM and combines intermediate level maintenance from multiple bases to one location" (DAF, 1998: 3). This is also known as a CIRF and is designed to handle all intermediate repairs while allowing the depot to still perform the same type repair it does under the traditional 3LM system.

Centralized Intermediate Repair Facility

"The motivation behind the CIRF concept is simple: larger facilities hold the promise of capturing economies of scale and thus could be…expected to handle the workload more economically than can be done with the traditional, decentralized arrangement" (McGarvey et al., 2008:1-2). The CIRF concept is not new; it has been experimented with by the USAF for the last 60 years. "The USAF has at times embraced the centralized concept of aircraft maintenance, and at other times opted for decentralized maintenance, meaning a preponderance of maintenance actions takes place at base-level" (Rowe, 2009:9). The decision to centralize or decentralize, "hinges not on the expected system cost but on the capacity and risk levels the Air Force is willing to accommodate in its operations plans" (Feinberg et al., 2000:6). The cyclic success and failures of a CIRF concept is evidenced throughout the professional military literature. Ames (2000) concluded 2LM did not achieve its intended benefit due to cost overruns associated with transportation. In essence, the maintenance bottleneck experienced at the base-level repair simply shifted to the depot. Cannibalization of aircraft parts and a steady decline in mission capable rates were a direct result of this shift in maintenance procedures (Ames, 2000). Numerous RAND Project Air Force studies found almost universal support for both overseas and domestic CIRFs (McGarvey et al., 2008). RAND studies posit CONUS-based CIRFs as a cost-effective maintenance strategy. Additionally, they found potential manpower cost savings more than offset increased transportation (shipping) costs. Furthermore, they argue many existing USAF repair networks already lend themselves toward a CIRF model when measuring cost and performance. Finally, RAND found that large user bases are naturally attractive as CONUS CIRF locations (McGarvey et al., 2008).

Measures of Effectiveness

Work in Process.

The primary measure of effectiveness for this research is WIP time. This is defined as the interval between a LRUs removal and its return to base supply and/or depot. The longer the WIP, the greater the in-process inventory of the system of study. Entities waiting for inspection, repair and transport all add to system WIP.

Machine Utilization.

Machine utilization is the next item of focus for this study. All three models begin with the same resource level for all machine types (R/EW and DAAE inspection stations as well as repair stations). While most consider high utilization best, it often comes with a penalty. Greater utilization equates to greater use and therefore higher preventive maintenance and upkeep costs. Finding the right balance between overuse and waste can be a difficult task. This research only examines utilization as a percentage and does not consider cost.

Queuing Theory

Queuing theory examines service facilities with respect to input parameters such as queue (waiting line), service times and server utilization. It is "used to predict the measure of system performance as a function of the input parameters. The input parameters include the arrival rate of customers, the service demands of customers, the rate at which the server works, and the number and arrangement of servers" (Banks et al., 2005:201) In queuing, "customers" refers to any type entity requesting "service" from a "system." As a result, service facilities, production systems, as well as repair and maintenance facilities, are modeled as queuing systems. Probability distributions approximate the time between entity arrivals (known as inter-arrival time) and the time required to serve customers. "The most popular object of queuing theory is the *M/M/1 queue*. The first "M" states that the arrival process is *Markovian*; that is the inter-arrival times are independent and identically distributed 'draws' from an exponential probability distribution (they arrive according to a Poisson process). The second 'M' stands for the service-time distribution (also exponential), while the '1' indicates a single server." (Kelton et al., 2007:19) There are many different variations of queuing systems; however, the theory is often used for relatively simple systems while simulation modeling tends to be reserved for addressing more complex scenarios. In this thesis effort, the customers modeled are 8 of the 33 LRUs comprising the AN/ALQ-161 system on the B-1B. Service represents maintenance of a LRU on an ATE test station and repair station. Ideally, queuing theory is used to determine the minimum number of test stations to accommodate the maintenance workload at each respective base. Although queuing theory is not used, the concepts such as system capacity, arrival process, queue behavior, queue discipline and service times are foundational concepts required to complete an accurate simulation model. Queuing theory's greatest strength is its simplicity and "can prove valuable as a first-cut approximation to get an idea of where things stand and to provide guidance about what kinds of simulations might be appropriate" (Kelton et al., 2007:20).

Modeling Approaches

"Models allow us to gain insight and understanding about the object or decision problem under investigation. The ultimate purpose of using models is to improve decision making" (Ragsdale, 2004:5). Ragsdale (2004) separates models into three categories: prescriptive, predictive, or descriptive (Table 1). There are two criteria for evaluating where a model fits: form of the function *f*(*), and values of independent variables:

Table 1. Modeling Techniques

(Ragsdale, 2004:8)

	Model Characteristics		
Category	**Form of *f*(*)**	**Values of Independent Variables**	**Management Science Techniques**
Prescriptive Models	known, well-defined	known or under the decision-maker's control	Linear Programming, Networks, Integer, Programming, Critical Path Modeling (CPM), Goal Programming, EOQ, Nonlinear Programming
Predictive Models	unknown, ill-defined	known or under the decision-maker's control	Regression Analysis, Time Series Analysis, Discriminant Analysis
Descriptive Models	known, well-defined	unknown or uncertain	Simulation, Queuing, PERT, Inventory Models

Applying these guidelines, a simulation model of the AN/ALQ-161 LRU repair process is classified as a descriptive model. "The cause and effect relationships between process variables and system outcomes are well known, and variability in process times makes the values of independent variables uncertain" (Vigus, 2003:15). Per Table 1, simulation is an appropriate tool for this type of model.

"As evidenced from the literature, logistics modeling generally employs one of three approaches, optimization, heuristics, and simulation. While each approach has advantages and disadvantages, combining approaches could enable the advantages of one approach to offset the disadvantages of another approach" (Shyong, 2002:16).

Optimization.

An optimization approach prescribes a best, or optimal, combination of values for variables over a given range to maximize the objective value of some mathematical programming model (Ragsdale, 2004). For a given range of values, this prescribed solution should prove to be the most effective approach. However, when the "exact range of values for variables is unknown, and the model produces some optimal solution for that solution space, that solution may not necessarily be the optimal solution for the problem at hand" (Vigus, 2003:16). The AN/ALQ-161 LRU repair process is too complex a process to fully model and characterize with an optimization approach.

Heuristics.

The second approach to logistics modeling, heuristics, is an effort to provide a working solution to the problem. Simply put, heuristics are rules of thumb that direct the user toward the best solution, but do not guarantee an optimal solution will be found. Heuristics provide ways of quickly finding satisfactory solutions to problems when using methods such as simulation and optimization prove to be undesirable or impractical (Vashi et al., 1995:197).

Simulation.

The third approach, simulation, was selected for this research. Simulation addresses the special requirements of a complex processes, not only by allowing for variability, but also by facilitating stochastic analysis. The LRU repair process is affected by changes in process times, lead times, arrival times, inventory levels, etc. Computer simulation allows researchers to model stochastic processes and to analyze the effects of various policies, not only on some objective function, but also on each intermediate variable, and derive probability distributions for a range of results versus a single predicted output value (Vigus, 2003:16-17). This research did not apply optimization or heuristic searches to conduct simulation-based optimization, such as available in software packages like ARENA (Kelton et al., 2007).

Related Logistics Research in Modeling and Simulation

There are many examples of successful simulation modeling of both intermediate and depot level maintenance. "Shyong (2002) evaluated the effects of various spare parts levels and queuing policies on process time and cost for the overhaul of the F101 LPT rotor at Tinker Air Force Base. His research demonstrated the value of simulation in evaluating cost and time improvement opportunities in other engine overhaul sub-processes" (Vigus, 2003:18).

Rodrigues and Karpowicz (1999) analyzed the impact of reducing transportation cycle times and consolidating inventories on the operational availability of the Brazilian Navy and Argentine Air Force A-4 fleets. They modeled the repair process of a select aircraft fleet for both countries, providing an effective managerial resource for long-term decision making to improve operational readiness. ARENA software was used for their report and proved very helpful in establishing the necessary requirements and structure for analysis for this study.

Vigus (2003) used discrete event simulation to assess the impact of process changes to various Programmed Depot Maintenance (PDM) lines for the Coast Guard's HH-60J search and rescue helicopter. He found that shorter process times would likely be achieved by increasing manning to a particular shop in the repair line. The similarity of independent variables and repair system logic provide a solid foundation for model creation and research of the AN/ALQ-161 LRU repair processes.

Summary

The AN/ALQ-161 ECM was introduced. Next, the LRU repair process was explained as well as associative 2LM and 3LM in the USAF. The concept of CIRF and how it relates historically to the USAF maintenance policies was highlighted. The significance of the LRU repair cycle was recognized for two main reasons: process time and WIP. A review of related logistics research revealed the popularity of the simulation modeling approach. In the next chapter, the simulation modeling approaches, as well as a detailed description of the simulation models and experimental design are presented.

III. Methodology

Introduction

This chapter discusses data and model development along with the respective assumptions required to create the three simulation models studied. Next, the experimental design used and a general recap of the issues pertaining to AN/ALQ-161 LRU repair process are briefly reviewed. Data sourcing along with its development are discussed as well as each model's development and logic. Finally, criteria such as initialization and replication are addressed.

AN/ALQ-161 Maintenance

The maintenance of the AN/ALQ-161 is represented by a very complex repair network. In reality, LRUs adhere to both a 2LM and 3LM structure. In a 2LM network, LRUs are removed from the aircraft and sent directly out, for either depot or contractor repair. Conversely, in a 3LM system, LRUs are pulled and sent to a "back-shop", or intermediate repair facility, for troubleshooting and possible repair. The latter process is used to scope the research and simplify the variability within the simulation model. Additionally, particular LRUs require certain ATE stations where set-up, tear-down, and process times vary dramatically. For this effort, any ATE maintenance procedure was assumed to be homogeneous for all LRUs, regardless of the station of repair. Once a LRU is deemed repairable, it proceeds through either one or two ATE stations (depending on LRU type). Once processed, they are sent to a respective repair station.

The final step in the process is a return of the LRU to its original inspection station for a final quality assurance test. LRUs have the potential to fail at any step in the intermediate repair cycle at which point they are declared not-repairable-this-station (NRTS) and are sent to depot for repair.

Data

Source.

All data used for this study was received from the B-1 Electronic Warfare Systems Manager (ACC/A4F1). The data (Appendix D-1) for 2008 showed average repair times and service rates by LRU. In addition, the number of LRUs produced by base was provided. However, LRU inter-arrival times at ATE stations were not provided. Thus, total arrivals for the year were used to approximate inter-arrival rates. Additionally, the majority of all repair rates received were overall averages and not independent values for base-level repairs. These factors lead to the use of triangular distributions in all models for inspection and repair times for each of the 8 LRUs.

Development.

The first step in this research was to filter the data for the 8 LRUs under study. Next, a interval of ±15% was calculated for the average run times. This is the actual repair time of each LRU averaged at the intermediate-level of repair (Appendix D.-1). Additionally, a workload percentage was provided for both bases and was calculated as follows:

$$Workload\ Mix = \frac{\left(LRUrepairtime(hrs)\ X\ \ TotalLRUproduced(yr)\right)}{TotalTimeAvail(yr)} \tag{1}$$

where *LRUrepairtime* is the time it takes to repair a respective LRU, *TotalLRUproduced* is the number of LRUs produced for that base for the year, and *TotalTimeAvail* is the total machine time and personnel time availability. For this study, only the machine if considered and the availability of the worker is not. Obviously, the machines can't work by themselves and people can't perform the work if the machines aren't available. However, in order to scope the problem they are considered simultaneously available. The workload mix percentage calculation, while not used in the creation of the simulation model, did provide a baseline to compare the results for validation. Average LRU repair times (Appendix D.-1) for Ellsworth AFB and Dyess AFB were used to calculate inter-arrival times. This is the time between parts arriving for repair and is calculated as:

$$\textit{Inter-arrival Time}\ (\lambda) = \frac{1}{\left(\textit{TotalLRUproduced} / 365 \text{ days}\right)} \tag{2}$$

Because yearly production numbers differed (Appendix D.-1) for each LRU, unique (λ) values were obtained. Finally, an interval of ±5% around the means was created for all service rates used. This provides a more realistic depiction throughout the model for LRU inspection stations.

Model

Development.

Three models were created using the data obtained. The first model approximates current LRU repair operations at Dyess AFB and Ellsworth AFB. While both bases are in the same model, there is no collaboration or resource sharing between the two bases. This repair independence approximates the current AN/ALQ-161 LRU repair process and provides baseline results for subsequent analyses. The second model mimics intermediate repair collaboration between the bases. This captures the hybrid-CIRF concept discussed in Chapter II. An example of this would involve a LRU that arrives for inspection at either base but transfers to another base if the present repair queue is too long. In queuing, this is referred to as balking. Notional transportation times were used for any transfer; however this study did not include the associated cost. The third model developed completely removed the base intermediate repair capability and set up a full CIRF to complete the LRU repair.

Animation.

While not intuitive, one of the first steps taken during model development was to consider how to best present the results obtained. The decision was made very early in the process to incorporate ARENA's animation capability. As a result, several working models using animation were obtained from different online sources. However, one site proved instrumental in the model development. Dr. Mousavi, the Director of the Advanced Manufacturing Engineering Program at Brunel University, England (Mousavi, 2010) has available examples of working ARENA models from the *Simulation with Arena* (Kelton et al., 2007) text. The animations were quickly modified to fit the three AN/ALQ-161 repair system models. Adding this visual component provides a quick and easy way to see process flow and system bottlenecks. Additionally, the graphics facilitated interest in the topic and allowed outside parties to quickly validate the models and troubleshoot other areas of concern during model development.

Model Description

Model 1.

Calculated inter-arrival times are used to generate LRU *customers* for both Dyess AFB and Ellsworth AFB within the model. After an entity is created, various attributes are assigned (Figure 1) to distinguish the entity. For example, LRUs are given a time of arrival, entity type, inspection time, and repair time based upon their type and location. The next step in the model logic is to route the LRU to a station and prepare its initial inspection. Half (4) of the LRUs require one ATE type, while the other half (4) require two. ATE sequencing was not mandatory, therefore an entity requiring both inspections could start at either ATE. However, those LRUs requiring both inspections defaulted to the DAAE inspection first, while the others are directed to the R/EW process. The routing of entities allowed the model to mimic the real-world by using a time delay associated with the removal and transportation of the LRU to a back-shop for repair. All delays used in the model are assumed to be uniformly distributed. Model animation and visualization showed entity arrivals by type to a particular station. Should a queue develop, it would be easily recognizable.

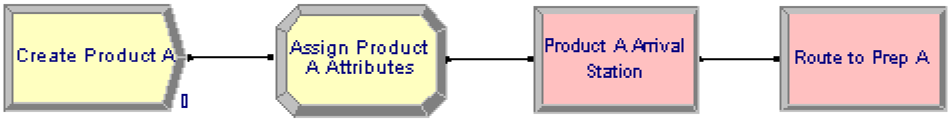


Figure 1: LRU creation, attribute assignment, and routing

Once a LRU is routed to the appropriate ATE station, a decision module is used to discriminate among LRUs repairable at this station (Figure 2). The probability of repair for each LRU was extracted from the original data on average annual service rate. A failed LRU is considered NRTS and is routed to the depot for repair. Conversely, a LRU passing inspection is sent to its predetermined ATE station. All repair and inspection times are modeled using a triangular distribution.

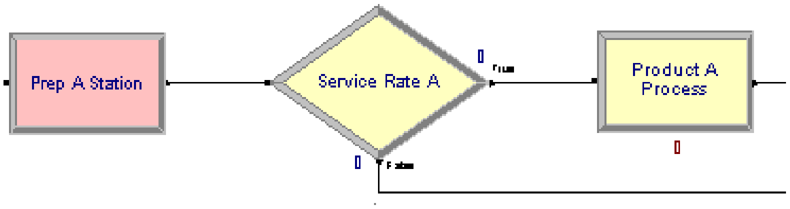


Figure 2: LRU station, probability of service and set-up

The predetermined ATE for each base's 8 LRUs are identical. Table 2 provides details for Ellsworth AFB and Table 3 provides details for Dyess AFB:

Table 2: Ellsworth AFB LRU Details

Actual LRU Name	ATE Required	Model Name	Inter-arrival time (λ) days
TX7 (Bd 7 TX)	R/EW	Product A	4.35
RFS7 (Bd 7 RFS)	R/EW & DAAE	Product B	5.29
RX4-8 (4-8 RCVR)	R/EW	Product C	20.28
ENC (Encoder)	R/EW & DAAE	Product D	11.77
TX5A -6 (Bd 5 Aft TX)	R/EW	Product E	10.14
RFS8 (Bd 8 RFS)	R/EW & DAAE	Product F	9.86
FCH (Channelizer)	R/EW	Product G	19.21
RP (TWF R/P)	R/EW & DAAE	Product H	28.08

Each LRU proceeds from its routing station to its required ATE station (Figure 3). There are two inspection stations: R/EW and DAAE. Both stations require one operator resource to operate. The LRU attribute *inspection time*, is used for that particular LRU. The repair lines for both bases are identical. The R/EW ATE model logic is straightforward.: LRUs arrive at the inspection station and the inspection is then completed on the LRU according to the *repair time* assigned. Immediately, a decision module assesses a probability of repair success. There is a 95% chance of a successful repair. A successful initial repair routes the LRU back for a expedited final inspection before being returned to its base supply.

Table 3: Dyess AFB LRU Details

Actual LRU Name	ATE Required	Model Name	Inter-arrival time (λ) days
TX7 (Bd 7 TX)	R/EW	Product A Dyess	5.7
RFS7 (Bd 7 RFS)	R/EW & DAAE	Product B Dyess	5.07
RX4-8 (4-8 RCVR)	R/EW	Product C Dyess	24.33
ENC (Encoder)	R/EW & DAAE	Product D Dyess	16.59
TX5A -6 (Bd 5 Aft TX)	R/EW	Product E Dyess	22.81
RFS8 (Bd 8 RFS)	R/EW & DAAE	Product F Dyess	16.59
FCH (Channelizer)	R/EW	Product G Dyess	19.21
RP (TWF R/P)	R/EW & DAAE	Not produced	Not produced

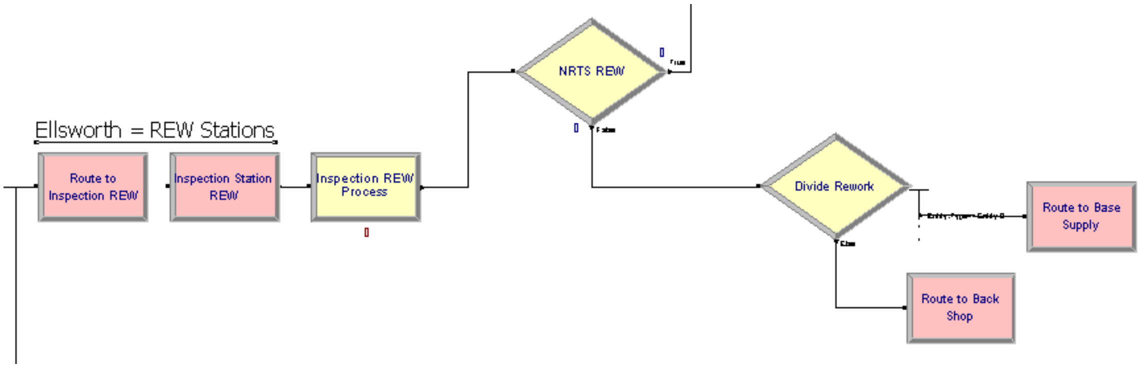


Figure 3: Model 1 R/EW Inspection Station

The only difference between the logic for the ATE stations is that LRUs requiring two inspection stations can balk. This means an entity arriving to the DAAE inspection station looks at the number in that queue and compares it to the number in the queue of the R/EW station (Figure 4). If the DAAE queue size is greater than one and the R/EW queue length is less than one, the LRU will balk to the other line. Both queue length values are notional and were set to facilitate future customization and add some resemblance to true common-sense maintenance through efficient resource utilization. A LRU that successfully proceeds through the DAAE inspection is then routed to the R/EW station as required.

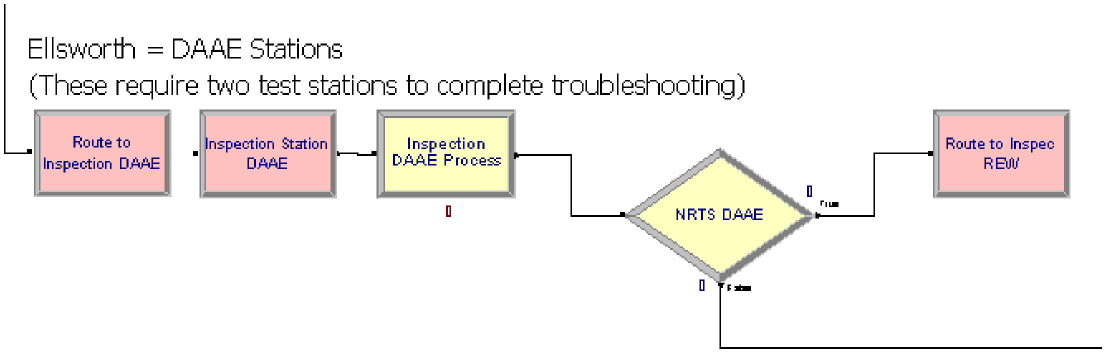


Figure 4: Model 1 DAAE Inspection Station

Once a LRU has completed its respective inspection station requirement it proceeds to the back shop (Figure 5). This repair process is similar to the inspection process and is based upon the average LRU *repair times* assigned earlier in the model. Notably, new and reduced inspection times are assigned to entities. LRUs return to inspection stations based upon their entity type. LRUs under re-inspection will have higher priority than items in the queue as well as shorter inspection times.

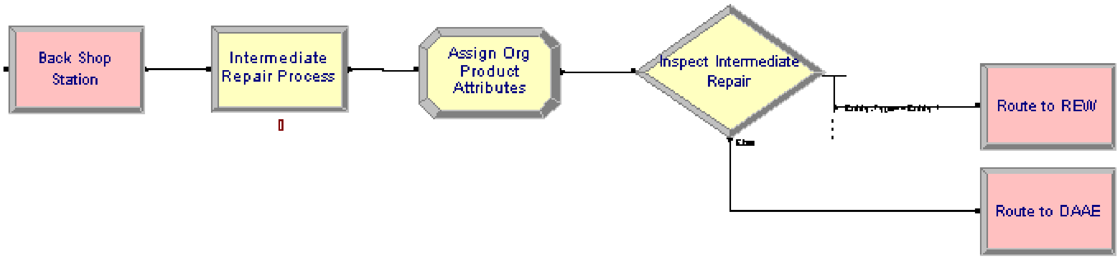


Figure 5: Model 1 Back-shop Repair Process

Finally, the repaired LRUs return to base supply based upon the new entity type that was assigned after the repair process.

Model 2.

Model 2 is very similar in process flow to Model 1, but differs in that system resources are shared. The logic follows the DAAE balking process; however comparisons are established between repair station queue lengths for Ellsworth AFB and Dyess AFB. Examining Model 2 animation showed definitive resource collaboration between the two locations.

As depicted in figure 6, resource sharing between Ellsworth and Dyess happens just before intermediate repair takes place. LRUs departing the R/EW inspection station, look ahead to repair station queue lengths of both bases. For example, an LRU from Ellsworth will "ship" if its repair station queue length is ≥ 10 and the Dyess repair station queue ≤ 10. Note that any entity that transfers to the other base is not returned to its original base after repair. Transportation costs are not calculated for this lateral move and ship times between each location is set to 1 day.

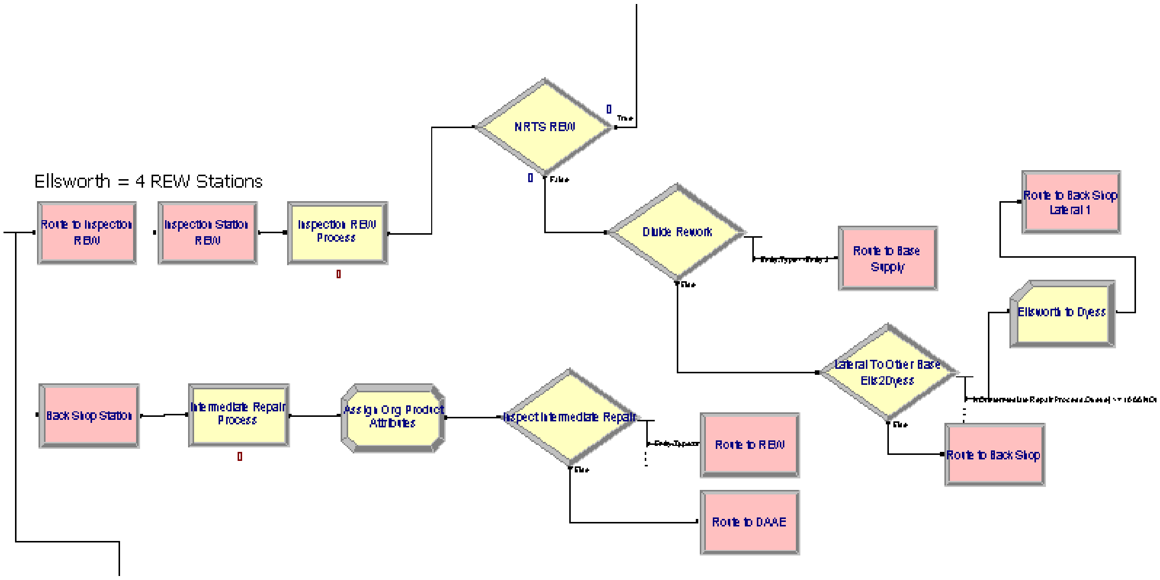


Figure 6: Model 2 Repair Station Collaboration

Model 3.

Model 3 simulates the full CIRF concept (Figure 7). Under CIRF, all intermediate repair processes, such as inspection and repair are removed from the base level repair network and transferred to the CIRF. LRU creation is Models 1 and 2, except for a slight difference in logic. The prepare module used to mimic ATE set-up time was modified to transportation time. This is an estimate of the ship time of a LRU to the CIRF. Ship times from Dyess AFB or Ellsworth AFB to the CIRF were two and three days, respectively. Once received, LRUs are separated by entity type and travel to their required ATE station. The inspection and repair process follows the same logic as in Models 1 and 2. Failures within the CIRF are not captured in the current model.

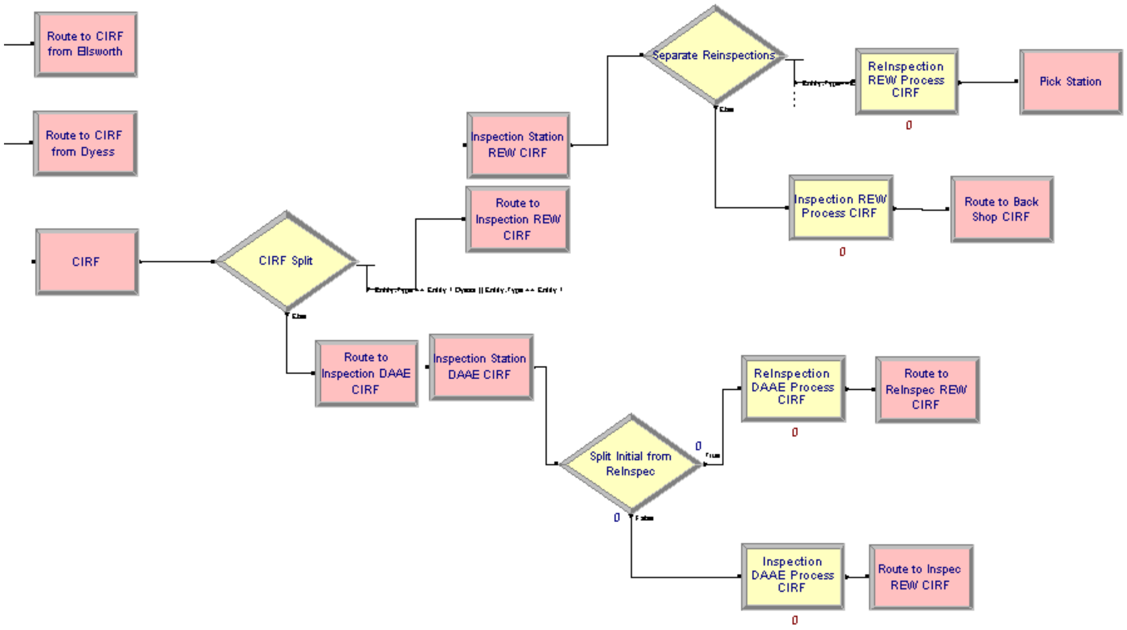


Figure 7: Model 3 CIRF

After the repair process for the CIRF, a new entity attribute is assigned along with new and shorter inspection times (Figure 8). As in other models, repaired LRU takes precedence in the queue during its re-inspection process.

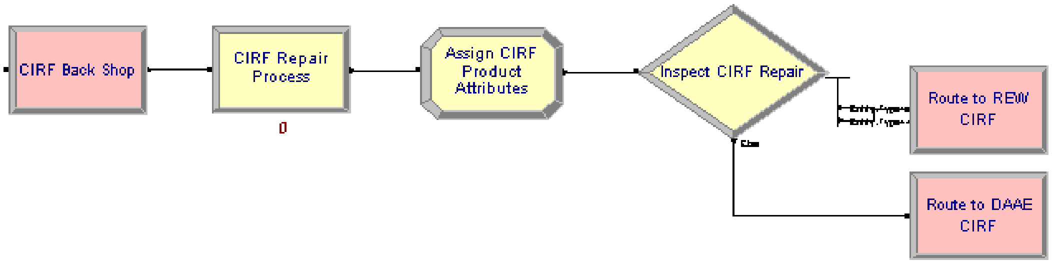


Figure 8: Model 3 CIRF repair process and routing

Initialization

All three models begin inthe *empty-and-idle* state. "This means the model starts out empty of entities and all resources are idle" (Kelton et al., 2007:312). A simulation must be intialized and stopped according to some criteria. Determining the warm-up period is not a exact science. Kelton et al. (2007) recommends using one of two different techniques. The first is to establish a single overall output performance measure (such as WIP) and monitor its output during simulation runs. Eventually, there's a period when steady state is reached. A process is in steady state when its measure of performance, such as average WIP, has settled down to some value (usually close to its long-term expected value). It is at this point that an initial warm-up period in ARENA is specified. The second technique runs the model for such a long period of time that any potential bias is "overwhelmed by the amount of later data" (Kelton et al., 2007:313). For all three models, a warm-up period of five days was used.

Replications

"The method of independent replications is used to estimate point estimator variability and to construct a confidence interval. The larger the sample size, the smaller the standard error of the point estimator" (Shyong, 2002:48). There are two ways the sample size can become large, either by longer simulation runs or more replications (Banks et al., 2005). The run length for all models was set to one year. A calulation was used to determine the appropriate number of replications required to satisfy an acceptable confidence interval of 95%. Using Shyong (2002) as a guide, five independent replications are used in this analysis.

Scenarios

A total of 20 different scenarios were used to analyze three maintenance structures. Tables 4 and 5 show the variations used (Appendix D-2). ARENA’s Processor Analyzer Tool was used to quickly modify the resources within each computer model experiment and compare the results. In all three models, the baseline is the initial condition where all resources (R/EW, DAAE and repair stations) are set to 1. Different combinations of resources make a unique scenario (Appendix D-2). Each iteration produced results that are compared against the baseline to determine levels of significance. The best scenario was for each model was then selected (Appendix-C).

Table 4: LRU Scenarios for Models 1 & 2

Scenario	Ellsworth		Dyess		Both	
Model 1	+1 repair	+2 repair	+1 repair	+2 repair	+1 repair	+2 repair
Model 2	+1 repair	+2 repair	+1 repair	+2 repair	+1 repair	+2 repair

Table 5: LRU Scenarios for Model 3

Scenario	Repair Station		Inspection Station	Both	
Model 3	+1	+2	+1 R/EW & +1 DAAE	+1	+2

Summary

In this chapter, the problem statement for the AN/ALQ-161 LRU repair process was revisited. Data sourcing along with its development were explained. Furthermore, the logic for each of the three simulation models was reviewed in detail. Finally, important criteria such as initialization and replication length were determined. In the next chapter, the results using each of the simulation models to compare various maintenance structure scenarios are presented.

IV. Results and Analysis

Introduction

This chapter presents the results of the experiment. It describes the steps followed in testing output data and offers conclusions based on the results.

Hypothesis and Hypothesis Testing

The experiment involves a hypothesis designed to examine what maintenance configuration may contribute to an improvement in WIP and machine utilization. Given outputs from simulations of the two alternatives, the hypothesis is:

$$H_o\text{:}\ P_1 - P_2 = 0$$

$$H_a\text{:}\ P_1 - P_2 \neq 0$$

where: P_1 = total average WIP for scenario 1 and P_2 = total average WIP time scenario 2. The null hypothesis, Ho, assumes no difference exhibited in WIP times between scenario 1 and scenario 2. If the test rejects the null hypothesis, there is a significant difference in WIP times and the alternate hypothesis is accepted. However, if the hypothesis test fails to reject the null, no conclusion regarding the alternate can be made (Vigus, 2003).

Test for Equal Variance

A test for equal variance for all scenarios was accomplished using ARENA's output analyzer. There was a significant difference in variance when comparing Model 1 to Model 2 and Model 3. For all cases, the null was rejected (Appendix B-1).

Hypothesis Testing

A paired t-test was accomplished (Appendix B-3) due to unequal variances of all scenarios output. This test produces confidence intervals for the difference of means. If the confidence interval "hooks zero", the test fails to reject the null (Vigus, 2003). Equal sample sizes were used for all three models.

When a confidence interval that does not contain 0, the null hypothesis was rejected. This supports the conclusion that the differences in mean outputs between scenarios 1 and 2 are statistically significant.

Measures of Effectiveness Results

WIP.

Initial WIP times for each model’s baseline are shown below in Figure 9. For all cases, the upper line (red) represents WIP times for Ellsworth AFB and the lower line (green) is Dyess AFB.

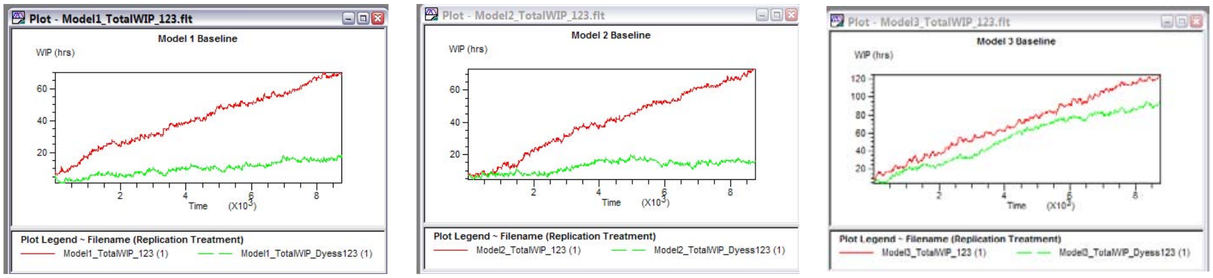


Figure 9: Baseline WIP for all Models

ARENA's output and process analyzer utilities were used to test for significance between each scenario. Appendix C shows the models’ WIP time for each of the 20 different scenarios. In each case, an individual confidence interval of 95% was used in the selection of the best case scenario. Finally, total WIP was calculated from the simulation statistic function in ARENA, producing the results in Table 6 below. The largest return on investment for all three models was seen, when resources were added to a repair station. For Models 1 and 2, adding resources to the Ellsworth AFB repair station had the greatest benefit from an enterprise viewpoint.

Table 6: Total WIP by scenario

Scenario	Model 1 Dyess	Model 1 Ellsworth	Model 2 Dyess	Model 2 Ellsworth	Model 3 Dyess	Model 3 Ellsworth
01-Model 1: Baseline	7.63	38.4	---	---	---	---
02-Model 1: +1 Repair to Ells	6.97	2.54	---	---	---	---
03-Model 1: +2 Repair to Ells	8.16	2.29	---	---	---	---
04-Model 1: +1 Repair to Dy	2.09	32.39	---	---	---	---
05-Model 1: +2 Repair to Dy	1.98	34.46	---	---	---	---
06-Model 1: +1 Repair to both	2.14	2.59	---	---	---	---
07-Model 1: +2 Repair to both	1.95	2.28	---	---	---	---
08-Model 2: Hybrid CIRF	---	---	10.15	36.66	---	---
09-Model 2: +1 Repair to Ells	---	---	6.34	2.59	---	---
10-Model 2: +2 Repair to Ells	---	---	6.96	2.3	---	---
11-Model 2: +1 Repair to Dy	---	---	1.79	31.11	---	---
12-Model 2: +2 Repair to Dy	---	---	1.66	35.24	---	---
13-Model 2: +1 Repair to both	---	---	1.79	2.52	---	---
14-Model 2: +2 Repair to both	---	---	1.65	2.32	---	---
15-Model 3: CIRF	---	---	---	---	53.66	71.33
16-Model 3: + 1 Repair	---	---	---	---	7.81	10.84
17-Model 3: +2 Repair	---	---	---	---	7.1	9.94
18-Model 3: +1 REW +1 DAAE	---	---	---	---	48.85	63.34
19-Model 3: +1 to everything	---	---	---	---	7.5	10.29
20-Model 3: +2 to everything	---	---	---	---	6.89	9.62

Machine Utilization.

Utilization for each scenario was calculated using the ARENA's process analyzer. This utility creates scenarios by changing resource levels and giving model output for comparison. Table 7 shows the results obtained. Scenarios 1, 8 and 15 are the baseline for each of the models. Note, values of 1 demonstrate a resource operating at maximum capacity. The best results for Models 1 and 2 were seen when two repair stations were added to both Ellsworth AFB and Dyess AFB. In Model 3 the best gain in machine utilization came from adding two resources to everything. This included R/EW and DAAE inspection stations as well as the CIRF repair station. It should be noted adding two repair stations to the CIRF model gave a comparable result to Model 1 and 2, for half the resources required.

Table 7: Machine utilization by scenario

Scenario	Repair Station Ells	Repair Station Dyess	R/EW Ells	R/EW Dyess	DAAE Ells	DAAE Dyess	Repair Station CIRF	R/EW CIRF	DAAE CIRF
01-Model 1: Baseline	1	0.99	0.25	0.39	0.22	0.3	---	---	---
02-Model 1: +1 Repair to Ells	0.66	0.98	0.29	0.39	0.25	0.29	---	---	---
03-Model 1: +2 Repair to Ells	0.44	0.99	0.29	0.39	0.25	0.29	---	---	---
04-Model 1: +1 Repair to Dy	1	0.52	0.25	0.4	0.22	0.3	---	---	---
05-Model 1: +2 Repair to Dy	1	0.34	0.26	0.4	0.21	0.3	---	---	---
06-Model 1: +1 Repair to both	0.67	0.52	0.3	0.41	0.25	0.31	---	---	---
07-Model 1: +2 Repair to both	0.43	0.33	0.29	0.39	0.24	0.29	---	---	---
08-Model 2: Hybrid CIRF	1	0.99	0.26	0.21	0.23	0.19	---	---	---
09-Model 2: +1 Repair to Ells	0.68	0.99	0.3	0.21	0.25	0.18	---	---	---
10-Model 2: +2 Repair to Ells	0.44	1	0.3	0.21	0.24	0.19	---	---	---
11-Model 2: +1 Repair to Dy	1	0.52	0.26	0.21	0.21	0.2	---	---	---
12-Model 2: +2 Repair to Dy	1	0.34	0.26	0.21	0.21	0.19	---	---	---
13-Model 2: +1 Repair to both	0.67	0.52	0.29	0.21	0.25	0.2	---	---	---
14-Model 2: +2 Repair to both	0.45	0.34	0.3	0.21	0.24	0.2	---	---	---
15-Model 3: CIRF	---	0	0	---	---	---	1	0.42	0.2
16-Model 3: + 1 Repair	---	0	0	---	---	---	0.81	0.53	0.32
17-Model 3: +2 Repair	---	0	0	---	---	---	0.54	0.53	0.32
18-Model 3: +1 REW +1 DAAE	---	0	0	---	---	---	1	0.21	0.1
19-Model 3: +1 to everything	---	0	0	---	---	---	0.83	0.27	0.16
20-Model 3: +2 to everything	---	0	0	---	---	---	0.55	0.18	0.11

Issues

Variance in the results for all cases was a problem (Appendix B-2). This was caused by several factors. First, the limited number of replications coupled with the triangular distributions used for both inspection and repair times all contributed to this fluctuation. Future extensions using this model should significantly increase the number of replications and ensure the triangular distributions employed are reasonable.

V. Conclusions

Introduction

This research used computer simulation to help predict the impact of different maintenance organizational structures on the LRU repair of the AN/ALQ-161. The two measures of effectiveness were used, work in process time and machine utilization.

Conclusions

Results from the literature review, from Chapter II and the experiment methodology, and from Chapter III support the answers to the four research questions presented in Chapter I:

1. **What are the advantages and disadvantages associated with resource sharing between the Ellsworth AFB and Dyess AFB maintenance processes?**

The main advantage recognized in the Model 2 baseline was decreased machine utilization for both inspection stations at Dyess AFB. The DAAE inspection machine utilization went from 30% to 19%, while R/EW machine utilization went from 39% to 21%. Additionally, 123 LRUs were shipped from Ellsworth to Dyess, thus facilitating resource collaboration and helping to more evenly distribute the workload for both bases. The disadvantages with this approach would be the cost associated with shipping LRUs between bases. In addition, the management of assets in route would increase system complexity. Finally, having multiple process owners would be an issue of concern.

2. **What are the advantages and disadvantages associated with implementing a Centralized Intermediate Repair Facility for all ALQ-161 LRU repair activities?**

   The first advantage recognized in Model 3 of the CIRF was the simplicity of the model 3 logic when compared to that of models 1 or 2. Surprisingly, WIP baseline times for LRU repair at the CIRF were dramatically higher in all cases. The advantage of this system is a reduction in cost associated with the consolidation of resources and personnel. While cost and manpower were not a focus in this study, it is easy to see that a single process owner and enterprise focus on repair management is advantageous.

3. **Does the prototype simulation model realistically represent the empirical data employed and the repair systems in place?**

   While all three models were created based on actual processes and driven by real-world data, notional distributions had to be used in order to scope the high level of complexity. The lack of empirical data was a limiting factor.

4. **What is the best process configuration for each model scenario employed or examined?**

Table 8 illustrates the best LRU repair network set-up for each model with regard to the performance measurements of WIP and machine utilization.

Table 8: Best configuration by model

	<u>**WIP (hrs)**</u>		**Machine Utilization**
	Ellsworth AFB	*Dyess AFB*	
Model 1	+2 repair stations to both bases	+2 repair stations to Ellsworth; +2 repair to both bases	+2 repair stations to both bases
Model 2	+2 repair stations to Ellsworth	+2 repair to both bases	+2 repair stations to both bases
Model 3	+2 to everything	+2 to everything	+2 to everything

Future Research

Further research to include inventory and storage of items at the CIRF could be a topic of interest. In this system a *pull process* could be created by establishing a pre-determined on-hand LRU inventory for each base. The majority of LRUs would remain at the CIRF and would not ship until required. The simulation can capture this through the use of a wait signal (delay module) loop. Items would release to a base when called and return to the iterative loop. Another is to include the SRU intermediate repair process. There are discussions about how to increase the organic repair capabilities for the AN/ALQ-161. Ideas range from performance based logistics being used on existing and future contracts to a complete restructuring of the SRU repair network. The vast majority of all SRU repair for this system is completed by contractor support.

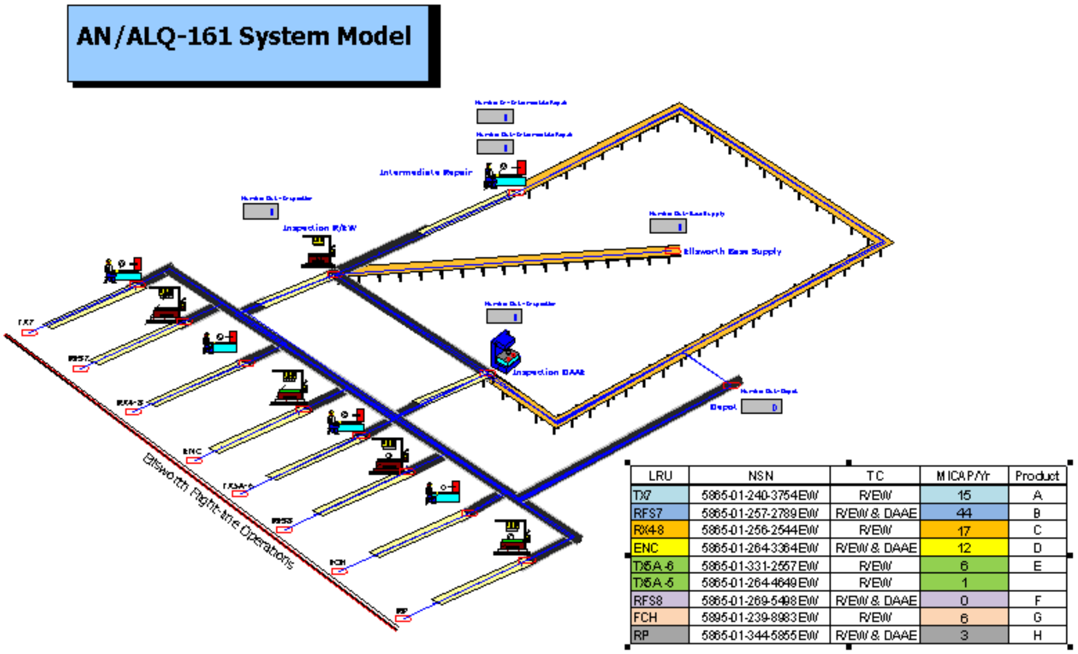
Data sourcing is always an issue in a computer simulation study. In a manner similar to the Vigus (2003) study, predictive capability could be improved for this and future models if the following are accomplished:

- Secure accurate process times for each level of repair,
- Receive manpower requirements for each repair process,
- Provide inter-arrival times with updated probability distributions, and
- Supply chain map of the AN/ALQ-161 LRU/SRU repair process.

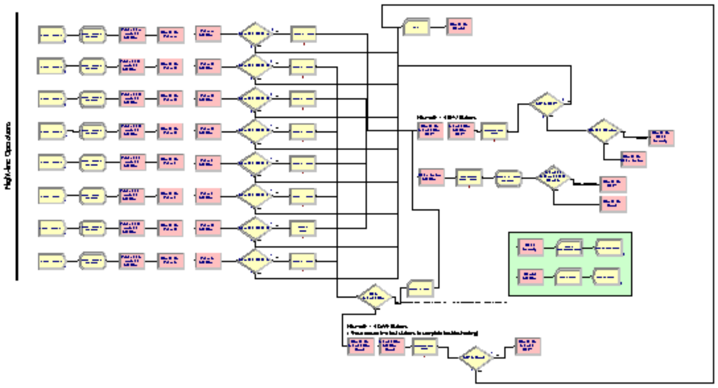
This seminal study provides a foundation for further discrete event simulation on the AN/ALQ-161 LRU/SRU repair process. Preliminary results show increased test stand utilization and reduced WIP by sharing resources between bases. Increasing model fidelity can provide managers with distinct areas for improvement or at a minimum, area for further investigation. The end result will be greater parts availability for a parts stressed weapons system.

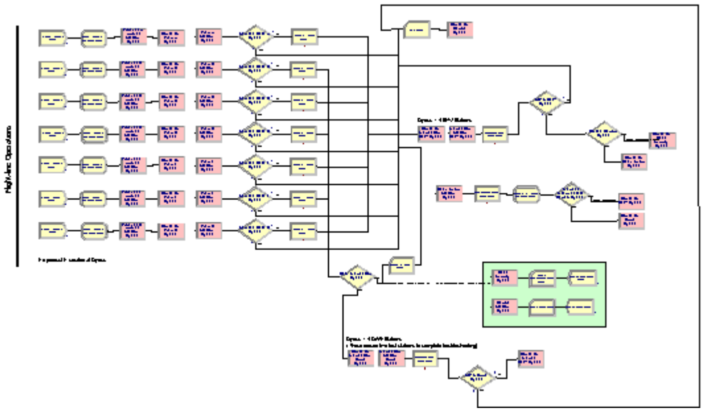
Appendix A. Model Logic and Animations (Static Displays)

Appendix A-1. Model 1, Independent Bases

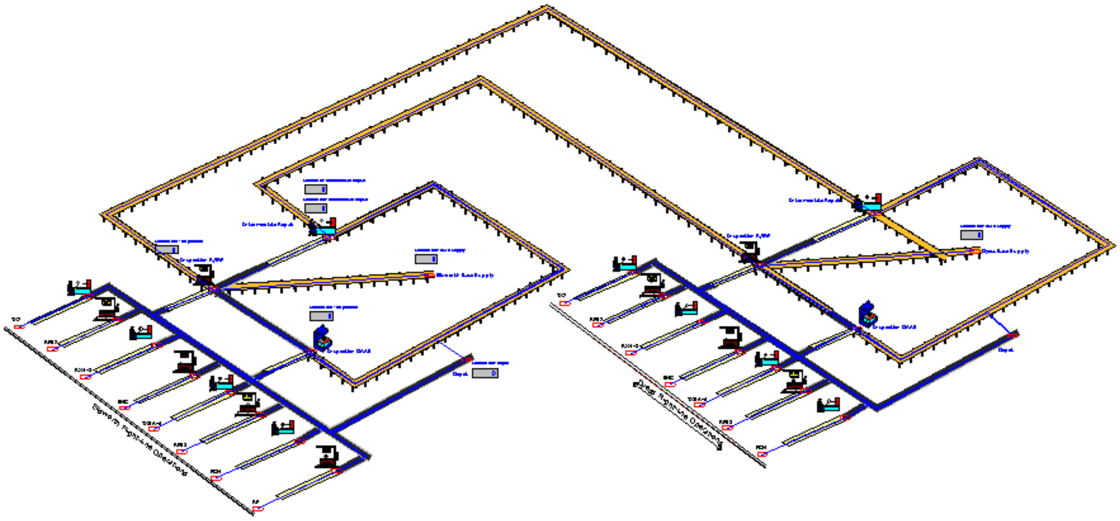


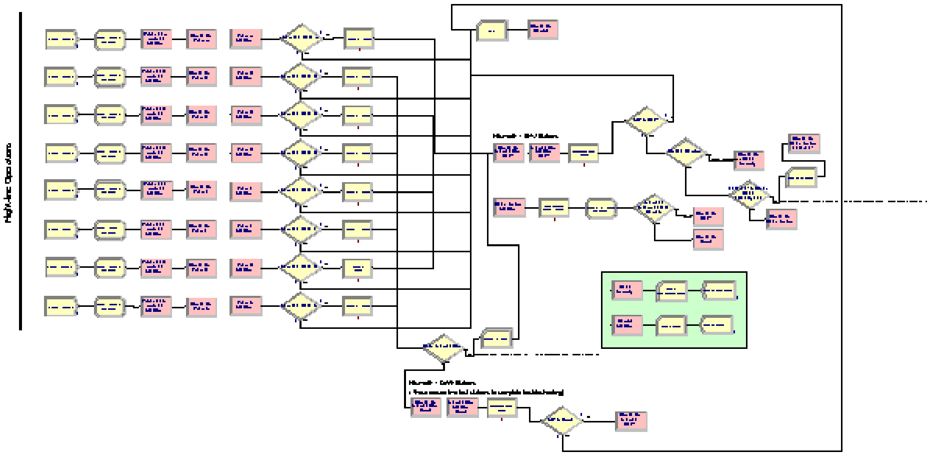
LRU	NSN	TC	MICAP/Yr	Product
TX7	5865-01-240-3754EW	R/EW	15	A
RFS7	5865-01-257-2789EW	R/EW & DAAE	44	B
RX4-8	5865-01-256-2544EW	R/EW	17	C
ENC	5865-01-264-3364EW	R/EW & DAAE	12	D
TX5A-6	5865-01-331-2557EW	R/EW	6	E
TX5A-5	5865-01-264-4649EW	R/EW	1	
RFS8	5865-01-269-5498EW	R/EW & DAAE	0	F
FCH	5895-01-239-8983EW	R/EW	6	G
RP	5865-01-344-5855EW	R/EW & DAAE	3	H

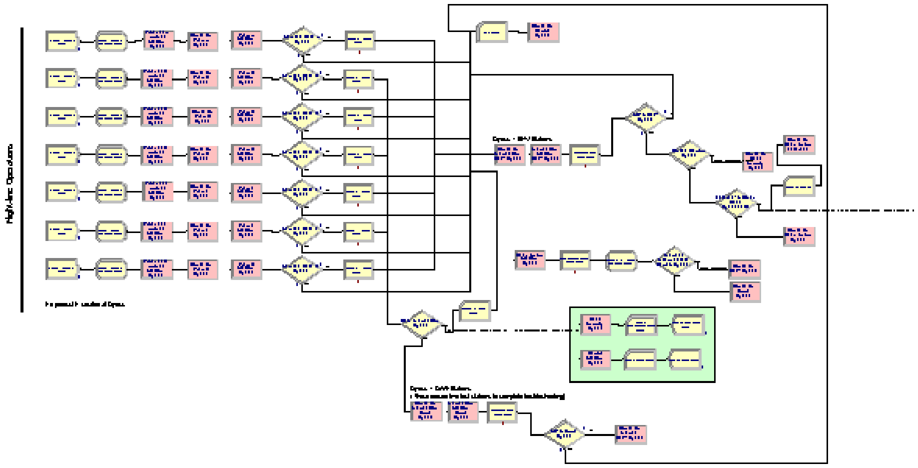




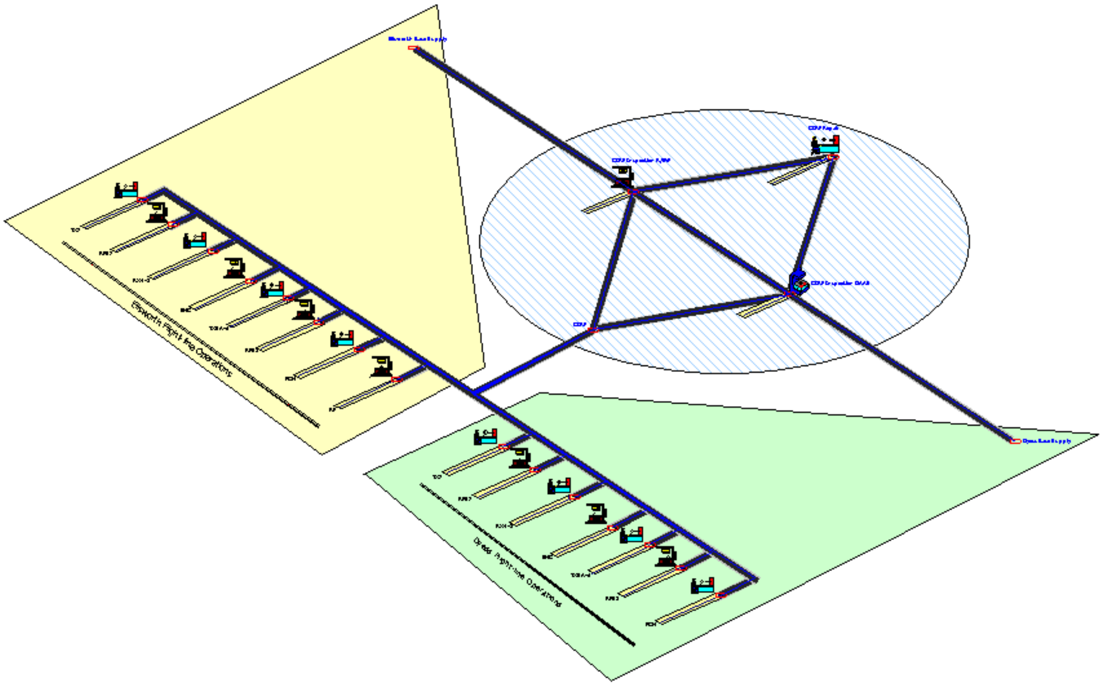
Appendix A-2. Model 2, Hybrid CIRF Concept

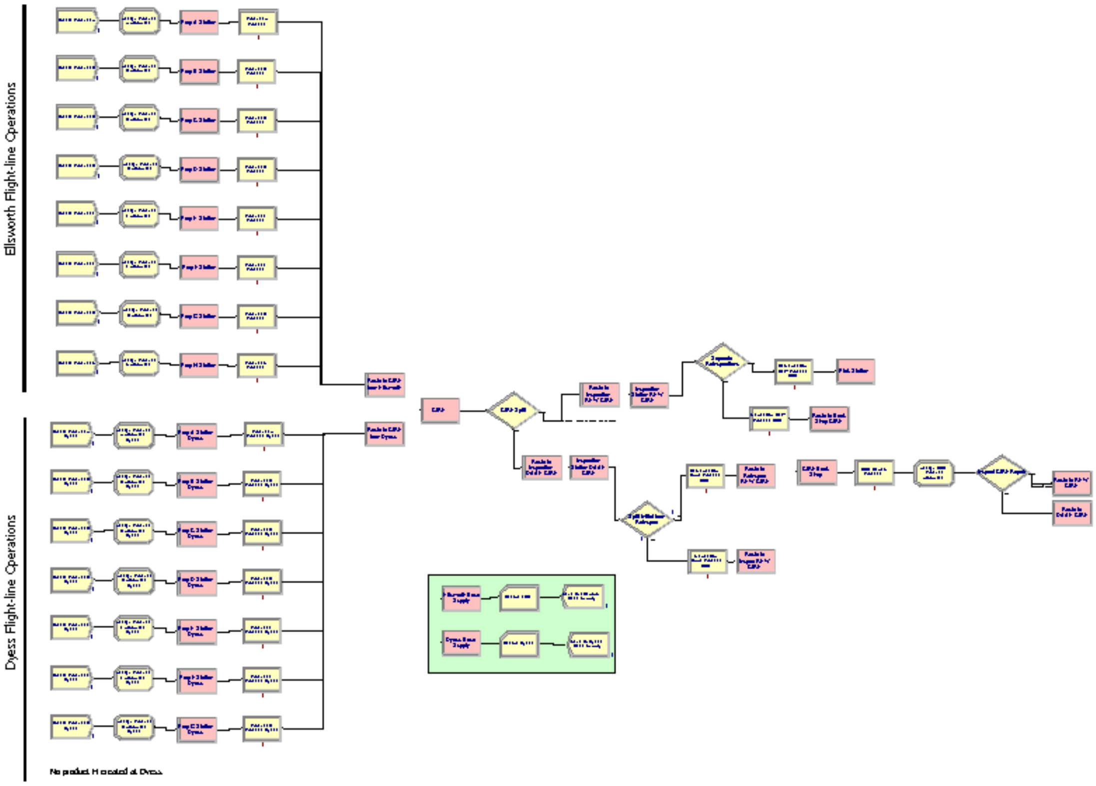






Appendix A-3. Model 3, CIRF Concept

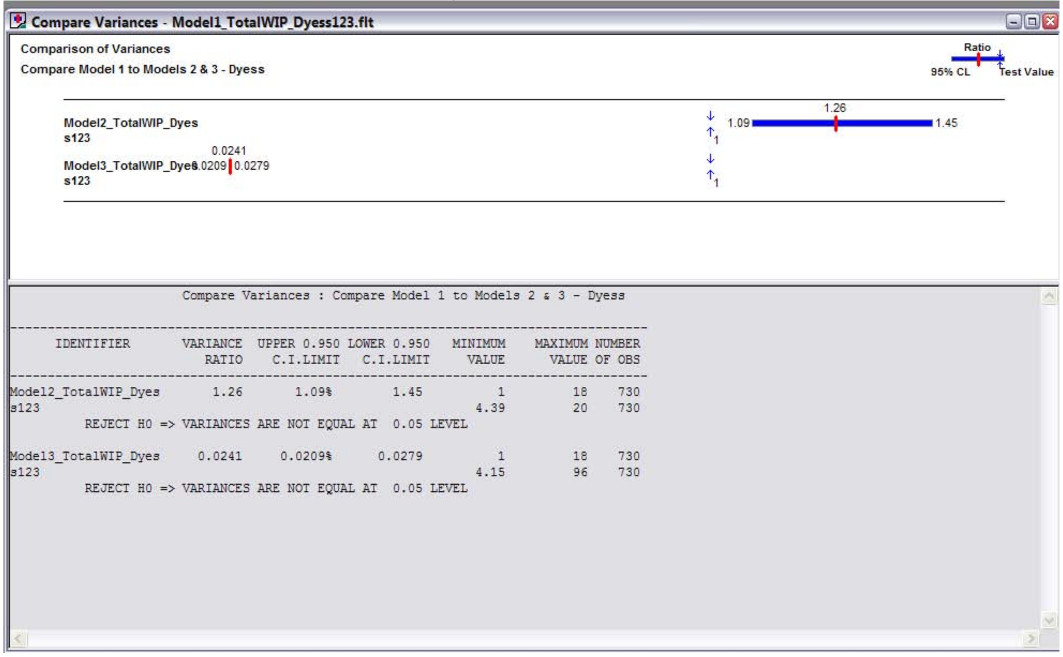




Appendix B. Statistical Results of Analyses

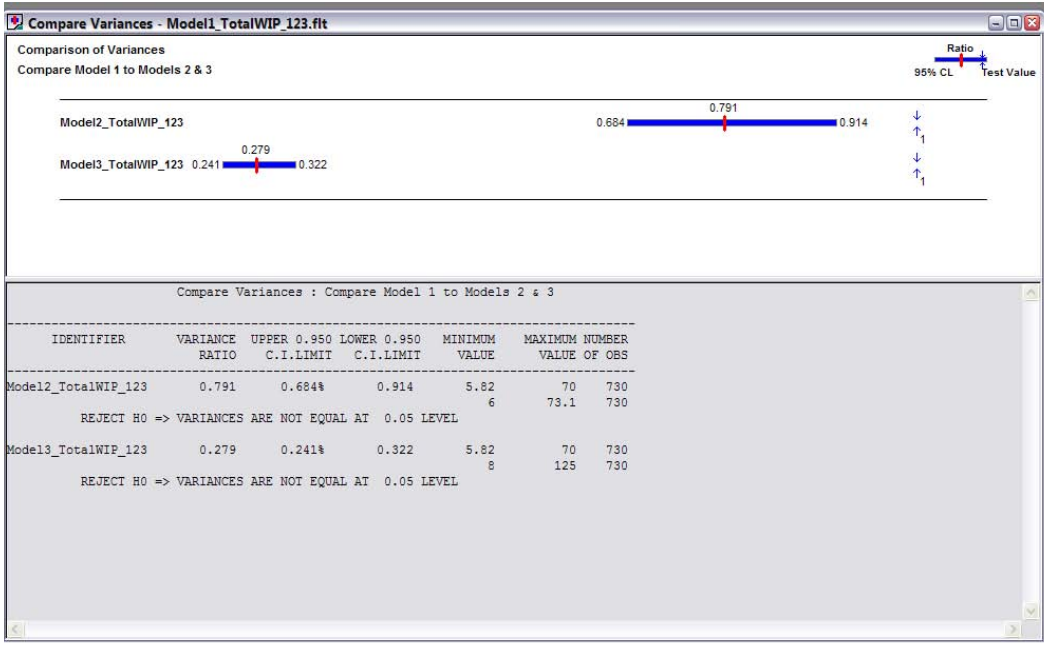
Appendix B-1. Comparison of Variance

Dyess AFB, TX



```
                       Compare Variances : Compare Model 1 to Models 2 & 3 - Dyess

-------------------------------------------------------------------------------------
      IDENTIFIER       VARIANCE  UPPER 0.950 LOWER 0.950   MINIMUM    MAXIMUM NUMBER
                          RATIO    C.I.LIMIT   C.I.LIMIT     VALUE      VALUE OF OBS
-------------------------------------------------------------------------------------
Model2_TotalWIP_Dyes       1.26       1.09%        1.45          1         18    730
s123                                                          4.39         20    730
          REJECT H0 => VARIANCES ARE NOT EQUAL AT  0.05 LEVEL

Model3_TotalWIP_Dyes     0.0241     0.0209%      0.0279          1         18    730
s123                                                          4.15         96    730
          REJECT H0 => VARIANCES ARE NOT EQUAL AT  0.05 LEVEL
```

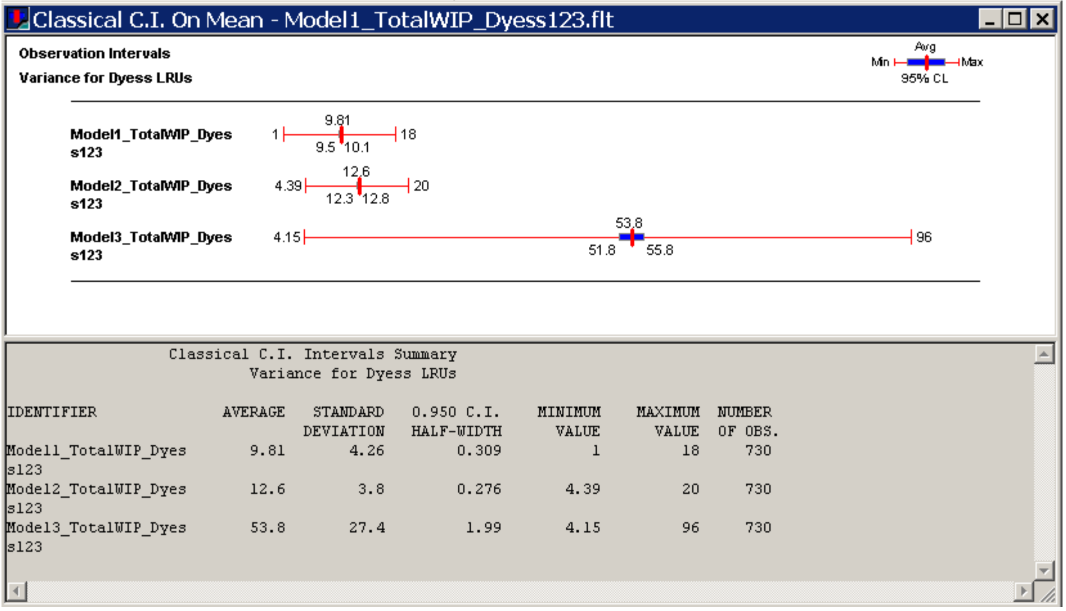
Ellsworth AFB, TX



```
                      Compare Variances : Compare Model 1 to Models 2 & 3

-------------------------------------------------------------------------------------
      IDENTIFIER       VARIANCE  UPPER 0.950 LOWER 0.950   MINIMUM    MAXIMUM NUMBER
                          RATIO    C.I.LIMIT   C.I.LIMIT     VALUE      VALUE OF OBS
-------------------------------------------------------------------------------------
Model2_TotalWIP_123       0.791      0.684%       0.914       5.82         70    730
                                                                 6       73.1    730
          REJECT H0 => VARIANCES ARE NOT EQUAL AT  0.05 LEVEL

Model3_TotalWIP_123       0.279      0.241%       0.322       5.82         70    730
                                                                 8        125    730
          REJECT H0 => VARIANCES ARE NOT EQUAL AT  0.05 LEVEL
```

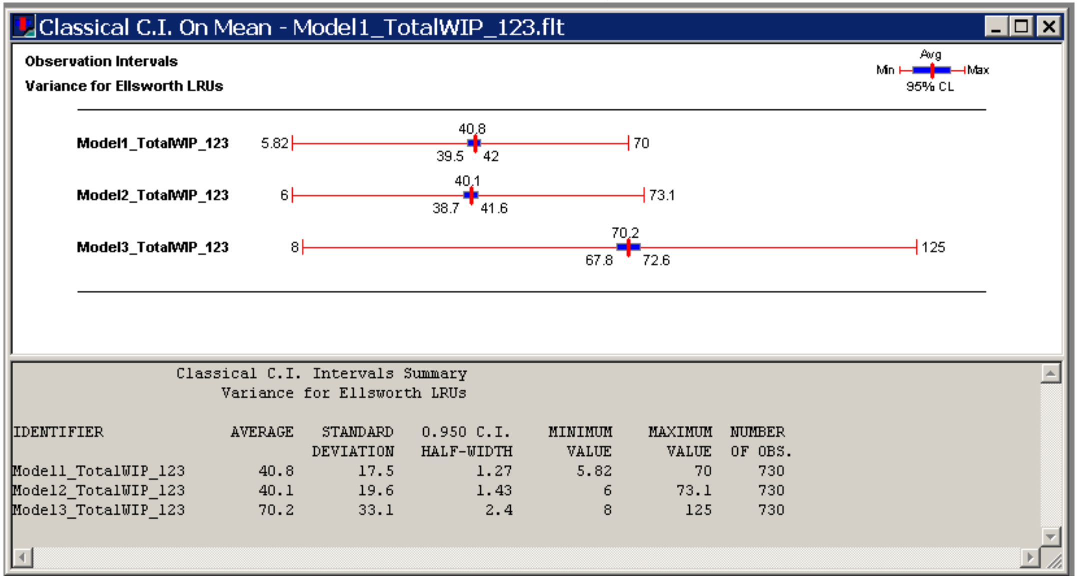
Appendix B-2. Variance

Dyess AFB, TX



```
                    Classical C.I. Intervals Summary
                           Variance for Dyess LRUs

IDENTIFIER              AVERAGE   STANDARD   0.950 C.I.    MINIMUM    MAXIMUM  NUMBER
                                  DEVIATION  HALF-WIDTH    VALUE      VALUE    OF OBS.
Model1_TotalWIP_Dyes       9.81      4.26       0.309         1         18      730
s123
Model2_TotalWIP_Dyes       12.6      3.8        0.276      4.39         20      730
s123
Model3_TotalWIP_Dyes       53.8     27.4        1.99       4.15         96      730
s123
```

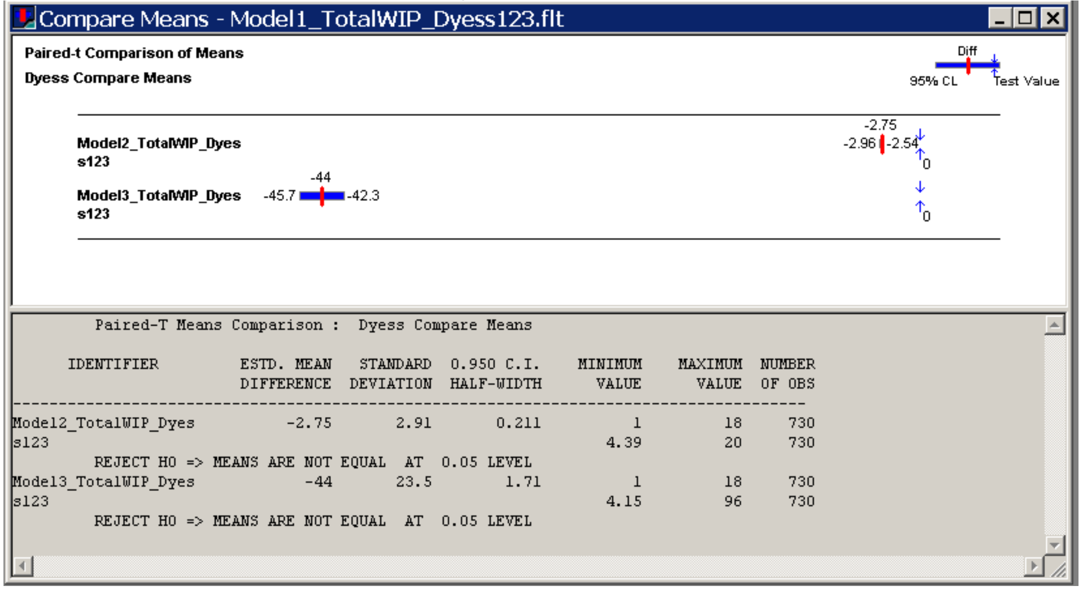
Ellsworth AFB, TX



```
                    Classical C.I. Intervals Summary
                        Variance for Ellsworth LRUs

IDENTIFIER              AVERAGE   STANDARD   0.950 C.I.    MINIMUM    MAXIMUM  NUMBER
                                  DEVIATION  HALF-WIDTH    VALUE      VALUE    OF OBS.
Model1_TotalWIP_123        40.8     17.5        1.27       5.82         70      730
Model2_TotalWIP_123        40.1     19.6        1.43          6       73.1      730
Model3_TotalWIP_123        70.2     33.1         2.4          8        125      730
```

Appendix B-3. Paired-t Test

Dyess AFB, TX



Paired-t Comparison of Means

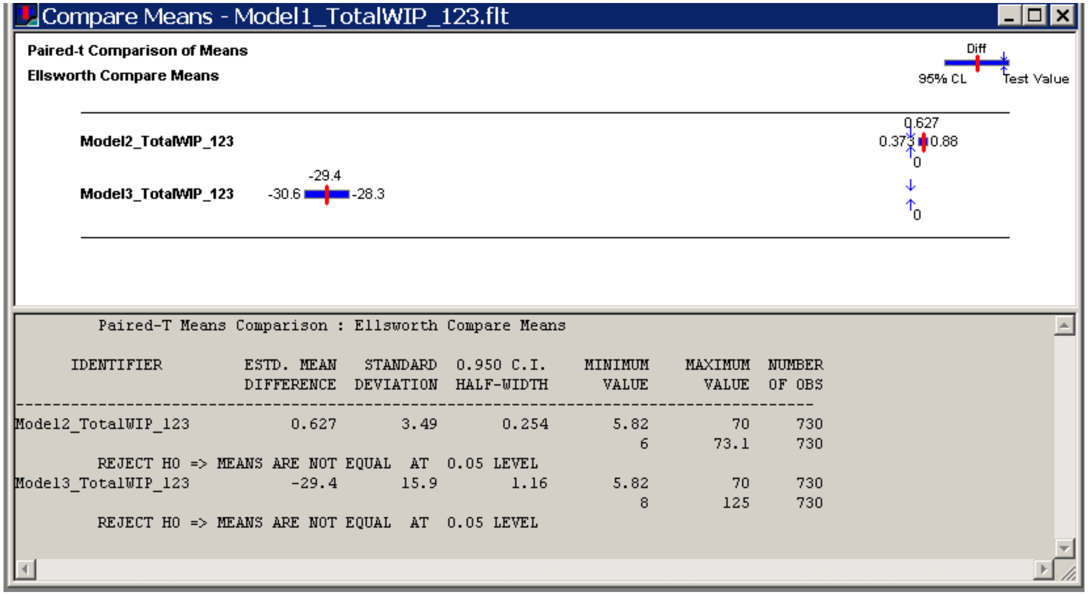
Dyess Compare Means

Model2_TotalWIP_Dyess123

Model3_TotalWIP_Dyess123

```
         Paired-T Means Comparison :  Dyess Compare Means

      IDENTIFIER           ESTD. MEAN   STANDARD  0.950 C.I.    MINIMUM     MAXIMUM  NUMBER
                           DIFFERENCE  DEVIATION  HALF-WIDTH     VALUE       VALUE   OF OBS
--------------------------------------------------------------------------------------------
Model2_TotalWIP_Dyes            -2.75       2.91       0.211         1          18      730
s123                                                              4.39          20      730
         REJECT H0 => MEANS ARE NOT EQUAL  AT  0.05 LEVEL
Model3_TotalWIP_Dyes              -44       23.5        1.71         1          18      730
s123                                                              4.15          96      730
         REJECT H0 => MEANS ARE NOT EQUAL  AT  0.05 LEVEL
```

Ellsworth AFB, TX



Paired-t Comparison of Means

Ellsworth Compare Means

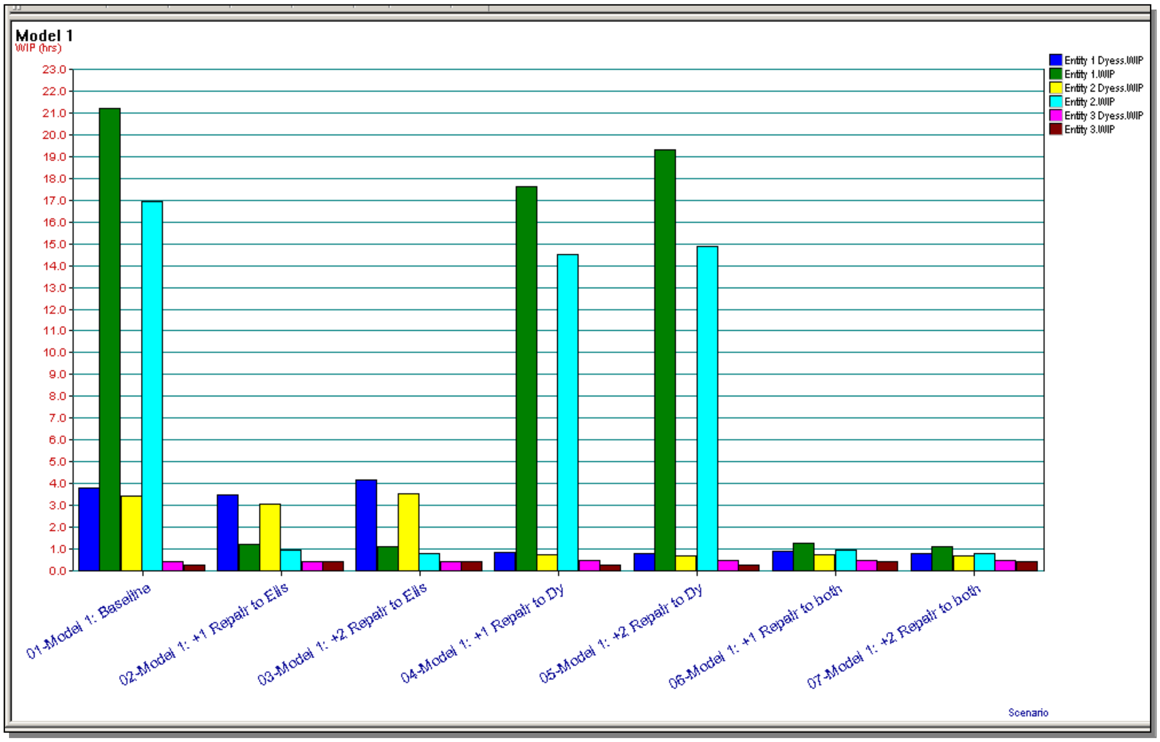
Model2_TotalWIP_123

Model3_TotalWIP_123

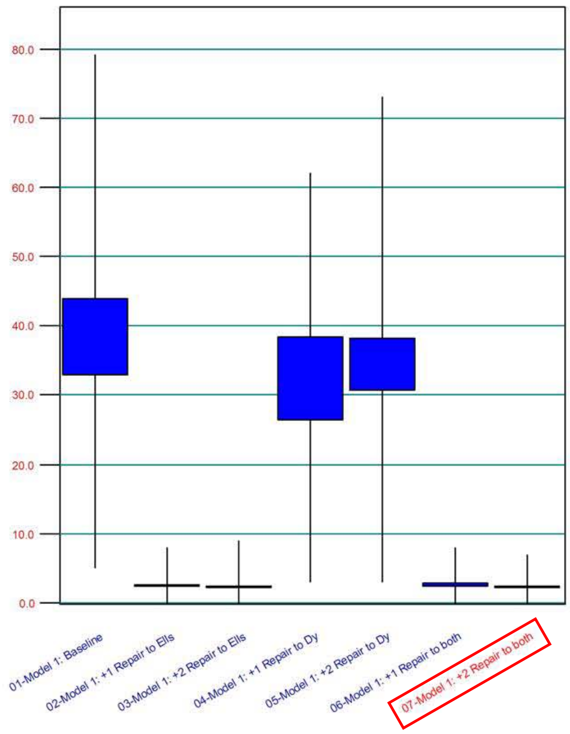
```
         Paired-T Means Comparison : Ellsworth Compare Means

      IDENTIFIER           ESTD. MEAN   STANDARD  0.950 C.I.    MINIMUM     MAXIMUM  NUMBER
                           DIFFERENCE  DEVIATION  HALF-WIDTH     VALUE       VALUE   OF OBS
--------------------------------------------------------------------------------------------
Model2_TotalWIP_123             0.627       3.49       0.254      5.82          70      730
                                                                     6        73.1      730
         REJECT H0 => MEANS ARE NOT EQUAL  AT  0.05 LEVEL
Model3_TotalWIP_123             -29.4       15.9        1.16      5.82          70      730
                                                                     8         125      730
         REJECT H0 => MEANS ARE NOT EQUAL  AT  0.05 LEVEL
```

Appendix C. Results Model vs. Scenario

Appendix C-1. Model 1

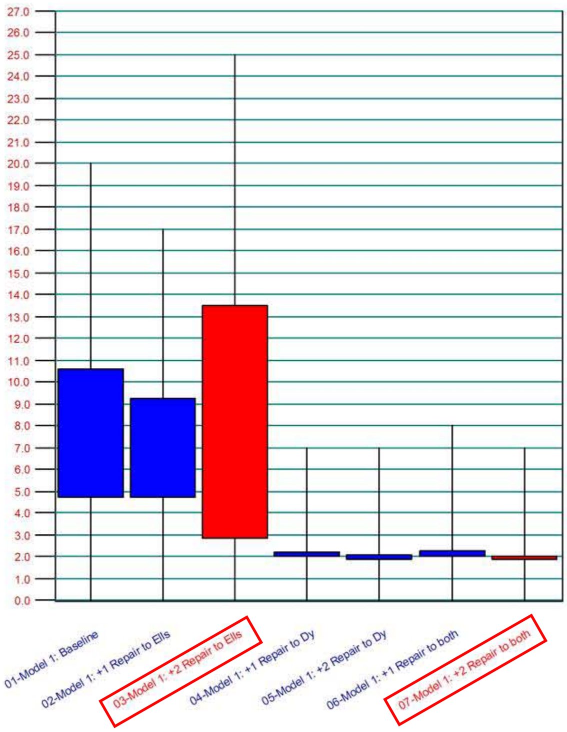


Appendix C-1A. Model 1, Best Case Ellsworth AFB



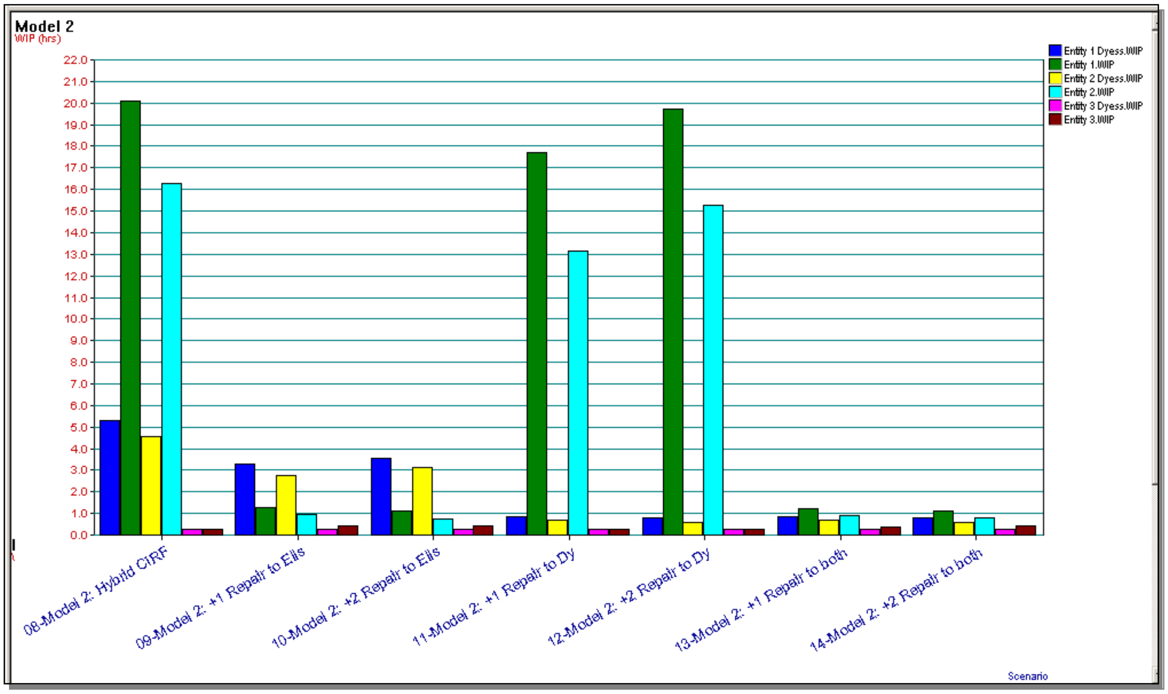
WIP (hrs) vs. Scenario

Appendix C-1B. Model 1, Best Case Dyess AFB



WIP (hrs) vs. Scenario

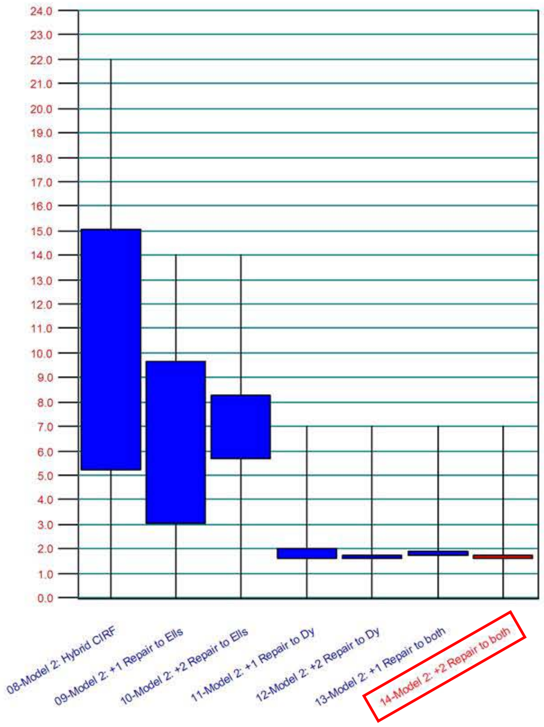
Appendix C-2. Model 2



Appendix C-2A. Model 2, Best Case Ellsworth AFB

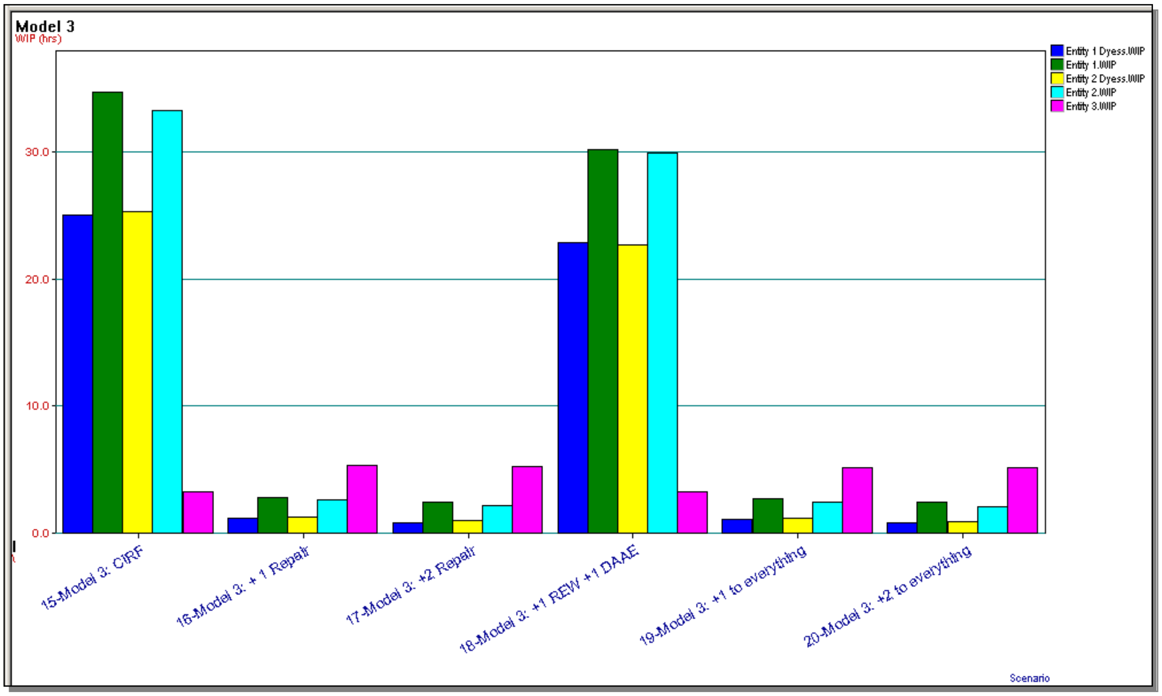
WIP (hrs) vs. Scenario

Appendix C-2B. Model 2, Best Case Dyess AFB

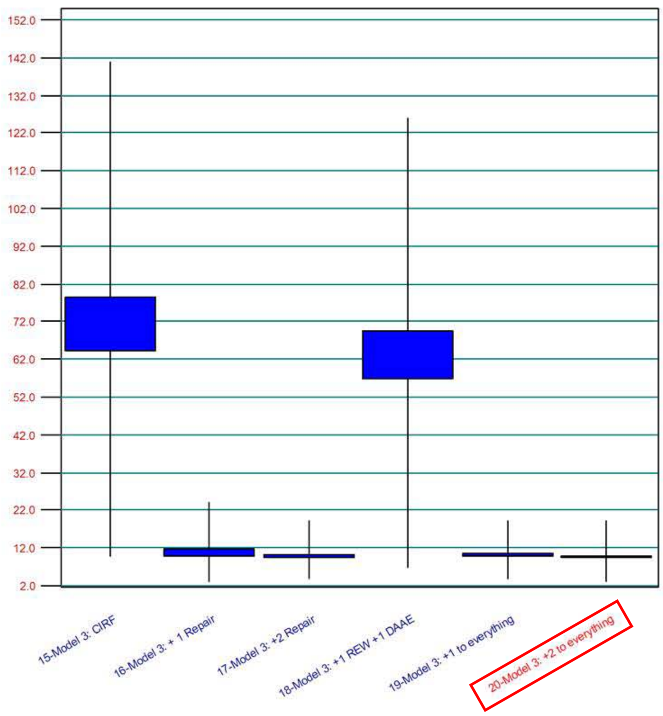


WIP (hrs) vs. Scenario

Appendix C-3. Model 3

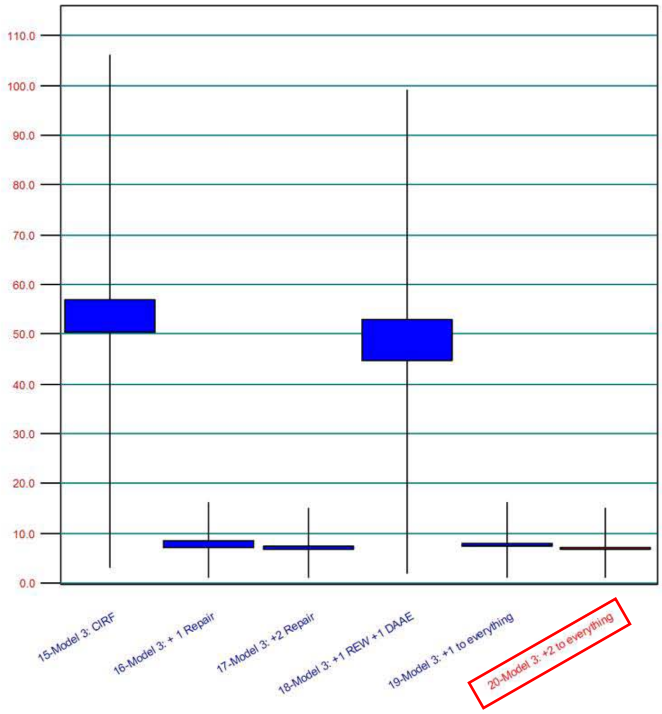


Appendix C-3A. Model 3, Best Case Ellsworth AFB



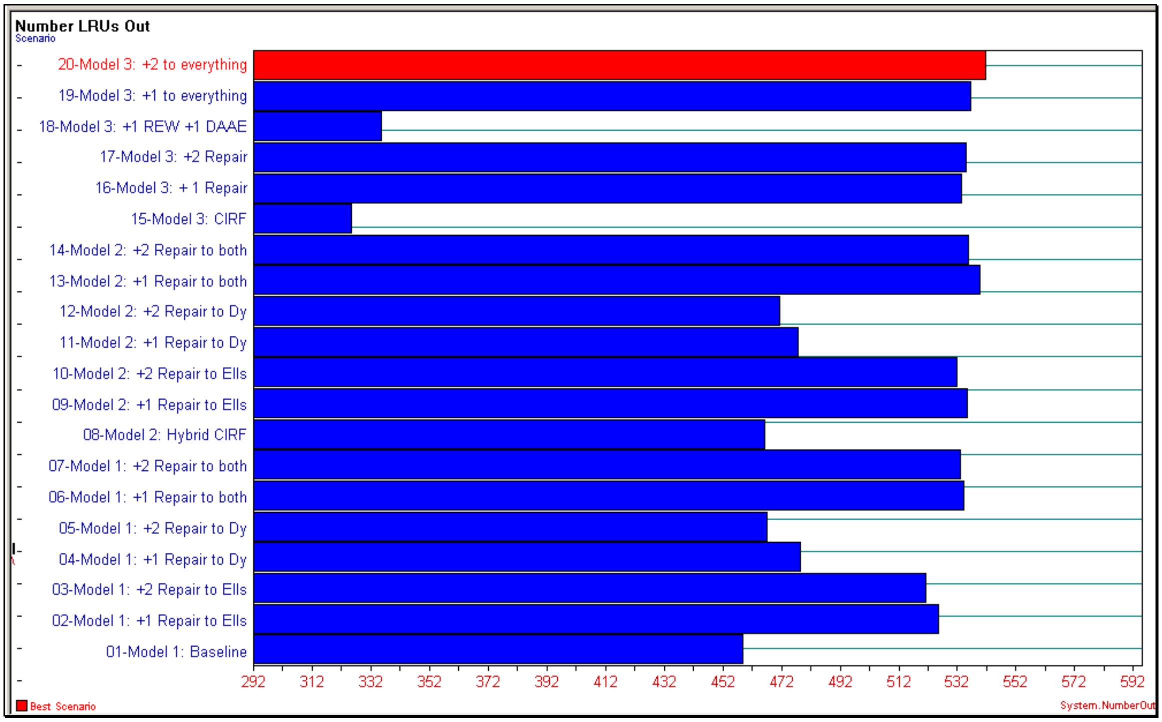
WIP (hrs) vs. Scenario

Appendix C-3B. Model 3, Best Case Dyess AFB



WIP (hrs) vs. Scenario

Appendix C-4. Number LRUs Output by Scenario



Appendix D. Data

Appendix D-1.

LRU	NSN	ATE Required	Average Run Times (hrs)	Serv Rate
TX7 (Bd 7 TX)	5865-01-240-3754EW	R/EW	56.35	94.7%
RFS7 (Bd 7 RFS)	5865-01-257-2789EW	R/EW & DAAE	38.22	88.1%
RX4-8 (4-8 RCVR)	5865-01-256-2544EW	R/EW	89.58	72.9%
ENC (Encoder)	5865-01-264-3364EW	R/EW & DAAE	51.13	92.7%
TX5A -6 (Bd 5 Aft TX)	5865-01-331-2557EW	R/EW	39.53	100.0%
RFS8 (Bd 8 RFS)	5865-01-269-5498EW	R/EW & DAAE	34.25	63.9%
FCH (Channelizer)	5895-01-239-8983EW	R/EW	42.15	85.3%
RP (TWF R/P)	5865-01-344-5855EW	R/EW & DAAE	41.50	54.5%

LRU	Dyess Production Jan thru Dec 08	Ellsworth Production Jan thru Dec 08
TX7 (Bd 7 TX)	64	84
RFS7 (Bd 7 RFS)	72	69
RX4-8 (4-8 RCVR)	15	18
ENC (Encoder)	22	31
TX5A -6 (Bd 5 Aft TX)	16	36
RFS8 (Bd 8 RFS)	22	37
FCH (Channelizer)	19	19
RP (TWF R/P)	0	13

Appendix D-2.

Scenario	**Base Tech**	**Base Tech Dyess**	**Inspec**	**Inspec Dyess**	**Inspec2**	**Inspec2 Dyess**	**CIRF Tech**	**Inspec CIRF**	**Inspec2 CIRF**
01-Model 1: Baseline	1	1	1	1	1	1	---	1	1
02-Model 1: +1 Repair to Ells	2	1	1	1	1	1	---	1	1
03-Model 1: +2 Repair to Ells	3	1	1	1	1	1	---	1	1
04-Model 1: +1 Repair to Dy	1	2	1	1	1	1	---	1	1
05-Model 1: +2 Repair to Dy	1	3	1	1	1	1	---	1	1
06-Model 1: +1 Repair to both	2	2	1	1	1	1	---	1	1
07-Model 1: +2 Repair to both	3	3	1	1	1	1	---	1	1
08-Model 2: Hybrid CIRF	1	1	1	1	1	1	---	1	1
09-Model 2: +1 Repair to Ells	2	1	1	1	1	1	---	1	1
10-Model 2: +2 Repair to Ells	3	1	1	1	1	1	---	1	1
11-Model 2: +1 Repair to Dy	1	2	1	1	1	1	---	1	1
12-Model 2: +2 Repair to Dy	1	3	1	1	1	1	---	1	1
13-Model 2: +1 Repair to both	2	2	1	1	1	1	---	1	1
14-Model 2: +2 Repair to both	3	3	1	1	1	1	---	1	1
15-Model 3: CIRF	---	1	1	1	1	1	1	1	1
16-Model 3: + 1 Repair	---	1	1	1	1	1	2	1	1
17-Model 3: +2 Repair	---	1	1	1	1	1	3	1	1
18-Model 3: +1 REW +1 DAAE	---	1	1	1	1	1	1	2	2
19-Model 3: +1 to everything	---	1	1	1	1	1	2	2	2
20-Model 3: +2 to everything	---	1	1	1	1	1	3	3	3

Base Tech = Intermediate Repair Station
Inspec = R/EW inspection Station
Inspec2 = DAAE Inspection Station
CIRF Tech = CIRF Repair Station
Inspec CIRF = CIRF R/EW Inspection Station
Inspec2 CIRF = CIRF DAAE Inspection Station

Appendix E. Blue Dart

Appendix E-1.

This research examined the line-replaceable-unit (LRU) maintenance procedures associated with the defensive electronic counter measure (ECM) system on the B-1B, designated the AN/ALQ-161. Of the 33 LRUs comprising the ECM, 8 were selected for study since they were those that represented the maintenance problems. Three simulation models were created to capture the maintenance process and were examined using CY 2008 data obtained from Air Combat Command. Variations to the resources within each model produced 20 different scenarios for performance comparisons. A best-case scenario was selected from each model and the results were compared to one another. In all models, two independent variables were measured: work-in-process (WIP) and machine utilization. The models created depict (1) current LRU maintenance operations at Dyess AFB, TX and Ellsworth AFB, SD, (2) a hybrid centralized intermediate repair facility (CIRF) with limited inter-base resource collaboration, and (3) the completely implemented CIRF concept.

The results indicate that increasing the repair stations provided the largest benefit and resource sharing among bases provided a mechanism to even out the machine utilization among Dyess and Ellsworth AFB maintenance processes.

The main contribution of this research is the definition of an analytical methodology for examining CIRF implementations and a discrete simulation tool that can be extended to conduct more thorough analyses.

Bibliography

Ames, William J. *Logistical Effectiveness of a Two-Level Maintenance*., MS Thesis, AU/ACSC/013/2000-04. Air Command and Staff College (AU), Maxwell AFB AL, Sep 2000 (ADA381766).

"B-1's Defensive Avionics Getting New Guts." Excerpt from unpublished article. n. pag. http://www.defenseindustrydaily.com/b1s-defensive-avionics-getting-new-guts-03132/. 15 Mar 2007.

"B-1B Lancer Strategic Bomber, USA.". Excerpt from unpublished article. n. pag. http://www.airforce-technology.com/projects/b-1b/. 17 Feb 2010.

Banks, Jerry, et al. *Discrete-Event System Simulation*. (4th Edition). Prentice-Hall, 2005.

Department of the Air Force (DAF). *Two Level Maintenance and Regional Repair of Air Force Weapon Systems and Equipment*. AFI21-129. Washington: HQ USAF, 01 May 1998.

Diamond, Richard C. MSgt. Command B-1 Electronic Warfare Systems Manager, USAF ACC/A4F1. Personal correspondence. 17 Feb 2010.

Gertler, Jeremiah. *Air Force Next-Generation Bomber: Background and Issues for Congress*., Congressional Research Service; 7-5700, RL34406. 22 Dec 2009.

Feinberg, A., et al. "EAF Support Challenges-LATIRN Intermediate Maintenance Concepts," *Air Force Journal of Logistics*, 1.XXIV: 4-7-40. 2000.

Kelton, David W., et al. *Simulation with Arena*. (4th Edition). McGraw-Hill, 2007.

Law, Averill M., and David W. Kelton. *Simulation Modeling and Analysis*. (4th Edition). McGraw-Hill, 2007.

McGarvey, Ronald G., et al. "Supporting Air and Space Expeditionary Forces: Analysis of CONUS Centralized Intermediate Repair Facilities," RAND Corporation, Project Air Force (Jan 2009).

Mousavi, Alireza. "Director of Advanced Manufacturing Engineering Programme." Excerpt from unpublished article. n. pag. http://people.brunel.ac.uk/~emstaam/. 2010.

Ragsdale, Cliff T. *Spreadsheet Modeling & Decision Analysis : A Practical Introduction to Management Science*. (4th Edition). Thomson South-Western, 2004.

Roark, Lance M. *B-1B Avionics/Automatic Test Equipment: Maintenance Queuing Analysis*., MS Thesis, School of Systems and Logistics, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, 1983 (ADA141175).

Rodrigues, Marcelo B., and Mario Karpowicz. *An Analysis of Operational Availability of Brazilian Navy and Argentine Air Force A-4 Fleets using Simulation Modeling*., MS Thesis, Naval Postgraduate School, Monterey, CA, 1999 (ADA376396).

Rowe, Ryan L. *Optimal CV-22 Centralized Intermediate Repair Facility Locations and Parts Repair*., Graduate research project, AFIT/ILS/ENS/09C-04. School of Systems and Logistics, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, Jul 2009 (ADA501531).

Shyong, Shenn-Rong. *Advanced Planning and Scheduling in the United States Air Force Depot-Level Maintenance*., MS thesis, AFIT/GLM/ENS/02-16. School of Systems and Logistics, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, 17 Apr 2002 (ADA400202).

Secretary of the Air Force, Washington, DC. *U.S. Air Force Long-Range Strike Aircraft White Paper*. University of Nebraska – Lincoln, 2001 (ADA433970).

Vashi, Vidyut H., et al. "The use of Response Surface Methodology to Optimize Logistics Simulation Models," *Journal of Business Logistics*, 16.2: 197. 1995.

Vigus, Steven E. *A Simulation-Based Analysis of the Impact of in-Sourcing a Major Process Element on the Coast Guard HH-60J Depot Maintenance Process*., MS thesis, AFIT/GAQ/ENS/03-03. School of Systems and Logistics, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, 27 Aug 2003 (ADA415691).

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 074-0188*

1. REPORT DATE *(DD-MM-YYYY)* 25-03-2010	**2. REPORT TYPE** **Master's Thesis**	**3. DATES COVERED** *(From – To)* Sep 2008 - Mar 2010

4. TITLE AND SUBTITLE A Simulation Based Methodology to Examine the B-1B's AN/ALQ-161 Maintenance Process	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Garza, Ricardo R., Captain, USAF	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S) Air Force Institute of Technology Graduate School of Engineering and Management (AFIT/EN) 2950 Hobson Street, Building 642 WPAFB OH 45433-7765	**8. PERFORMING ORGANIZATION REPORT NUMBER** **AFIT-LSCM-ENS-10-04**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) INTENTIONNALY LEFT BLANK	**10. SPONSOR/MONITOR'S ACRONYM(S)** **N/A**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) **N/A**

12. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This thesis looks at the maintenance procedures associated with the defensive electronic counter measure (ECM) system on the B-1B, designated the AN/ALQ-161. Computer simulation of the current line-replaceable-unit (LRU) maintenance network for Ellsworth AFB and Dyess AFB is modeled. In addition, two hypothetical repair networks are proposed and analyzed. This research considers the applicability of this type of computer simulation, using ARENA software to study the AN/ALQ-161 repair system. The contribution of this research is a discrete simulation methodology specific to the AN/ALQ-161 LRU repair line. Two response variables of interest were addressed, work-in-process and machine utilization. A total of 20 different repair scenarios were analyzed for the three different LRU networks simulated. A best-case scenario is selected from each model and the results are compared to one another.

15. SUBJECT TERMS

B-1B, AN/ALQ-161, Discrete Event Simulation, Line-replaceable-unit (LRU), Queuing Theory, Work-in-progress (WIP), Automatic Test Equipment (ATE), Centralized Intermediate Repair Facility (CIRF), Hybrid CIRF, Two-level Maintenance (2LM), Three-level Maintenance (3LM), Process Time, Intermediate Repair, Organic Repair, Depot Repair, Cycle Time

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Dr. Raymond R. Hill, PhD (ENS)
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(Include area code)*
U	U	U	UU	81	(937) 785-3636, ext 7469; e-mail: raymond.hill@afit.edu

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18