SIMULATION OF AUTONOMIC LOGISTICS SYSTEM (ALS) SORTIE GENERATION

THESIS

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AFIT/GOR/ENS/03-07

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Paul D. Faas

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Abstract

The current Air Force logistics operations system is reactive in nature, meaning that after the aircraft detects a part failure, the maintenance person must perform fault isolation procedures and then steps are taken to repair or replace the faulty item. This may or may not include ordering of a replacement item from base supply. The Autonomic Logistics System (ALS) concept changes this reactive process into a proactive one with the employment of technologies such as prognostics and distributed information network. This new approach to the logistics process shows the potential for cost savings, increased aircraft operational availability, and better system performance.

The ALS basic function can be compared to the human body's nervous system. The body's nervous system performs activities automatically or without constant thought like respiration and blood circulation. This same concept can be applied to the Air Force logistics system. Certain logistics tasks can be handled automatically or autonomously. Ordering parts for a broken system, calling the right maintenance specialist to the right aircraft reporting a problem, notifying the maintenance control center that a certain aircraft has a malfunctioning system and will not be available for the next sortie, and other possible applications. Since the ALS can handle these routine tasks, the maintenance personnel are free to perform more important tasks such as maintaining and repairing the jets.

This thesis explores the impact of this concept on the aircraft sortie generation process by building a discrete event simulation tool to allow the study of the baseline existing system and the ALS.

SIMULATION OF AUTONOMIC LOGISTICS SYSTEM (ALS) SORTIE GENERATION

I. Introduction

The Air Force needs tools that allow analysis and evaluation of newly emerging operational concepts. This thesis builds such a tool through the use of modeling and simulation. This tool will help decision makers perform what-if analyses to determine whether these concepts will provide benefits over current systems. These benefits may include, a cost savings, increased operational availability, and better system performance.

The Joint Strike Fighter (JSF) aircraft program office is developing a newly emerging operational concept called the Autonomous Logistics System (ALS). The program office is in the system development and demonstration phase of the program with Lockheed Martin as the prime contractor. This new logistics system shows the potential for great savings over the current way the Air Force conducts logistics operations by employing emerging technologies such as prognostics and making use of a distributed information network to accelerate the information flow. This thesis builds a discrete event simulation tool of the current sortie generation process and the new ALS to allow comparisons to be made between two systems; the current maintenance system and the ALS.

Background

The current Air Force logistics operations system is reactive in nature, meaning that after the aircraft detects a part failure, the maintenance person performs fault isolation procedures and then any steps to repair or replace the faulty item. This process is usually started when the aircraft detects a fault, which sets a flag and sends a notice to the pilot. Depending on the severity of the fault the mission can continue and the information is saved for maintenance debrief. The new ALS is a proactive approach to the logistics operations. Meaning that when the same scenario takes place, a number of actions will automatically kick-off. They include, but are not limited to, isolating the fault, taking the necessary actions to work around the problem and possibly continue the mission, notification of ground personnel, ordering the equipment and right personnel to repair the aircraft, and if necessary, even ordering a replacement part from base supply. This new process will make the jet more reliable and easier to maintain and will also make the weapon system more affordable.

The JSF is not the only program addressing these new technologies; other organizations are investigating this new logistics concept. The Air Force Research Laboratory (AFRL) is investigating whether a prognostics and health management (PHM) system, the heart of the ALS, can have a have significant impact to the current aircraft fleet i.e. F-16, F-15, C-5, C-17, etc. Also, the Army and Navy are placing a Health Usage Monitoring System (HUMS) on their helicopter fleet.

Autonomic Logistics

To understand an ALS, consider the basic functions of the human body's nervous system. The body's nervous system performs activities automatically or without constant thought like respiration and blood circulation. This same concept can be applied to the Air Force logistics system. Certain logistics tasks can be handled automatically or autonomously. Ordering parts for a broken system, calling the right maintenance specialist to the right aircraft reporting a problem, notifying the maintenance control center that a certain aircraft has a malfunctioning system and will not be available for the next sortie, are some of the possible applications. Since the ALS can handle these routine tasks, the maintenance personnel are free to perform more important tasks such as maintaining and repairing the jets.

The heart of the ALS is a fully functional PHM. The PHM can detect aircraft system faults, perform on-board diagnostics and fault isolation, and delay maintenance if a system can either be reconfigured or is not required for the next mission, and report its status and findings. The other key system for the ALS is the Distributed Information System (DIS). This is the information side of the ALS. It makes available the PHM data to all the appropriate logistics functions, keeping them informed of status and making requests for parts, manpower and equipment if the situation needs these items.

Previous work

Rebulanan (2000) and Malley (2001) conducted initial thesis research into the ALS and PHM systems respectively. Rebulanan constructed an Autonomic Logistics simulation called ALSim as a tool to allow comparison between ALS and the current maintenance process. His research showed that higher aircraft availability could be obtained with an ALS. Malley (2001) built on that research by adding more detail to the PHM capability in ALSim. The PHM capability utilized inputs from notional JSF sensors and employed an artificial neural network to predict remaining service life. Both programs were written in the JAVA® programming language.

Discrete Event Simulation Model Development

The research conducted in this thesis will look more in-depth at the failure information and will take a different approach to the model building. The model is built in Arena®, a discrete event simulation software package. The model is structured to allow easy insertion of new objects that are deemed appropriate for implementation. The model will include many aspects of a minimal, yet effective, ALS, assumed present at the base level. This will allow comparison between current system procedures and the envisioned ALS of the future. Sensitivity analysis of the model will pinpoint areas of greatest concern and potential. The simulation tool will examine an Air Expeditionary Force (AEF) scenario. A wing working in an AEF scenario needs assurance that their aircraft can safely and effectively perform the deployed mission without a great deal of last minute inspections and parts swapping. This simulation tool can help ascertain if the deployment will function smoothly in the tightly constrained AEF deployment time block. Once the units have deployed, the simulation tool can help ascertain if supply and maintenance will be able to plan for: 1) component failures, and 2) when and where the components should be delivered thus minimizing man-hours, cost of spares and transportation, and reducing the on hand valuable components.

Aircraft Sortie Generation Process

Aircraft maintenance is the heart of flight line operations and it of course takes the most time. The sortie generation process has been the same for many years. It takes several different specially trained personnel to generate an aircraft for the day's mission. The process is cyclical in nature; Figure 1 shows the typical process.

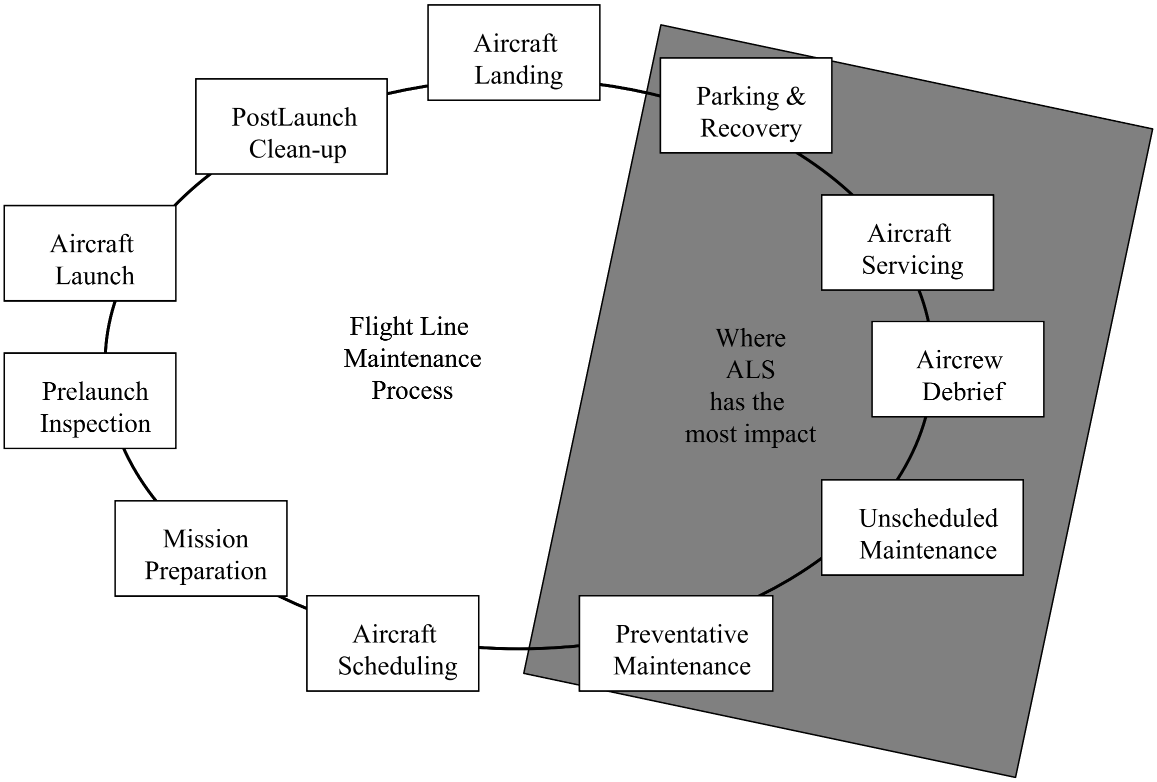


Figure 1. Sortie Generation Process

The starting point is generally considered to be the aircraft landing. After moving to the parking location and engine shutdown, post flight servicing is conducted, while the aircrew conducts their debriefings to the maintenance crew. Numerous routine maintenance functions are required to ready the jet for the next mission, plus any unscheduled maintenance derived from the recorded faults collected during the flight. The aircraft are prepared for flight by the ground crews, the pilots load the assigned mission, take-off, perform the mission, and land to the complete the cycle.

The ALS hopes to make positive impacts on this process. These impacts should come via more information sharing, better information, and more timely information. The box in Figure 1 indicates where the ALS will have the greatest impact. This will also be the place that we will focus our modeling efforts.

Problem

Air Force decision makers need a simulation tool to study the effects of the emerging Autonomic Logistics System (ALS) technologies on the Air Force's sortie generation process. This discrete event simulation model will facilitate quick turn studies providing concrete measures of performance.

Research Objective

The model will be developed in Arena® with extensive use of dynamic graphics to allow for better definition of required objects and interactions. The modules from Arena® will be written such that object-oriented code may be quickly developed from the model.

Scope

This research will develop a discrete event simulation model to emulate the effects of a baseline sortie generation process and a fully operational Autonomic Logistics System (ALS) to include a prognostic and health management (PHM) system and distributed information system (DIS) at the base level. This model will lay the groundwork for an object-oriented model that will eventually give decision makers the ability to simulate existing and emerging aspects of the Autonomic Logistics System (ALS).

The baseline scenario is the existing organization level logistics operations. The model is structured to allow for easy incorporation of additional or updated objects (such as types of aircraft, maintenance equipment/process, refueling equipment/process, operating locations, etc.) The model focuses on the F-16 aircraft and the radar subsystem more specifically using actual data from the F-16 radar systems that are flying at Hill AFB, UT. The code is constructed to ensure easy reusability for other aircraft or subsystems that a user wishes to consider.

Thesis Organization

This thesis is organized in five chapters. The second chapter contains a detailed literature review on the following subjects; Sortie Generation, Autonomic Logistics, Health Usage Monitoring System, and other simulation programs.

Chapter three describes the methodology that went into development of the Arena® sortie generation model and where the data was obtained. Chapter four contains the results from the simulations while the fifth chapter includes conclusions and recommendations for future research.

II. Literature Review

Introduction

This literature review examines the research that defines the sortie generation and the autonomic logistics processes. Defining these processes will help with the model development discussed in chapter 3. This chapter also includes discussions of the two key ALS components PHM and DIS, another PHM system (HUMS), condition-based maintenance (CBM), and other simulation packages that were located during the literature review.

Sortie Generation Process

As discussed in Chapter 1 the sortie generation process involves several factors and entities. The requirements for maintenance and the sortie generation process are found in AFI21-101 (2002:12), "Aircraft and equipment readiness is the maintenance mission. The maintenance function ensures aircraft and equipment are safe serviceable, and properly configured to meet mission needs." Flight line maintenance includes processes to inspect, service, and maintain aircraft on the flight line. An important factor in maintenance is knowing the status of the aircraft to include the systems and subsystems that make up such an aircraft. Today's maintainers rely on the on-board diagnostics to indicate a problem during post flight servicing and inspection. Only after this notification can they then undertake the fault isolation and repair process. As discussed in the next section, ALS equipped aircraft will conduct a majority of these tasks autonomously while at the same time keeping the maintainers informed of weapon system status, making their job a great deal easier by pointing to specific parts that require replacement or indicating when such maintenance is required. As indicated in Chapter 1, we wish to identify time savings due to an ALS system, as well as other benefits from such a system.

Figure 1 defines the sortie generation process; an ALS can have a positive impact throughout the process. Starting at the top of Figure 1, the landing procedure, an ALS equipped aircraft can relay critical system information while the aircraft waits for the runway to become available and after landing while it taxis back to the parking location. Currently, some aircrews report the aircraft status over the radio, giving the ground crews a head start on the repair process. However, this status usually only includes the maintenance fault lists (MFL) flags. After engine shutdown the aircrew may conduct a short discussion with the ground crew before heading to the mission debrief area. During parking and recovery, the aircraft is prepared for ground operations, and aircraft servicing commences. This servicing includes checking fluid levels and refueling the aircraft. During the aircrew debriefing, involving the aircrew and maintenance personnel, any discrepancies are discussed, documented, and placed into a computerized information system, in the F-16 case the Core Automated Maintenance System (CAMS). The maintenance personnel are looking for both current faults and repeat faults. Next, if required, a maintenance crew heads to the aircraft to conduct the repair to return the aircraft to operational status. This is referred to as unscheduled maintenance since these faults occur over the course of the sortie mission, meaning maintenance was unplanned. Figure 2 shows the possible steps in this maintenance process.

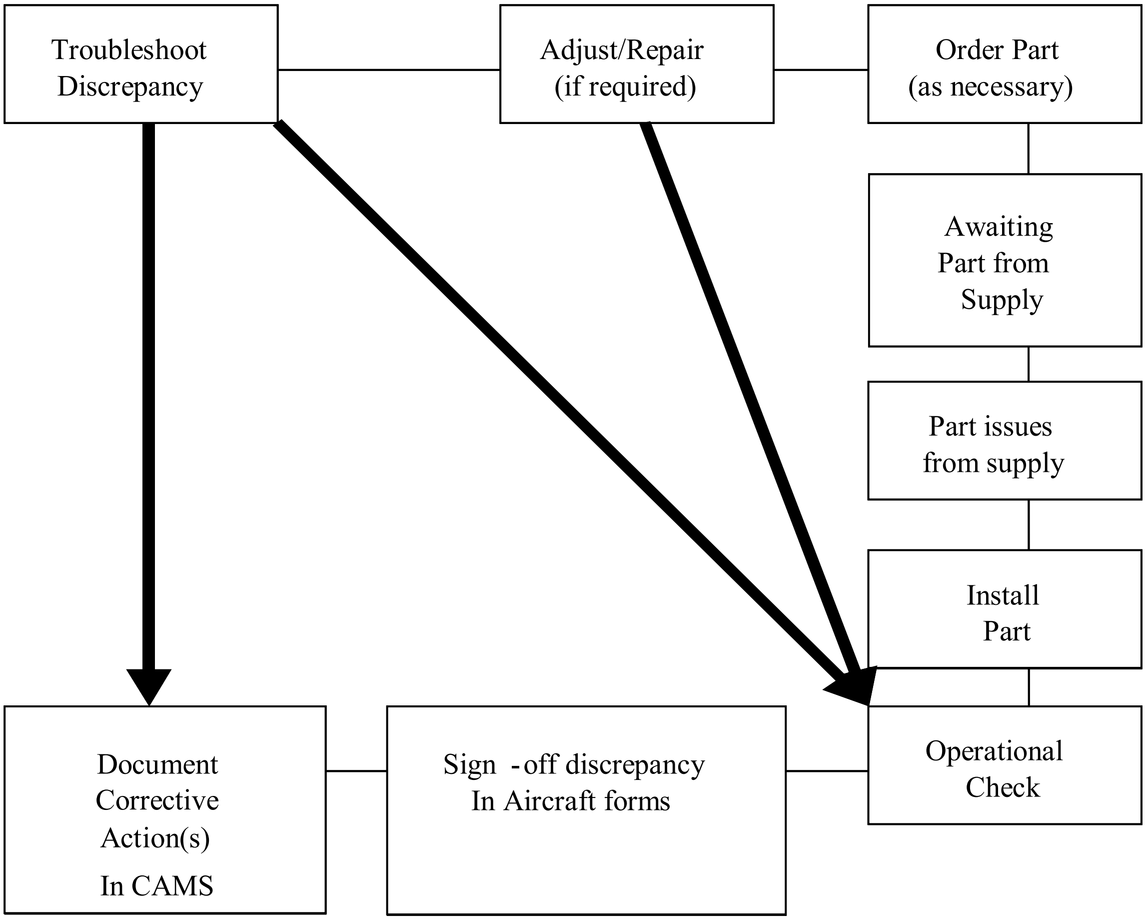


Figure 2. Unscheduled Maintenance Process

The process is cyclical with steps possibly skipped based on the severity and type of the repair. A great deal of time is saved using an ALS system. Parts are ordered ahead, since the PHM system has already diagnosed and isolated the fault. Documentation is created by the PHM and "signed off' by the maintainer once the repair is complete. Lastly, a PHM instills confidence that the correct part was removed and replaced. The last step on many fault isolation trees includes a statement that reads, "replace item A, test system, if fault still exists replace item B." This type of fault isolation can be frustrating and time consuming. However, with accurate PHM, the correct item is removed and replaced the first time.

The next step may involve preventative maintenance and periodic inspections, Time Compliance Technical Order installations, system calibrations, and Time Change Item (TCI) replacements. TCIs are conducted on the critical parts replaced or repaired based on accumulated flight hours, not based on part condition. The TCI area is another area where PHM and condition based maintenance may supercede the need for these maintenance actions. The PHM can check system status and indicate when parts require maintenance, rather the traditional way of changing parts based on operating hours.

The next steps prepare the aircraft for the next mission and may include weapon loading, software loading, fuel adjustment, etc. Now the aircraft is ready for preflight inspections. The crew chief conducts his inspection and then the aircrew performs their inspection. The aircraft engine is started, and the last few items are completed, and the aircraft taxis to the end of the runway. Certain aircraft require an end of runway inspection prior to aircraft launch. Post-launch cleanup is then conducted; storing of fire extinguishers, inlet covers, etc., and conducting foreign object damage (FOD) inspections (Cardona and Sanford, 2001). Figure 3 shows a notional timeline of a sortie indicating how an ALS can save time in the repair process.

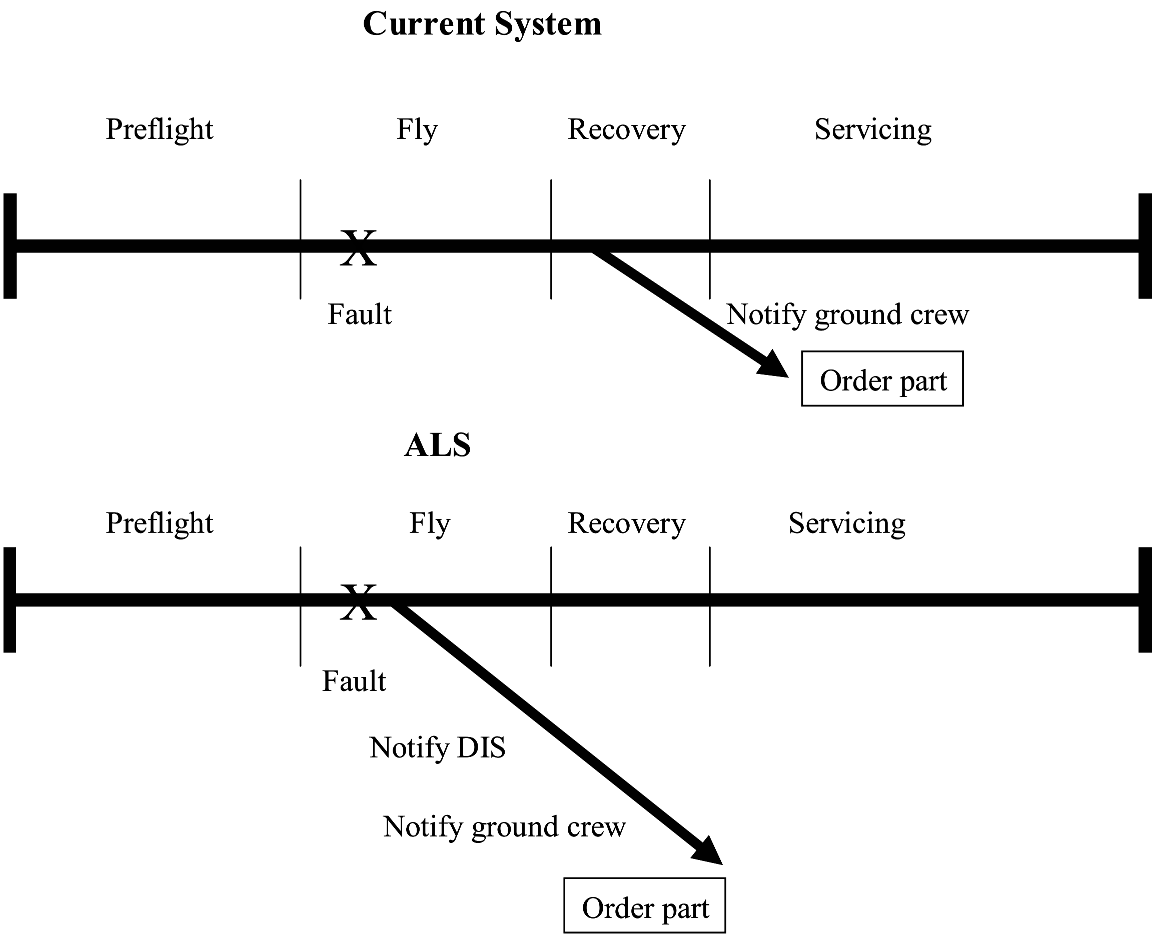


Figure 3. Notional Timeline for an Aircraft with and without an ALS system

In the current process, the ground crew is only notified of a fault prior to landing if the pilot radios in or on the ground after engine shutdown. However, this is usually just the maintenance fault lists (MFL) list and the ground crew does not have the diagnostics to determine the problem. The aircraft is diagnosed to determine the part that needs replaced. The part is ordered only after this process is complete.

For this same scenario under the ALS, the onboard PHM would notify the DIS through a Passive Aircraft Status System (PASS) of a fault and which part to order. This order action notifies the appropriate aircraft maintenance specialist. In theory, the right maintainer, the right part, and the right equipment meet the aircraft upon its return. This significantly reduces the time to repair the jet and return it to operational status. The autonomic logistic concept relies on two main objects to make the system function. First, is the PHM system, the heart of the ALS. PHM continuously monitors the aircraft for problems to include pending failures as well as after the fact failures. The other important factor is the Distributed Information System (DIS), responsible for tracking and relaying the maintenance requirements to appropriate elements of the logistics chain.

Autonomic Logistics

According to Smith et al (1999), the autonomic logistics concept grew out the JSF Concept Exploration phase with the Advanced Integrated Diagnostics Study. “The study effort reviewed current aircraft systems and available technologies for promising techniques in prognostics, diagnostics, sensors, diagnostic design tools, maintenance systems and software systems (Smith, 1999:13).” The goal is to move logistics from the current reactive mode to a proactive one. During JSF Concept Development the concept architecture was developed from a program called Advanced Strike Integrated Diagnostics (ASID). “Architecture features –such as the diagnostic design process, benefits of integrated information flow and feedback between operation, support and design function – were found to be important attributes (Smith, 1999:13).”

PHM

According to Becker et al (1998) machine prognostics is, “where failure modes and the remaining life of a system can be predicted (Becker, 1998:20).” This is a simple way to think of prognostics. A useful analogy is the way doctors make prognosis of human health. Diagnostics tests such as X-rays and blood tests are conducted and analyzed by lab technicians and other specialists after which the doctor prescribes a treatment plan. The same process applies to electrical and mechanical systems. Sensors provide reasoners and electronic decision makers with current system status and operating conditions and these reasoners make a prognosis of system health. If a problem is pending, a notification is sent to the flight line maintainer. According to Becker et al, (1998), “The aim of prognostics is to stop disabling of fatal failures before they happen (Becker, 1998:20).”

According to Ferrell (2000) the requirements for a PHM are:

a. Provide system health status to enable pilot alerts, reconfiguration, graceful degradation, and system capability assessment in the event of failure.

b. Detect and isolate failures and report failure information to trigger the Autonomic Logistics process to effect maintenance.

c. Collect and analyze component performance data to predict remaining life of selected components for the purpose of enhancing safety and better maintenance and spares planning.

DIS

The Distributed Information System (DIS) is more than just a stream of aircraft data; it takes the aircraft data and coverts it into information. The following is a proposed list of that information:

a. Maintenance Information/knowledge
b. Supply chain management information
c. Health and usage information
d. Forecast aircraft availability data
e. Best use of resource recommendations
f. Training Management (Henley: 2000)

In addition to providing the above information, the DIS also tracks system, subsystem, and part trends and other issues. This additional data is used to better manage the aircraft fleet. If a particular part is showing signs of degradation and that aircraft is scheduled for other repairs, then the degraded part is replaced along with the scheduled maintenance.

The Passive Aircraft Status System (PASS) is a component of the DIS that speeds the information transfer. The PASS functions autonomously, first storing PHM data and then downlinking that information to the ground units of the logistics chain. AFRL conducted a study of existing concepts and possible implementation of these for use on legacy aircraft. AFRL was able to devise an architecture and build a desktop demonstration in JAVA®. The demonstration showed possible timing of data transfer and the appearance of potential computer screens for the maintainer (Botello: 2000).

Other PHM Systems

The Army and Navy are currently fielding the Health and Usage Monitoring Systems (HUMS) into their helicopter fleet. This was an important factor for the condition based maintenance (CBM) policy that the Navy wants to implement (Schaefer and Haas: 2002; Deaton and Glenn: 1999). CBM is not a new concept, a great deal of articles have been published for ground-based machinery. Caterpillar seems to lead the field in this implementation with on-board diagnostics and remote information passage back to a central processing facility. The Navy is moving towards this type of maintenance policy and away from the standard time-based policy. The standard time-based policy specifies that items be repaired or replaced based on flight hours or some other usage time limit. The CBM policy is to ascertain the condition of the critical part through sensor outputs and reasoner algorithms to repair or replace the parts only after a certain wear is detected.

Schaefer and Haas investigated the impact of HUMS on the Navy's logistics processes using a simulation model to examine HUMS impact on process reengineering, sensor failures, and false alarm rates (Schaefer and Haas:2002). They focused on the operational level of helicopter logistics, specifically ten high maintenance subsystems. The processes with the model were based on a database of information which included, mean time to repair (MTTR), unscheduled and scheduled maintenance man-hours per flight hour, maintenance action, aircraft, and flight. They provide some interesting conclusions. First, they found that the baseline phase maintenance or scheduled maintenance represented a bottleneck, and second that false alarm rates have an adverse impact on availability (Schaefer and Haas:2002).

Another program the Navy is investigating is called the Thinline Health Monitoring System (THMS). This was a demonstration applied to their Submarine Towed Array Systems (TAS). The TAS is a critical submarine mission component that if it fails to operate, repairs are deferred until the submarine returns to port (Bishop and Matzelevich: 2001: 5). The contractor, Areté Associates and Life Cycle Engineering (LCE) constructed this proof-of concept device to operate at the submarine level, similar to aircraft level for the Air Force. The THMS device included data collection, storage, health assessment, and a prognostic capability. This device utilized a Bayesian Belief Network as its prognostics engine. The contractors showed that this proof-of-concept is feasible and that it has the potential to increase the TAS operational availability and provide a cost savings.

Condition-Based Maintenance

There are numerous papers on condition-based maintenance (CBM). This section discusses a few related to Department of Defense issues. According to Nickerson and Nemarich (1990), CBM is motivated by the increasing complexity in Naval machinery and the decreases in the military budgets. The Navy, like the Air Force, utilizes a time-based repair process rather than evaluating the condition of the machine to determine if maintenance is necessary. CBM needs several items to operate. First of all monitoring systems, algorithms to turn data into system state information, and forecasting abilities to predict future states (Nickerson and Nemarich: 1990). According to Nickerson and Nemarich, Table 1 shows the potential benefits. They caution that all tools of the system must be in place to receive the benefits.

Table 1. CBM Benefits (Nickerson and Nemarich: 1990)

Reduce maintenance induced failures	50%
Reduce maintenance actions	35%
Increase Availability	20%
Reduce inspection and repair hours	20%
Reduce spare parts provisioning	20%
Reduce good parts removal	10%
Extend equipment life/overhaul cycle	10%

Several companies and universities have formed a consortium to examine ways to incorporate CBM. This consortium is called Machinery Information Management Open Systems Alliance (MIMOSA). The member organizations include Boeing, Caterpillar, MIMOSA, Newport News Shipbuilding, Oceana Sensor Technologies, Penn State ARL, Rockwell Automation and Rockwell Scientific. According to Mitchell (2002) the alliance has the “initial objectives of providing a common, open protocol for exchanging complex condition information.” The consortium is striving towards a JAVA® based eXtensible Markup Language (XML) viewer for the transfer of maintenance information over the Internet.

Other Simulation Projects

Several simulation research projects have been conducted in the area of sortie generation. It is appropriate to highlight those related to this research. These simulation projects come from academia, small disadvantaged businesses, larger companies and government. Two previous AFIT theses directly relate our research effort. These were the work of Capt Rene Rebulanan and Capt Mike Malley, both former Graduate Operations Research (GOR) students.

Rebulanan (2000) developed an ALS simulation model simulating the sortie generation process both with and without the ALS. The purpose of his research was to examine system performance and interaction of the ALS with the logistics chain (Rebulanan: 2000; 5). Rebulanan's model was written in the JAVA® program language using the SILK® software package and was called ALSim. Rebulanan concentrated on specifying the impact of the ALS on the sortie generation process. The main parts of the model included the Joint Distributed Information System (JDIS), PHM, and the logistics maintenance and supply chain (Rebulanan: 2000; 7). The main measures of effectiveness of this model were aircraft availability, number of sorties generated and time waiting for supply. The results showed that a statistically significant higher availability rate, and number of sorties generated could be obtainable with an ALS installed in the aircraft. However, the wait time was not significantly reduced when employing the ALS (Rebulanan: 2000: 56).

This research parallels Rebulanan's work establishing a more generic approach to ALS while expanding the functionality of the model components. In addition, this effort incorporates more input data from the REMIS system and other emerging historical databases to provide a closer match to the real sortie generation system.

Malley (2001) extended Rebulanan's research adding more definition to the PHM system in the ALSim model (Malley: 2001: 27). Since a true JSF PHM is still in development and data was not available for modeling purposes, Malley generated notional sensor signals used by the PHM. PHM performance was based on Artificial Neural Networks (ANN) trained to evaluate when a part was degrading past a pre-established point of performance and then to predict this point based on assigned failure thresholds. These failure thresholds could be modified to study the effects of the different levels. The study focused on the probabilities of false alarm and detection and their associated times (Malley, 2001: 28). Malley's research provided a detailed approach to model the JSF PHM and some associated issues that may be encountered.

Models of the sortie generation process have also been developed using Distributed Interactive Simulations. These are large-scale simulations, which typically involve players from several different units at locations spread across the world. They are usually run in real-time with no single simulation in control of the entire process (Miller: Class handouts, OPER671). These simulations are becoming increasingly important due to the fact that flying hours and war games are so expensive. These simulations are very detailed and complex, however they tend to leave out an important aspect of the simulation; the logistics of the operations. According to Banks and Styz (1997), the simulations set sortie generation rates too high and logistics operations beyond capabilities. Banks and Styz developed a tool called the Airbase Logistics System in AFIT's Virtual Environments Laboratory as a means of "accurately portraying airbase logistics." Since it was too expensive to build a tool from scratch, their approach used existing tools that were integrated to interface with current Distributed Interactive Simulations systems.

The government and its contractors have built other stand-alone simulation tools to model AF logistics such as SIMFORCE (2000), LogSam™ (2002), and LCOM (1990). The largest of these tools is the LCOM model developed by the RAND Corporation for the Air Force. LCOM has been in use since 1972 and has been validated against actual data including Desert Storm data. SIMFORCE and LogSam™ are relatively new software tools that were developed by Kelley Logistics Support Services, and Synergy Corporation respectively. SIMFORCE is written in Arena®. Below is more detail on each model.

LCOM

The Logistics Composite Model (LCOM) was adopted as the Air Force Standard for modeling logistics manpower requirements. LCOM is a large-scale computer simulation used to model manpower and other logistical requirements (XO website: 2002). It can handle large and small weapon systems and contains data preparation modules, a main simulation program, post processors, and models Air Force direct maintenance activities at the wing level. LCOM is used to evaluate weapons system logistic resource impact due to weapons system modification and is used for what-if analyses during weapon system acquisition (XO web site; 2002). The fundamental processes modeled are requirements for sortie demand, system reliability and maintainability, unscheduled and scheduled maintenance tasks, and ability to service demands (people, parts, equipment). LCOM measures of effectiveness include:

- Operations (e.g. sorties flown, missions cancelled);
- Activities (e.g. average time to complete, resource wait time);
- Personnel (e.g. man-hours utilized);

- Supply (e.g. number of spares backordered);
- Shop repair (e.g. number of items repaired);
- Equipment (e.g. equipment used); and
- Aircraft (e.g. number of aircraft available) (XO web site; 2002)

LCOM utilizes historical databases CAMS, and Reliability and Maintainability Information System (REMIS) along with the engineering data, Logistics Support Analysis (LSA), during it's processing. The model is written in SimScript II.5 and runs on an UNIX HP750 or personal computer. Various verification and validation audits include a favorable comparison to Desert Storm data (XO web site: 2002). "LCOM stochastically models the logistics (personnel, spare parts, test/repair equipment/facilities) required to support a weapon system operation under a given scenario" (XO web site: 2002). The process steps modeled are shown in Figure 4.

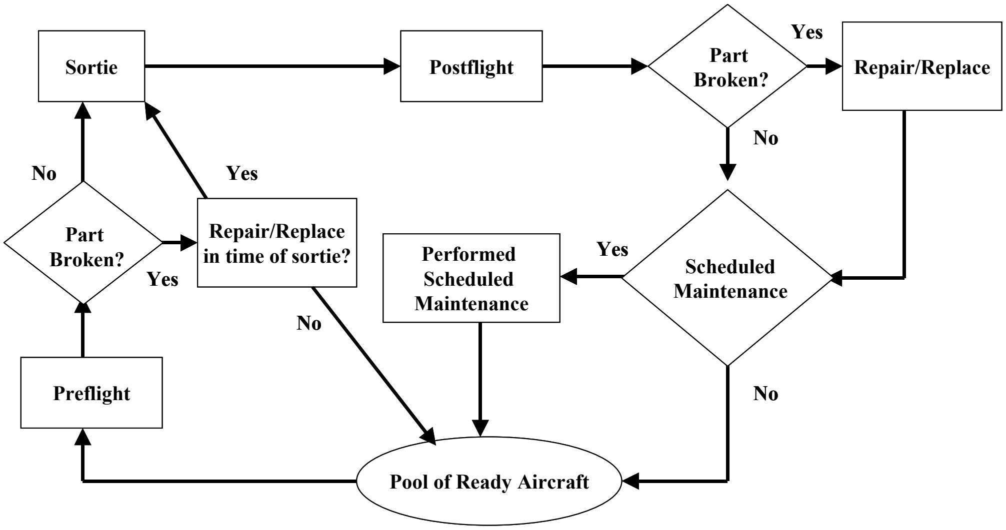


Figure 4. LCOM Sortie Generation Process

Figure 4 shows how the basic process flows, but not shown are some of the key details of the simulation. Stochastic random variables are used to determine first if a part is broken, then also if a replacement part is available for installation, and are the personnel and equipment available to repair the aircraft.

The next section highlights a desktop simulation tool built by a small disadvantaged business. This model simulated the sortie generation process but their approach was more focused on usability by the maintenance leadership. These maintenance managers can use Scalable Integration Model for Objective Resource Capability Evaluations (SIMFORCE) at their desktop and do not require a long set-up time to get results.

SIMFORCE

The Scalable Integration Model for Objective Resource Capability Evaluations (SIMFORCE) was built by Kelley Logistics Support Services and is written in the Arena® software language. SIMFORCE simulates the wing level logistics activities to include the manpower, equipment, and facilities constraints. It was built to allow decision makers to formulate what-if problems and analyze maintenance manpower utilization rates. For example, a decision maker can determine how many crew chiefs would be required if a certain sortie generation rate was desired. The inputs and outputs are devised and analyzed in Excel® (Brown and Powers: 2000). Although LCOM and SIMFORCE simulate the same process their intended users differ. LCOM provides the Air Force leadership with manpower estimates for new weapons systems or revised estimates for proposed changes. SIMFORCE provides wing level maintenance mangers a decision support tool for conducting what-if problems, for example, “How is next week’s deployment going to affect their ability to conduct operations?”

LogSAM™

The Logistics Simulation and Analysis Model (LogSAM™) is built by Synergy Inc. LogSAM™ also simulates the aircraft sortie generation process. The model is broken down into several modules, aircraft generation, sortie generation, preflight and launch, and post flight evaluation (Smiley: 1997). Added features include its ability to schedule sorties based on the Air Tasking Orders (ATO). These ATOs describe what targets to attack along with numbers and types of aircraft to use (DTIC web site: 2002). Synergy has also expanded LogSAM™ to include a module called LogBase™. LogBase™ simulates enemy attacks and the effect those attacks have on sortie generation capability (Synergy web site: 2002). The other models discussed can simulate combat conditions (increase sortie activity) however, it seems that LogSAM™ has the unique feature of simulating attacks from the enemy.

The three models discussed above all have a certain unique purpose. LCOM is a large government operated simulation tool that provides excellent manpower prediction. SIMFORCE is a desktop/web enabled tool allowing the maintenance manager to formulate and run what if scenarios. LogSam™ is another desktop tool that not only conducts sortie generation simulations but allows war-time losses to be simulated. They all simulate the sortie generation process, however, they simulate today's flying conditions and not the future possibilities that will exist. This research will attempt to investigate these evolving technologies and their impact on the aircraft sortie generation process.

Conclusion

The basic sortie generation process has remained constant over the past few years. An aircraft flies a sortie, lands, is parked and recovered, is serviced, the aircrew debriefs the maintenance personnel, the aircraft is checked for failures, if none exist, it is scheduled and then prepped for the next mission, taxis out and takes off for another sortie. This cyclical process is repeated according to the daily flying schedule or until either a failure occurs or phase maintenance is required. If a failure occurs the aircraft is sent to unscheduled maintenance and several other actions are conducted to repair the aircraft is the most expedite manner.

As the literature search indicates several simulation tools have been developed to investigate the process, as it exists today. However, several new concepts are emerging to make the process more efficient to save limited maintenance resources. The ALS concept is one of these concepts that are being investigated. The literature search indicates a gap in tools to simulate the sortie generation process along with the affect of ALS on this process. This research builds a simulation tool to address ALS affects on the sortie generation process.

III. Methodology

Introduction

This chapter describes the Autonomic Logistics Systems sortie generation simulation model built for this research effort. The following sections contain the key model assumptions, the model definition, and the results of the input analysis that was conducted on three data sets. The model was built to represent the aircraft sortie generation process defined in Figure 1 from Chapter 1. A few differences from Figure 1 exist due to the nature of not being able to model the real world exactly and certain instances where changes were necessary.

Assumptions

Several assumptions were made during the model building process, these are broken down into model scope, key distinctions from the real process, and output differences from the real process.

This model simulates the F-16 aircraft sortie generation operations but is scoped to only cover in detail the four LRUs that make-up the AN/APG-68 radar. The other subsystems are modeled to experience failures at preflight inspection, where they fail per a percentage of scheduled sorties. When these other systems fail, troubleshooting, testing, and documentation maintenance tasks are carried out that are discussed in later sections but no parts are removed or replaced nor supply ordered. The entire supply system is not modeled either, the delivery of parts from the depot to the flight line are simulated via delays and transfer of simulated parts. The manpower resources are built to simulate the various logistics specialties such as crewchiefs, various maintenance specialists, refuelers, weapon specialists, etc. but their entire day is not fully modeled. For ease in modeling, these manpower resources are available 24 hours a day so that they can be seized by the aircraft wherever required. This means that these resources have low utilization since they are not required for work while the aircraft is flying or when it is waiting for the next day's scheduled takeoff. The model was run with eight refuelers, eight weapons specialist, sixteen crewchiefs, sixteen maintenance specialists for debriefing, and sixteen phase inspection resources available to service the aircraft. There were four maintenance specialists available to repair the aircraft. These numbers are not typical base manning levels, but provide a reasonable pool of resources since the focus of this effort was to measure the ability to produce sorties and increase aircraft availability with the ALS system not to consider the impact of manpower usage. Other sortie generation models discussed in Chapter 2 can perform these kinds of studies.

The next few assumptions are where the model does not replicate the real process. First, the Can not Duplicate (CND) and Retest Okay (RTOK) events were not accounted for in the model. These happen on the flight line or at the test bench when a reported failure cannot be repeated or the bench testing shows no faults to be repaired respectively. However, the false alarms of the ALS PHM were modeled so that the analysis could include these actions. A false alarm is where the PHM system indicates a failure but one really does not exist. These false alarms mimic CND and RTOKs since these are not true LRU failures. Also as will be discussed later, the worst case impact is assumed for false alarms with part removal and replacement simulated for every occurrence. If an aircraft is sent to unscheduled maintenance from a preflight failure, only troubleshooting, operational checkout, and documentation are conducted. If an aircraft is flagged for a LRU failure then a part is removed and replaced every time. The diagnostics gives a 100% accuracy, which is not realistic in the real world, however, again the goal of this research was to compare ALS performance to current day operations. Partial mission capable rates are not calculated since there is only the one system being simulated. The aircraft only has three maintenance states, preflight failure, radar failure, or phase maintenance.

The next assumptions note how the output differs from the real world. Possessed aircraft hours equals the total simulation time. This is true since no aircraft leave flying status (they do not get deployed or sent to the depot). The Mission Capable rate is calculated by subtracting the Not Mission Capable rates for Supply and Maintenance. We are only explicitly modeling a single aircraft system (radar system) and how the failures of this system, with or without ALS, affect our selected MOEs. Therefore, resource levels and other model parameters were selected to obtain a reasonable (approximately 80%) overall Mission Capable rate for our baseline model.

The model does not specifically account for the time for not mission capable for both supply and maintenance. The aircraft is either waiting on supply or it is being maintained (maintenance personnel always available with modeled resource levels). The simulation is modeled to simulate 24 hours a day operations five days a week. Typically each resource only works about 8 hours a day. The weekends are not simulated even though they may be used in the real world to repair aircraft.

F-16 AN/APG-68 Radar

"The AN/APG-68 is an X-band, all weather, multimode Fire Control Radar (FCR) featuring extensive Air-to-Air (A/A) and Air-to-Ground (A/G) capabilities" (Castrigno, 2002; 20). It consists of four LRUs; the antenna, the modular low power radio frequency, the dual mode transmitter, and the advanced programmable signal processor (Castrigno, 2002; 54). These LRUs are abbreviated ANT, MLPRF, DMT, and APSP respectively in the model. A portion of the data for this research was obtained from the Reliability and Maintainability Information System (REMIS) database maintained by Air Force Material Command. It was complied over a two-year period examining F-16 failures at Hill AFB, UT. The details of how this data was analyzed are found in the input analysis section.

Input Data Analysis

The input data was drawn from several sources. The following explains how the data were transformed for use in the simulation model. The first data set was used to determine the sortie duration. This data came from the Data Transfer Cartridge (DTC) of the aircraft located at Hill AFB, UT. The DTC data was from a three-month period during the summer of 2002. Hill AFB takes care of transferring the data to a Microsoft Access database. From there the data was transferred to Microsoft Excel® spreadsheets for transforming the time recording into raw data. Next, the data was put through the Arena® Input Analyzer to determine an appropriate distribution for modeling the process. Evaluating the mean square error of the curve fit between the empirical data and the selected theoretical distributions, the normal distribution looked most reasonable. Also, after plotting the data, it seemed to closely match the normal distribution.

Another data set from Hill AFB contained the sortie rates, MC, and TNMCM rates by tail number for the 388th Fighter Wing. This data spanned the year 2001. This data was used mostly to double-check the output of the simulation.

The third data set was 18 months of REMIS data used to determine the LRU MBTF. A better name may be mean time between LRU replacement, because the analysis did not include reviewing bench level and depot level testing to determine if this LRU was a CND or RTOK unit. The analysis that was done included scaling the REMIS database down to just the tail numbers from Hill AFB and then further cutting the database back to only the tail numbers for the 4th Fighter Group. This provided enough data for analysis to determine the mean time between replacement. Lining up the operating times and looking at the difference of operating time between LRU replacement, and then averaging these numbers across the twenty tail numbers, the mean time between replacement was calculated. Table 4 shows notional MBTF numbers. The database did not include LRU failures for ASPS for that timeframe so twenty other tail numbers were selected from the larger database to calculate the mean time between replacement.

Model Introduction

The first items to be described are the different views of functional areas setup in the model. Taking advantage of the named views in Arena®, several of these views were established for ease in navigation. Table 2 shows these functional areas and provides the associated hot key used to recall that view. This will also be the template for the following paragraphs that describe the individual areas of the sortie generation model. The model is setup with Arena's® stations and routings so that white space exists between the different areas that were simulated. These station and routing modules move the aircraft entities between the appropriate areas. This white space also was done to make the model easier to understand and made changes easier as the model evolved. Another benefit of the station and routing concept was that both the baseline sortie generation and ALS function exist in one model. The setting of one variable on the graphical user interface defines whether the ALS is on or off.

Table 2. Model Views

View	Hot Key
Animation	(a)
Create	(c)
Mission Preparation	(m)
Preflight Inspection	(p)
Aircraft Launch	(t)
Flying	(f)
Landing	(l)
Parking and Recovery	(r)
Servicing and Debrief	(s)
Failure Checking	(d)
Preventative Maintenance	(v)
Hold	(h)
Unscheduled Maintenance	(u)
Supply	(y)
PHM	(z)

This model is a collection of process delays, decision modules, and routing stations setup to simulate the baseline sortie generation process or the ALS process depending on what output is desired by the user. The majority of process delay times are from several subject matters experts interviewed during the course of the model building and a RAND study on sortie generation (2002: 3). Table 3 shows these processes, associated times, and cumulative time.

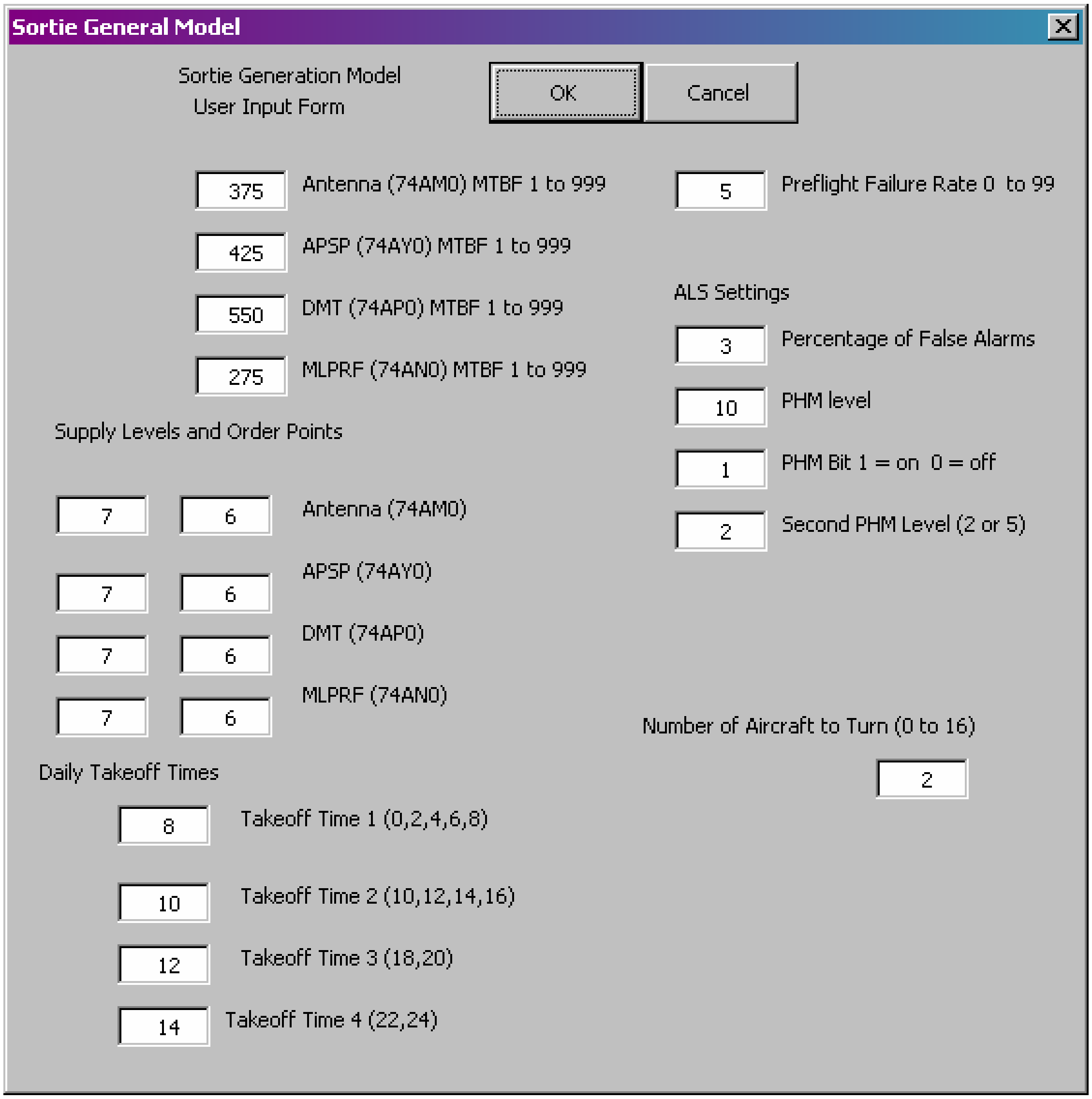
Table 3. Model Process Times

Area	Mean Process Times (min)	Cumulative Mean Times (min)	Turn Around Times (min)	Turn Around Cumulative Mean Times (min)
Mission Preparation Refuel	10	10	5	5
Mission Preparation Re-arm	30	40	15	20
Preflight	60	100	10	30
Engine start, Final system checks, Taxi, & Arm	10	110	10	40
Takeoff	3	113	3	43
Fly	61	174	61	104
Land and Taxi	15	189	15	119
Park & Recovery	7	196	7	126
Servicing	60	256	60	186
Debrief	15	271	15	201

Preventative and Unscheduled maintenance and supply times are not included in the table since not every aircraft goes through those processes every flight. These times are described in their associated paragraphs below.

Graphical User Interface

The model is built with a graphical user interface (GUI) to allow the user to change any of the twenty-two different parameters prior to each replication. A picture of the GUI is shown in Figure 5. Table 4 includes the list of variables and attributes that can be changed and a brief description of each. These values are the baseline starting points for each of the variables. The false alarm and PHM Level 1 variables will be changed from run to run to make comparisons from the existing sortie generation operations to one with an ALS.



Sortie Generation Model
User Input Form

375 Antenna (74AM0) MTBF 1 to 999
425 APSP (74AY0) MTBF 1 to 999
550 DMT (74AP0) MTBF 1 to 999
275 MLPRF (74AN0) MTBF 1 to 999

5 Preflight Failure Rate 0 to 99

ALS Settings
3 Percentage of False Alarms
10 PHM level
1 PHM Bit 1 = on 0 = off
2 Second PHM Level (2 or 5)

Supply Levels and Order Points
7 6 Antenna (74AM0)
7 6 APSP (74AY0)
7 6 DMT (74AP0)
7 6 MLPRF (74AN0)

Number of Aircraft to Turn (0 to 16)
2

Daily Takeoff Times
8 Takeoff Time 1 (0,2,4,6,8)
10 Takeoff Time 2 (10,12,14,16)
12 Takeoff Time 3 (18,20)
14 Takeoff Time 4 (22,24)

Figure 5. Graphical User Interface

Table 4. GUI Variable Description

Variable	Description	Initial Value	Units
attANTfail	Time until failure of the ANT LRU	375	hours
attAPSPfail	Time until failure of the APSP LRU	425	hours
attDMTfail	Time until failure of the DMT LRU	550	hours
attMLPRFfail	Time until failure of the MLPRF LRU	275	hours
varSupplyLevelANT	Initial supply of ANT LRUs	7	N/A
varSupplyLevelAPSP	Initial supply of APSP LRUs	7	N/A
varSupplyLevelDMT	Initial supply of DMT LRUs	7	N/A
varSupplyLevelMLPRF	Initial supply of MLPRF LRUs	7	N/A
varOrderLevelANT	Order level for the ANT LRU	6	N/A
varOrderLevelAPSP	Order level for the APSP LRU	6	N/A
varOrderLevelDMT	Order level for the DMT LRU	6	N/A
varOrderLevelMLPRF	Order level for the MLPRF LRU	6	N/A
varTakeoff1	Takeoff time for the 1st group of 4 A/C	0800	hours
varTakeoff2	Takeoff time for the 2nd group of 4 A/C	1000	hours
varTakeoff3	Takeoff time for the 3rd group of 4 A/C	1200	hours
varTakeoff4	Takeoff time for the 4th group of 4 A/C	1400	hours
varPreflightFail	A/C that will fail the preflight inspection	5	percent
varFalseAlarm	A/C that will experience a false alarm	3	percent
PHMLevel	Level for aircraft to receive maintenance	10	hours
PHMBit	Determines if PHM if on or off (0 = off / 1 = on)	1	N/A
varSecondPHMLevel	Level for aircraft to wait for maintenance and return to taxi or flying	2	hours
NumTurn	Number of A/C to perform a turn around flight	2	N/A

Animation

The animation area contains resource modules, queues, stations, and routing lines that are used to display the aircraft and supply entities and the paths that they move on throughout the simulation. Also, plots are generated for the status of key output parameters. Figures 6 and 7 show these areas.

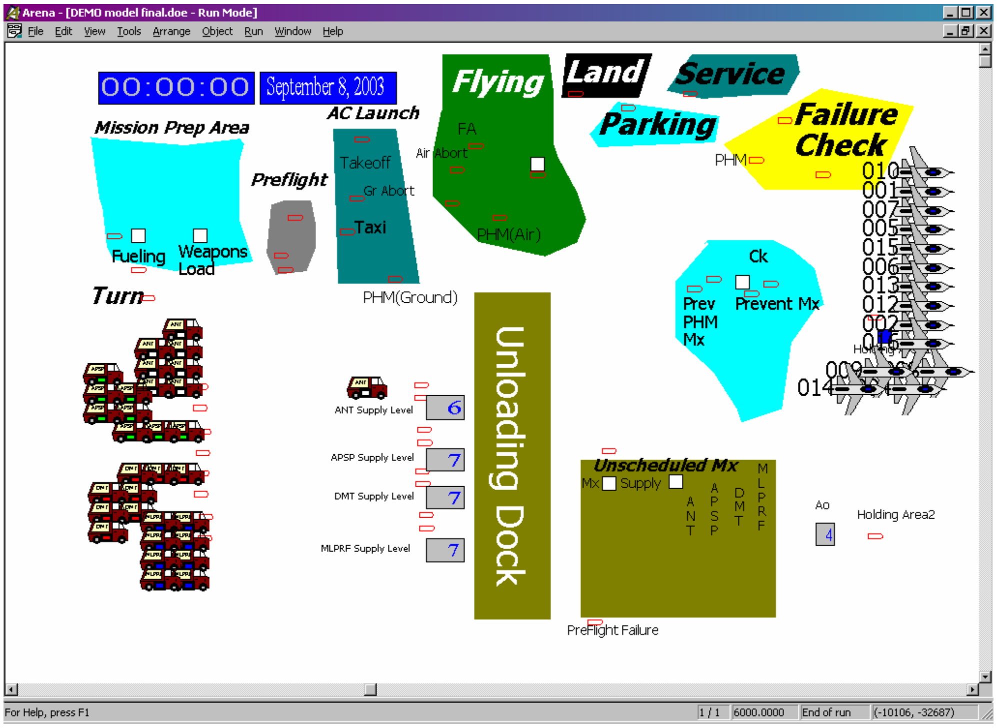


Figure 6. Animation Area

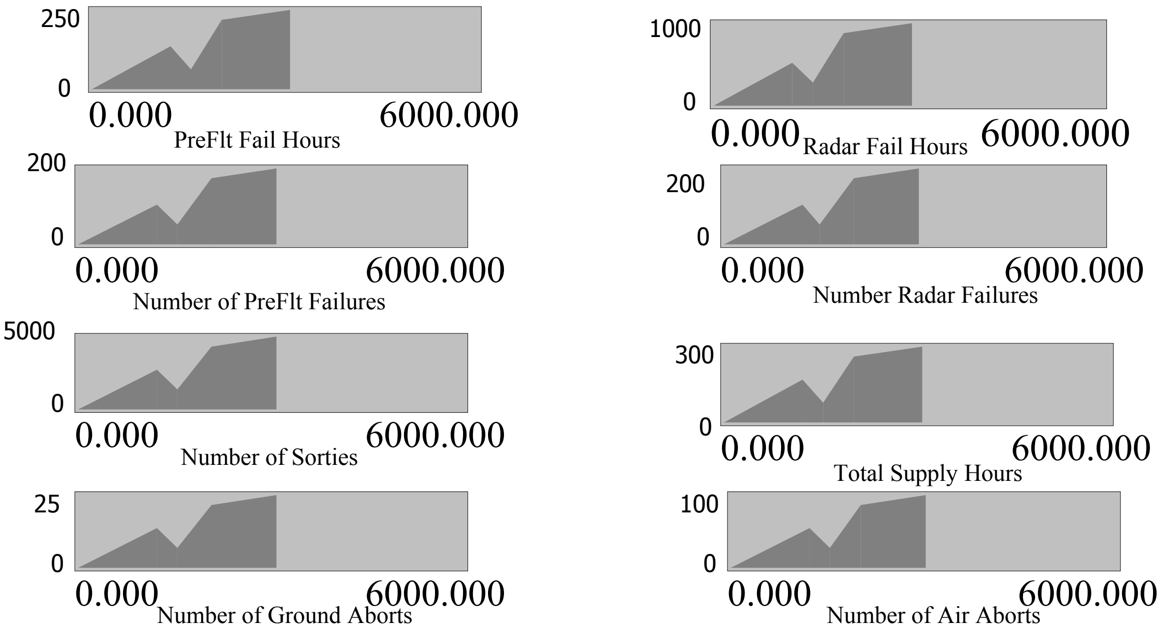
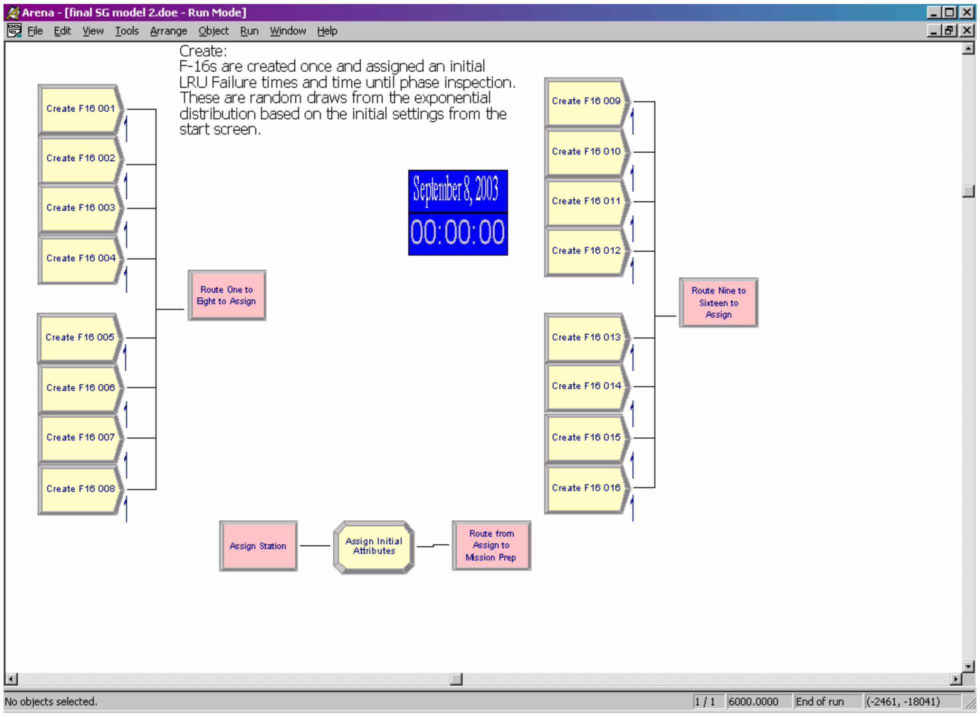


Figure 7. Dynamic Plots

Some of the set-up was modeled after Arena® examples and a paper from the literature search that showed how forming zones made the animation better (Raivio et al: 2001). The animation was also very helpful in program debugging. Monitoring how the aircraft and supply entities progress through the system helped to make sure that they are moving according to their intended flow.

Create

The sixteen aircraft entities are created in the model at the start of each replication. Figure 8 shows a view of this area.



Create:
F-16s are created once and assigned an initial LRU Failure times and time until phase inspection. These are random draws from the exponential distribution based on the initial settings from the start screen.

Figure 8. Aircraft Create Area

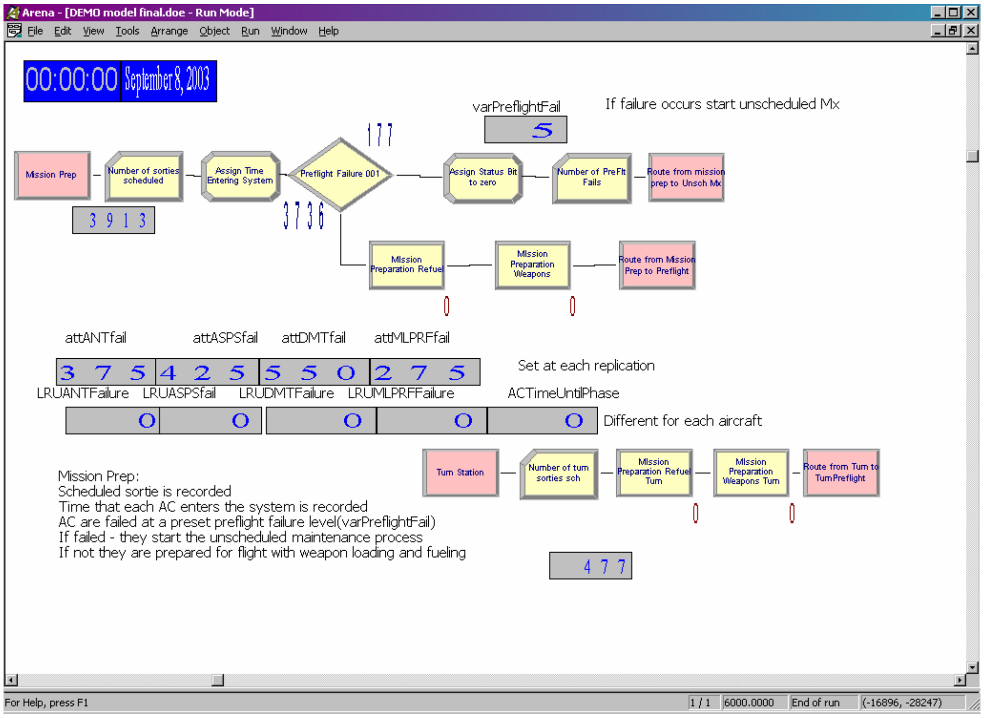
These aircraft entities enter into the sortie generation cycle shown in Figure 1. These entities are created once and never leave the simulation. However, the entities are not running continuously in the model, they are held at the end of a simulated day, waiting for the next takeoff cycle to begin. The takeoff times are set by the user at the beginning of the replication and remain constant through the replication. The default times are 0800, 1000, 1200, and 1400. The aircraft are released into the next day's cycles four at a time. If an aircraft goes into the prevent maintenance process or is held in unscheduled maintenance longer than a day, that aircraft would return to the hold area after completion of these tasks and then wait for the next scheduled takeoff time. This process will be explained further in the Hold section.

Before leaving this area, the aircraft are assigned an initial time until failure for the four simulated F-16 radar LRUs and time since last phase inspection. The LRU failure time is a random draw from the exponential distribution with the mean set at the beginning of the replication. These failure times are based on the input analysis of the REMIS data. The user does have the option to change these numbers on the GUI screen. These times are setup like a countdown until failure time. Once the simulation detects a failure, described in a later paragraph, then part of the simulated repair process is to make a new random draw from the exponential distribution with the same mean time from the beginning of the replication.

The random draw for time since last phase inspection is set up similar to the draw for failure except in the model when an aircraft accumulates flying time, this time is added to the time since last phase inspection that was drawn. This random draw from the uniform UNIF(0,300) distribution gives an aircraft an initial time since last phase inspection so that all the aircraft are not entering phase maintenance at the same time. Also different from the failure time, once each aircraft has reached 300 hours the phase inspection is started. Then once completed, their time since last phase inspection is reset to zero. The aircraft entities leave the create area and are routed to the mission preparation area with the routing time set to zero.

Mission Preparation

The literature states that the real world sortie generation cycle starts with the landing of the aircraft. However, it was more convenient to start the simulation with the mission preparation area. As stated above, the flying schedule is a users choice, the default is starting mission preparation at 0800, 1000, 1200, and 1400.



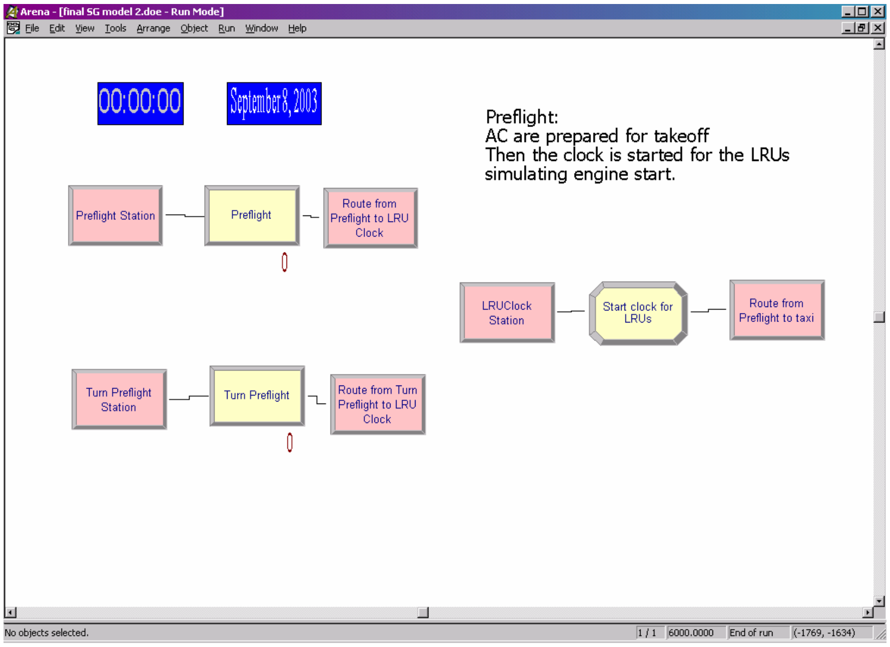
Mission Prep:
Scheduled sortie is recorded
Time that each AC enters the system is recorded
AC are failed at a preset preflight failure level(varPreflightFail)
If failed - they start the unscheduled maintenance process
If not they are prepared for flight with weapon loading and fueling

Figure 9. Mission Preparation Area

Figure 9 shows the modules and flow of the mission preparation area. Since there is no time change in the movement from the previously described create area or from the hold area described later, these are the times the mission preparation will start for the aircraft. Each entering aircraft passes through a record module to record a sortie being scheduled, next it is assigned a starting time of TNOW, which is the current simulation time in Arena®. This is the global time of the simulation and is used various places to facilitate calculation of failure times and process times for further output analysis. A decision module determines if an aircraft system other than the radar has failed. This check is a simple decision based on certain percentage of preflight failures that is set at the start of the simulation. This check is done before the fueling and weapons loading process modules since an aircraft would checked for failure before refueling. If an aircraft is selected to have a preflight failure it has an attribute called Status Bit that is set to zero so later decision modules know where the entity came from. After the assign module the aircraft passes through a record module to note that a preflight failure has occurred and then it is routed to the preflight station of unscheduled maintenance. The unscheduled maintenance will be described in a later paragraph. If the aircraft passes the inspection then it enters the refueling and weapon loadings modules. These are separate process modules that seize the resource refueler and weapon loader and delay the aircraft for a triangle distribution of TRI(8,10,12) and TRI(25, 30, 35) minutes respectively. The capacity of each resource is eight, simulated for the 24 hour day. The model has the ability to move a certain number of aircraft back to mission preparation if they are being simulated to be an integrated combat turn. This means an aircraft lands and parks and immediately returns to the mission preparation area. Similar steps are conducted with process modules for the turn around area except these times are adjusted. These times are TRI(4, 5, 6) and TRI(10, 15, 20) for refueling and weapons loading. These times are adjusted since it should not require the same length of time for a turn around mission. The total preparation time before the first scheduled takeoff, which includes mission preparation, preflight, taxi and takeoff, is about 2.5 hours. Next the aircraft are routed to the preflight area.

Preflight Inspection

The simulated aircraft have been refueled and weapons loaded and are ready for the preflight inspection by the crewchief. Figure 10 shows how this process is split into two based on if an aircraft is performing a turn around flight.



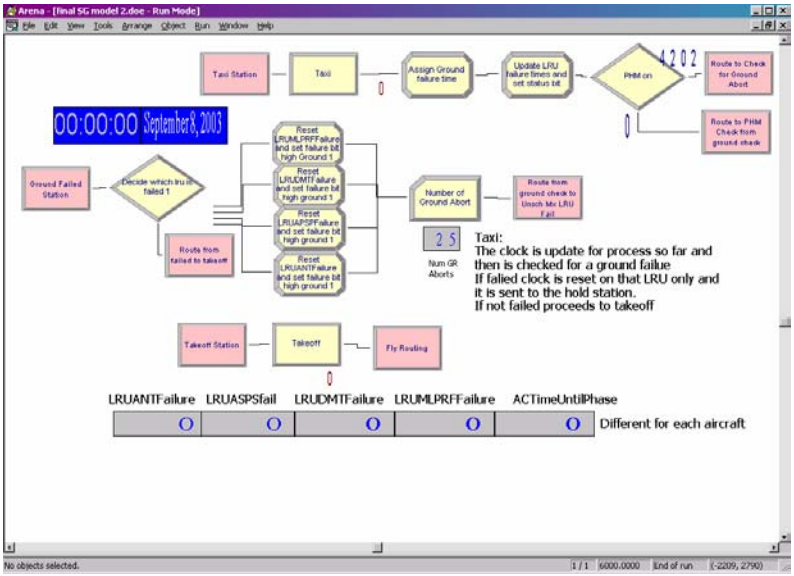
Preflight:
AC are prepared for takeoff
Then the clock is started for the LRUs
simulating engine start.

Figure 10. Preflight Area

Once the aircraft have arrived to the preflight station they travel through a process module where they seize a crewchief and are delayed via a random draw from the triangle distribution TRI(50, 60, 70). If being routed from the turn mission preparation area, they are only delayed TRI(5, 10, 15). After they are finished with that process the clock is started on the LRUs. This is done by setting the LRU failure start time attributes for each aircraft equal to TNOW. Later in the simulation these attributes are compared to the current TNOW and that difference is used to compute the time that a LRU was operating. This process decreases the time before failure for the LRU and eventually will trigger a failure. The aircraft have completed refueling, weapon loading and preflight and they are now ready for taxi and takeoff.

Aircraft Launch

Since the aircraft have been prepped for flight, they are ready for engine start, final system check, and taxi. Figure 11 shows the aircraft launch area.



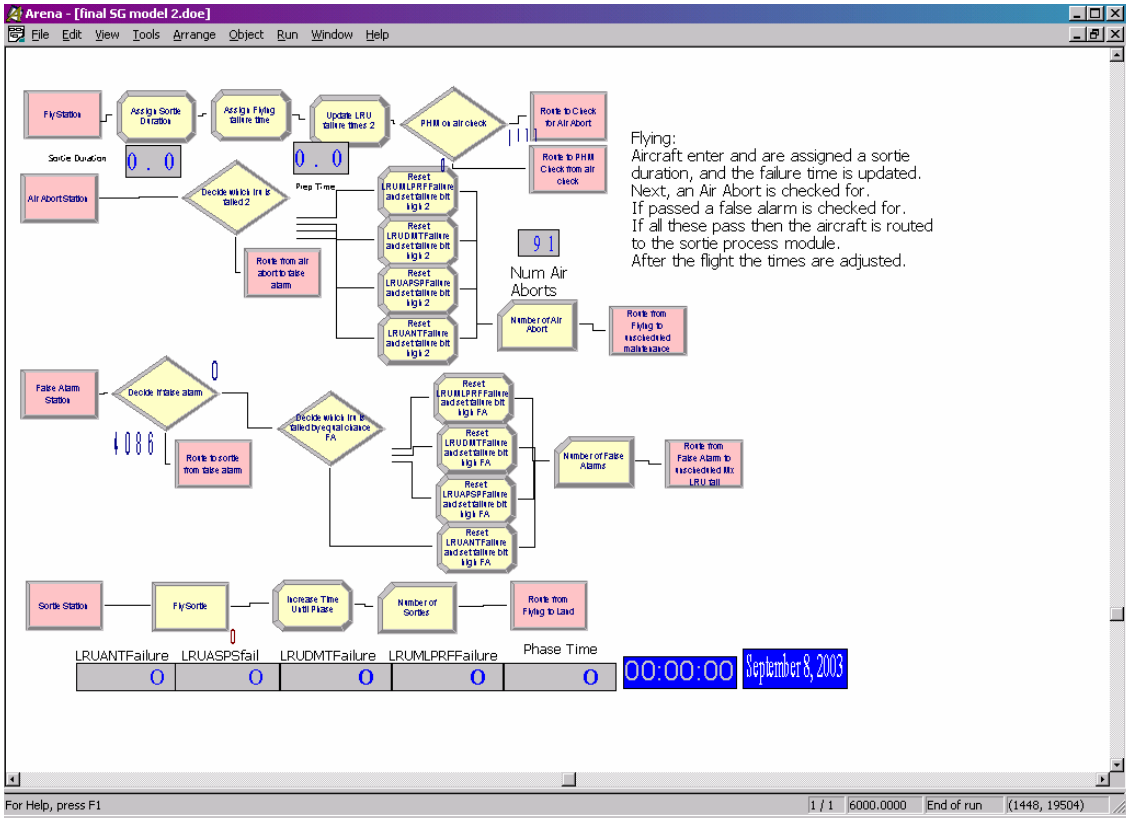
Taxi:
The clock is update for process so far and
then is checked for a ground failue
If falied clock is reset on that LRU only and
it is sent to the hold station.
If not failed proceeds to takeoff

Figure 11. Aircraft Launch Area

The aircraft enters a process module where it seizes a taxiway and simulates engine start, final systems check, and taxiing to the runway. There are four taxiways resources available. The aircraft are delayed according to the triangle distribution, TRI(7, 10,12). Next the LRU failure times are updated for each aircraft, this is for failure checking in this area. Then the aircraft enter a decide area to determine if they are to be routed for PHM checking. The PHM checking happens at four areas and it will be described in later sections. If the PHM is off, then the aircraft entities are routed to the first failure checking area. Three of these checking areas exist and the only difference between these areas is the counting for ground or air aborts and entity routing. The failure checking compares all the LRU failures times against what level is set, usually zero. If all failure levels are greater than zero then the entity is routed to the takeoff area. If a failure is detected then the entity is moved through an assign area that corresponds to the LRU that is indicating failure. Its LRU failure time is redrawn from the exponential distribution with the same mean as before. Also in this assign area, an attribute is attached that indicates which LRU failed. This attribute will be used for routing later in the unscheduled maintenance area. Next, a record module records the ground abort. Then the aircraft is routed to the unscheduled maintenance area. If no failure exists, the aircraft is routed to a process module that simulates the takeoff. The aircraft grabs the only runway, if available, and then is delayed by the triangle distribution, TRI(2, 3, 4). There is only one runway simulated so the other aircraft must wait for the aircraft to takeoff or land if it is already being used. After the process delay the aircraft is routed to flying.

Flying

The aircraft has now been prepped, has taxied and taken off. Several checks and assignments are made in this area, these are shown in Figure 12.



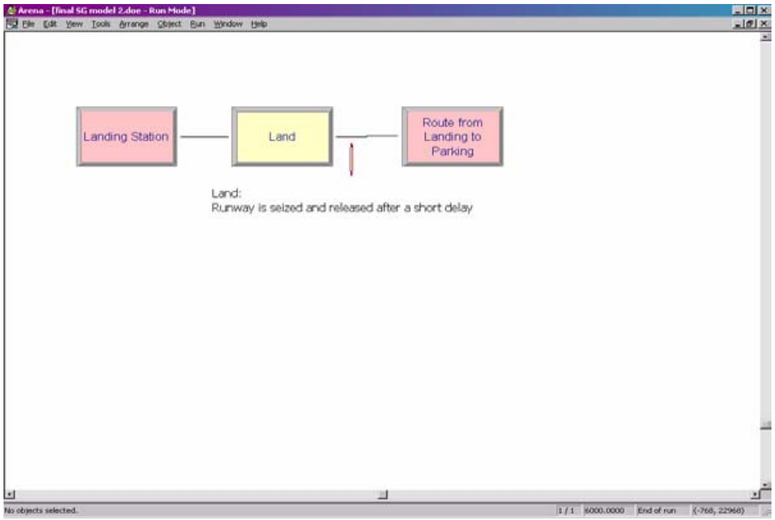
Flying:
Aircraft enter and are assigned a sortie duration, and the failure time is updated.
Next, an Air Abort is checked for.
If passed a false alarm is checked for.
If all these pass then the aircraft is routed to the sortie process module.
After the flight the times are adjusted.

Figure 12. Flying Area

After entering from the taxi and takeoff area, an assign area makes a random draw from the normal distribution with mean 2 hours and standard deviation of 0.5 hours. These are also notional numbers. If the draw is less than 15 minutes then the sortie duration is set at 15 minutes. The sortie duration was built from Hill AFB, UT input data described above. Also, like the previous area, the failure time is decreased according to how long they have been operating. Once these assignments are complete then the aircraft goes through a decision module to determine if the PHM is turned on. If PHM is being simulated the aircraft is routed to the PHM failure check area described later. If the PHM is off, the aircraft is routed to check for an air abort. Since the sortie duration is assigned a priori, a check can be made for an air abort. The check is made to see if any of the LRU's remaining life is less than the assigned sortie duration. If less than sortie duration, then a new failure time is drawn, an air abort is counted, and the aircraft is routed to the unscheduled maintenance area. If it passes this check, then it is routed to the false alarm check station. The false alarm check is similar to the air abort and ground abort check except the percentage of false alarms are set by the user at the GUI and they are only used when the PHM is on. A decision module is set-up so that equal chance exists for each LRU failure. If a false alarm occurs it is counted and the aircraft is routed to unscheduled maintenance. Otherwise, the aircraft is routed to the flying process module where a flying resource is seized and delayed for the sortie duration. Sixteen resources are available for flying since it did not make sense in this model to restrict the number of pilots. After the sortie process, the time since last phase inspection is increased by the sortie duration and the number of hours flown is increased by that same number. Next, a sortie is recorded to be compared to the number of scheduled sorties for the flying efficiency calculation. Then the aircraft are routed to the landing area.

Landing

Once the aircraft is routed to the landing area, it enters a process module where the runway is seized, if available, and delayed according to the triangle distribution, TRI(14, 15, 16). Figure 13 shows the station and routing and one process module for this area.



Land:
Runway is seized and released after a short delay

No objects selected.

1 / 1 6000.0000 End of run (-768, 22968)

Figure 13. Landing Area

As noted above there exists only one runway resource, so a landing aircraft must wait if another entity has already seized the runway. After landing processing, the aircraft is routed to the parking and recovery area.

Parking and Recovery

The parking and recovery area has two main functions happening concurrently, these are shown in Figure 14.

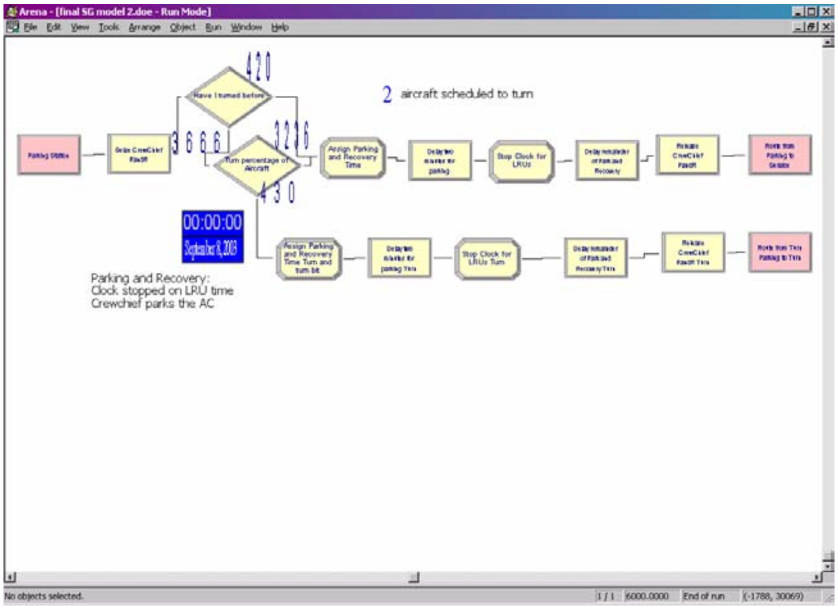


Figure 14. Parking and Recovery Area

First the crewchief resource is seized and held while the aircraft is moved through this entire mode. Next, the aircraft is checked to see if it already has been chosen for a turn around that day. If so, it is sent along a path that will eventually take it to the hold area. If not, the aircraft proceeds to another decision module to see if it will be turned around for another consecutive flight. This decision module makes it determination on how many to turn around based on the preset number by the user. This is modeled this way to insure the same aircraft is not repeatedly turned around. This sets up two identical paths that the aircraft can take and they have similar modules so only one will be defined here. The aircraft enters an assign module to have the parking and recovery time determined. This time is a random draw from the triangle distribution TRI(5, 7, 9). Two minutes is subtracted from this time but will be accounted for in the next module. This is done to allow two minutes for aircraft parking and then the clock is stopped on the LRUs, simulating engine shutdown. The remainder of the parking and recovery time is processed, the crewchief is released and then the aircraft proceeds to service and debrief or mission preparation if the aircraft is being turned around for another flight.

Service and Debrief

Once the aircraft has entered the service and debrief area it is assigned service and debrief times via an assign module. These times are from the triangle distribution, TRI(45, 60, 75) for service and TRI(10,15,20) for debrief. These nodes are set-up to run concurrently, whichever time is greater is processed first and then the remainder of the time is processed in the second delay. Figure 15 shows the split for the larger process time.

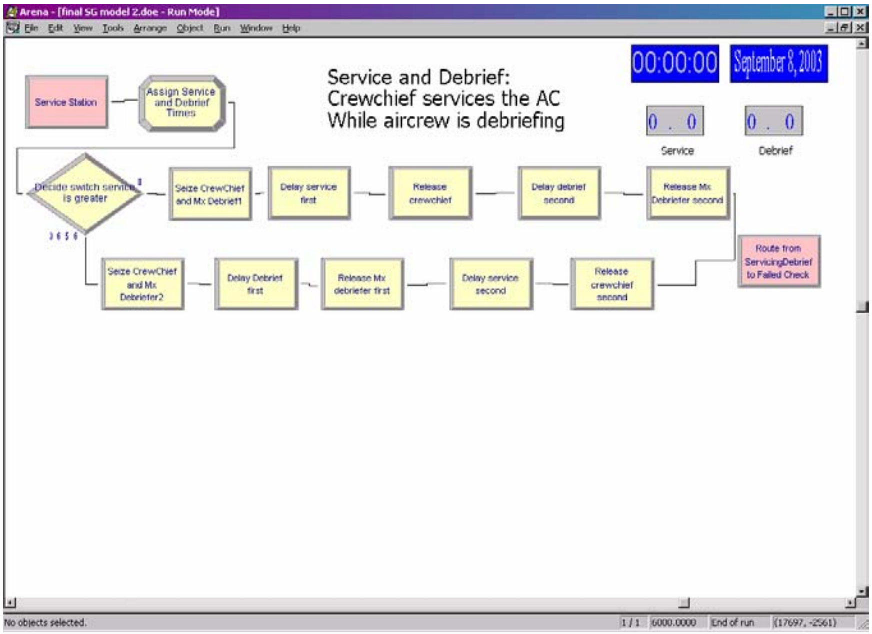
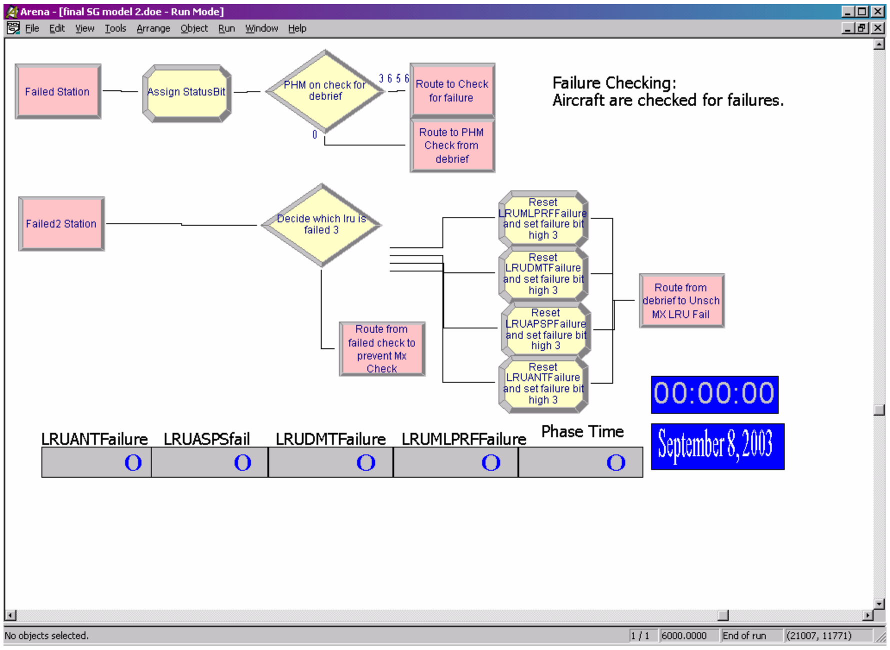


Figure 15. Service and Debrief Area

The current process times do not require the next decision area since the maximum debrief time is less than the minimum service time, but the logic is included in case there was a change to the times. This decision area sends the aircraft to the path that has the largest process time. Depending on which time is larger either the crewchief or maintenance debriefer is seized first. Once the process is complete for either the service or debrief, that resource is released and the other resource is seized. After the second process is complete the second resource is released and then the aircraft is routed to the failure check station.

Failure Checking

In this area the aircraft is checked for any LRU failures, or like the other checks any LRU failure times less than the preset level. Figure 16 shows a view of this area.



Failure Checking:
Aircraft are checked for failures.

LRUANTFailure	LRUASPSfail	LRUDMTFailure	LRUMLPRFFailure	Phase Time
0	0	0	0	0

No objects selected. 1 / 1 6000.0000 End of run (21007, 11771)

Figure 16. Failure Checking Area

After the aircraft enters the area, an assign module assigns the Status Bit to three and then the aircraft is routed through a decision area to see if PHM is on. If this is a PHM run, then the aircraft is routed to the PHM area and does not return. If PHM is not on, the aircraft is routed to the decision module to see if any LRUs are below the preset failure level, again usually zero. If no failure is present then the aircraft is routed to be checked for phase maintenance being required. If a failure exists the failure time is redrawn from the exponential distribution and the aircraft is routed to unscheduled maintenance.

Preventative Maintenance

After debrief or unscheduled maintenance the aircraft are routed to preventative maintenance. Figure 17 shows a view of this area.

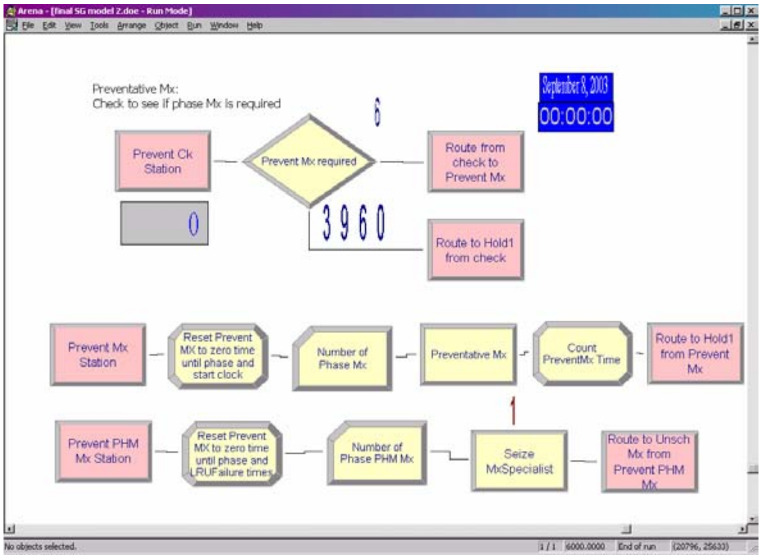


Figure 17. Preventative Maintenance Area

The first thing that happens is a check to see if enough flight time has accumulated to require phase maintenance. This phase is done based on a set number of flight hours, for the F-16 that equals 300 hours. In the Flying area the individual aircraft accumulate flying hours based on sortie duration. The starting point is determined by a random draw from the uniform distribution UNIF(0,300). This gives every aircraft a different time that it will enter phase and then return to phase. This is helpful since phase maintenance is scheduled to last from 5 to 8 days based on a random draw from a triangle distribution. The aircraft are then reset to zero phase time so again different spacing is maintained. After the check to see if enough time has accumulated, the aircraft are either routed to the hold area or to the phase maintenance area. In the phase maintenance area, the aircraft attributes are changed to reflect phase having been conducted, a record area updates the number of aircraft that have been through phase, eight maintenance specialist are seized and delayed with the aircraft for the time specified above, and then once released the time in phase is recorded. The aircraft are routed to the hold area where they will reenter the model based on the predetermined start times. Under the PHM scenario similar activities take place but the opportunity for unscheduled maintenance is available. If the aircraft enters the PHM checking area with an LRU almost ready to fail and phase maintenance within the PHM Level of hours until phase maintenance, then the aircraft is routed to the Prevent PHM Mx Station. At this series of modules, the aircraft seizes the maintenance specialists and starts phase maintenance but then simultaneously the aircraft is routed to unscheduled maintenance to repair the LRU. After returning from unscheduled maintenance, the aircraft phase maintenance is completed and then the aircraft returns to the hold area. The reason this was modeled this way was another opportunity to save maintenance time while phase is being conducted. The real world will be monitoring for these conditions to exist so even though the PHM does not exist the thought was that this may be a feature that it would utilize.

Hold

The aircraft enter the hold station and are first delayed by the difference from the first takeoff time to the last plus one hour and then are routed to another hold module until triggered by another entity. Figure 18 shows these two holds and the modules that trigger the collection of some of the output statistics.

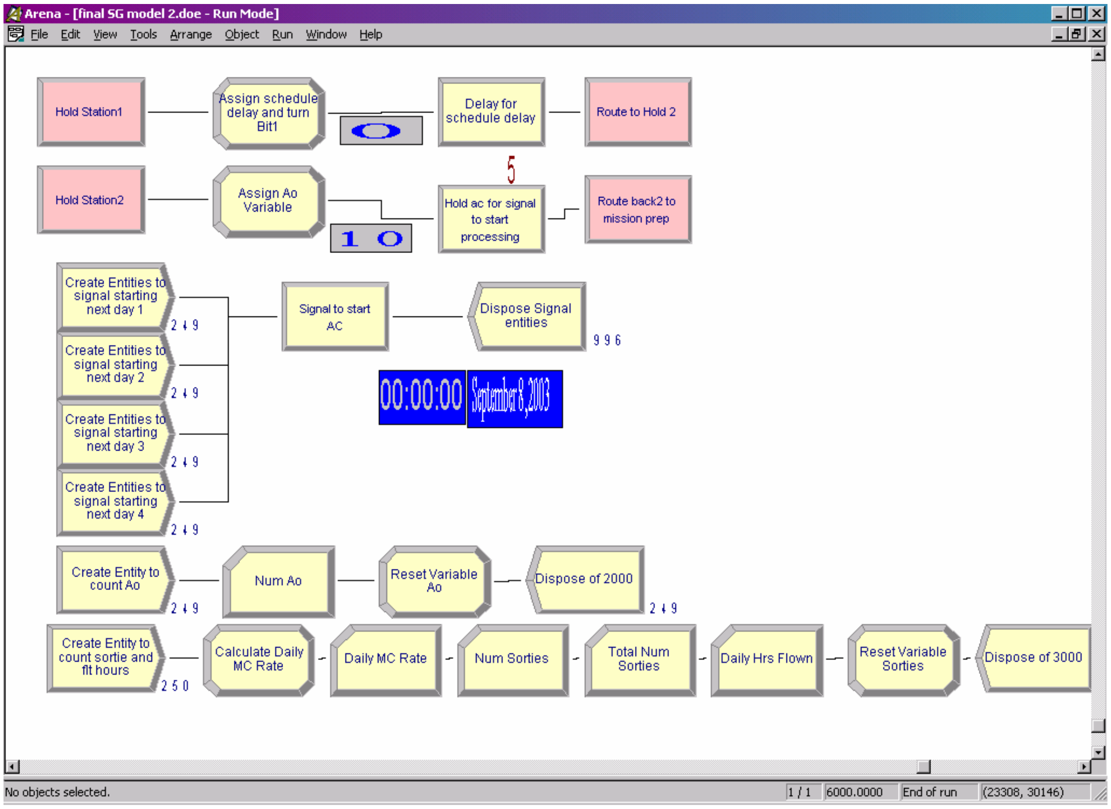


Figure 18. Hold Area

These new entities are created per the predefined starting schedule. The entities are created, then trigger a signal to the hold module which will release up to four aircraft entities. There are an infinite number of trigger entities created. If any aircraft are in preventative maintenance or unscheduled maintenance then less than four are released. Two other entities that are created in this area, signal the collection of the daily aircraft availability and number of sorties.

Unscheduled Maintenance

This is one of the most complicated and most important areas since it determines the maintenance time and supply times used in post processing analysis.

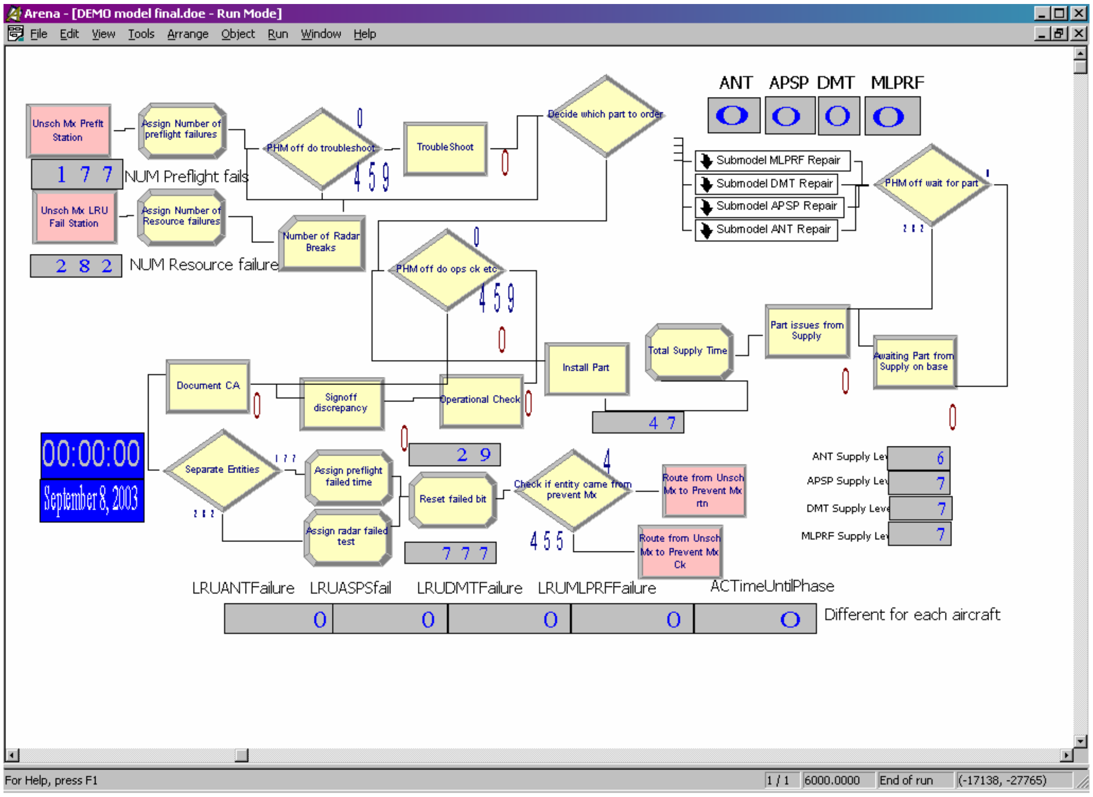


Figure 19. Unscheduled Maintenance Area

Figure 19 shows the view of the unscheduled maintenance area. Aircraft entities enter this area from various places in the model if an LRU is less than the preset failure level or in the PHM case below the PHM preset level. They can also enter this area from the preflight failure area of the mission preparation area. Entities entering from the preflight failure first are routed to an assign module that sets an attribute equal to one for separation from the radar failures at two points of this area. Also, the other starting time attribute is set to TNOW, and lastly a variable that counts the number of preflight failures is updated. This is a duplicate counting from the mission preparation area but a good double check. As stated in the assumptions, preflight failures simulate a failure of a system other than radar but no parts are replaced. Next the entity enters a decision area to determine if PHM is on. If PHM is on, troubleshooting is bypassed since the PHM will have already conducted this troubleshooting. If not on, the entity starts the troubleshooting process by seizing a maintenance specialist and is delayed by the triangle distribution, TRI(20, 24, 30). After troubleshooting the aircraft enters another decision area for determining which LRU to order from supply. Since this is a preflight failure, no order is required and the aircraft is sent to another decision module to determine if PHM is on. If not the aircraft enters a series of delays that seize the maintenance specialist at each processing module. These are operational check TRI(15, 20, 25), signoff discrepancy TRI(5, 10, 15), and document corrective action TRI(5, 10, 15). If PHM is on, these delays are again bypassed expect for document corrective action since the ALS system will be able to complete these items independently and present documentation to the maintenance specialist via a handheld computer device for a quick verification and sign off. Next, the aircraft entity is split from the radar failure entities and another set of assign modules record the time the entity has spent in the system and it resets status bits. Lastly, the aircraft enters the last decision module to determine if this aircraft came from PHM preventative maintenance, explained in the previous paragraph.

If a LRU failure occurs the aircraft entity enters from a different station and is assigned key attributes. These attributes are the same as before but are key to counting radar failures and the amount of hours that an aircraft spends in maintenance. The aircraft enters the decision module to see if PHM is on. If not troubleshooting is conducted with the same time as above. Next, the aircraft enters the decision module to see which LRU needs to removed, replaced, and ordered. When the aircraft traveled through the failed LRU assign module to reset the failure time, that assign module also assigned an attribute bit to one. So the aircraft is routed to the appropriate LRU area. All these LRU areas are the same so only one will be described. The aircraft first enters a process module that seizes a maintenance specialist. The aircraft is delayed by the triangle distribution, TRI(45, 60, 70), and then the aircraft enters an assign module that reduces the supply variable by one and the supply time is assigned TNOW. The aircraft then enters a decision module that determines if a part needs to be ordered. This level is set at the GUI screen, the default is to order a part as soon as one is used. If a part is to be ordered another decision module is entered to determine if parts are available. If available, the aircraft enters a signal module to signal that a supply entity needs to be released from its hold module. If parts are not available, then the part enters a similar signal module, then stops at the hold area waiting for the supply entity to release it. After the supply entity releases the aircraft is enters a decision to see if PHM is on. If it is on, then the entity bypasses the time to waiting for the part to be delivered from supply since the part would have already been ordered by the ALS. If PHM is off, the aircraft enters a delay module TRI(0.5, 2, 2.5) hours waiting for the part to issued from supply and it then enters a process module to be delayed for the paperwork to be completed, TRI(5, 10, 15). The aircraft then enters an assign module to calculate the time waiting for supply and then enters a process module to replace the LRU. In this module a maintenance specialist is seized and the aircraft is delayed TRI(60, 84, 120). After, that the aircraft enters the same path as described above for a preflight failure at the operational check area. Also, like described above these entities are split from the preflight entities and times in maintenance are updated.

Supply

If flagged for repair, the aircraft entity is moved to the unscheduled maintenance area where it will eventually reach the supply ordering area. The aircraft are separated based on which LRU flagged the repair and sent to the respective repair and ordering cycle. There exists four identical repair and ordering cycles in the model. Figure 20 shows one of these ordering areas.

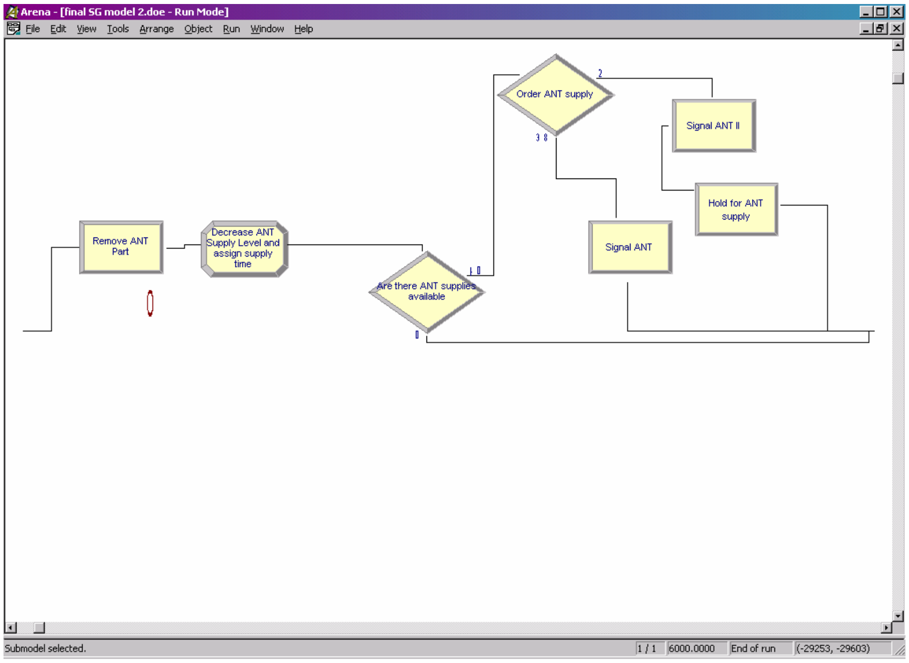
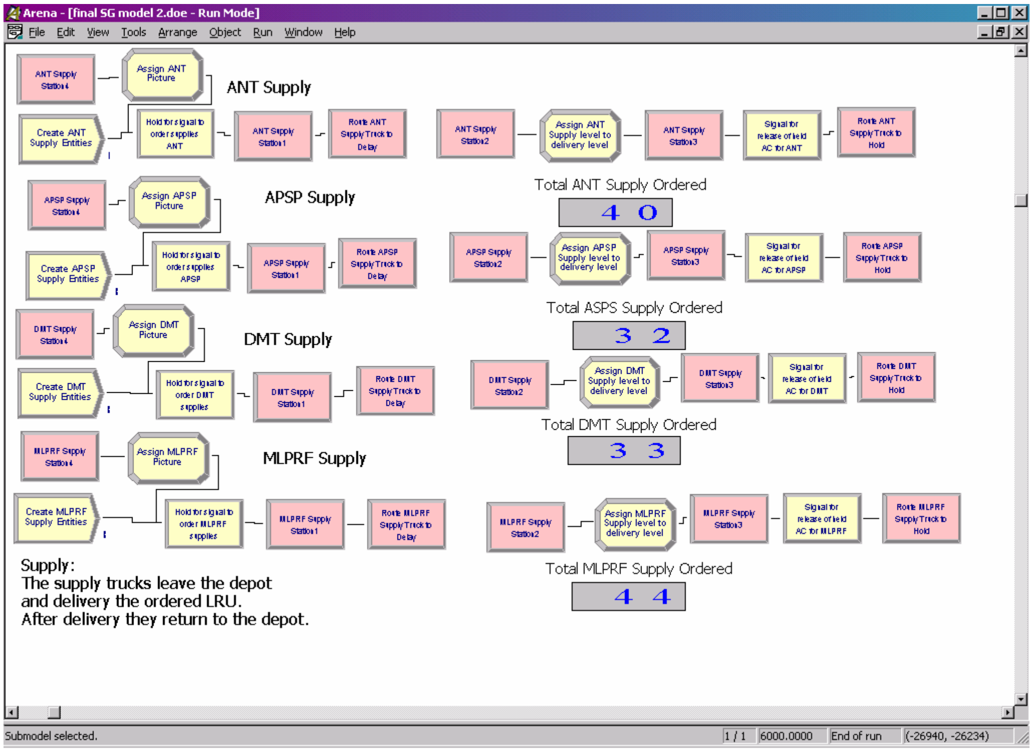


Figure 20. Ordering of Supplies in Unscheduled Maintenance

As discussed above, first the aircraft experiences a simulated removal, and then the attributes and variables are adjusted. Next a decide area determines if a replacement spare needs to be ordered. The subject matter experts suggested once a part is used another is ordered. However, the user can set a different level at the beginning of the replication if so desired. If a part is to be ordered another decision area is set up to make sure enough parts are available. The aircraft is held in a Hold area until a part arrives or if a part is available then the aircraft triggers another entity to start the part ordering process. This other entity represents a supply truck being sent from the depot or manufacturer to the base. Figure 21 shows the routing of these entities. Note in this area that the calculated process times are modeled as delays in the routing from station to station.



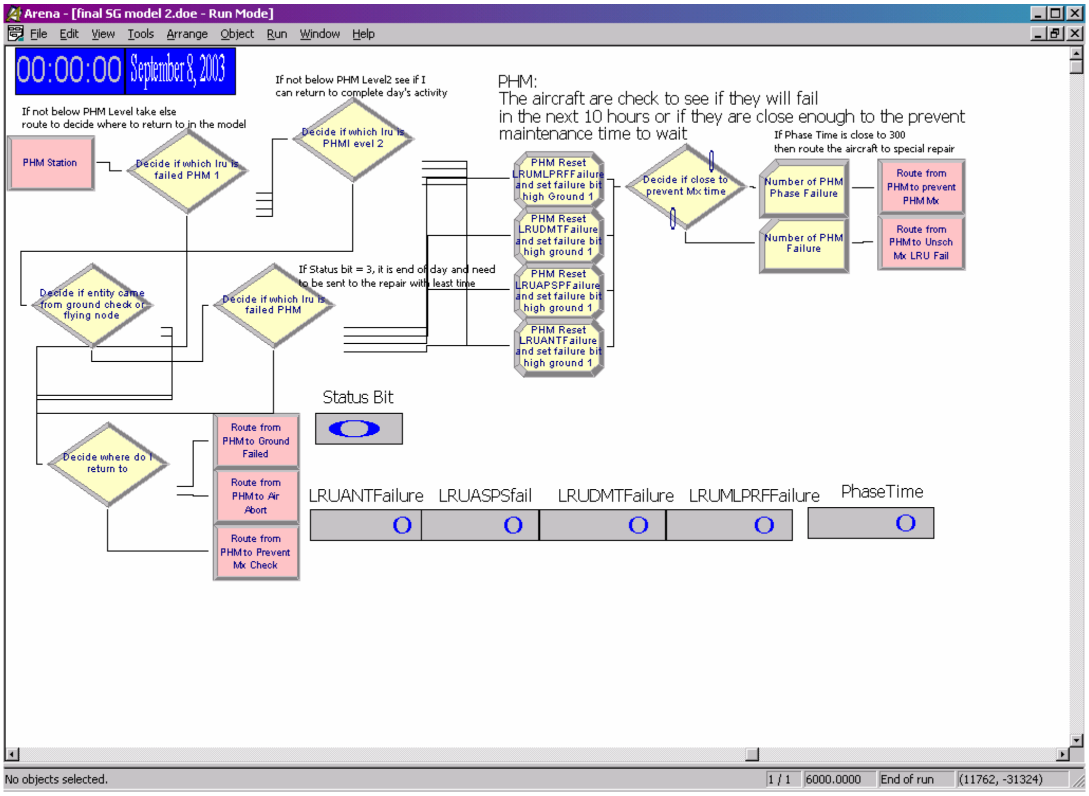
Supply:
The supply trucks leave the depot
and delivery the ordered LRU.
After delivery they return to the depot.

Figure 21. Supply Area

Eight entities are held waiting for a signal that a part is required. If the aircraft initiates the signal then only one truck leaves the depot and proceeds to the base. This model is not intended to fully represent the depot to base process, just simple delays are set-up to allow for simulation of supply. The delay for travel to the base is a triangle distribution of TRI(0.1, 0.3, 0.5) days. Once the simulated part arrives on base the attributes and variables are updated and then a signal is sent to release one aircraft from the parts not available hold. The delay for the return to depot is from the uniform distribution, UNIF(0.25, 0.5) days. The supply entity returns to the hold area awaiting another signal that a part is needed. After being released the aircraft goes through a decision area to determine if the PHM is being simulated. If no, then the aircraft must wait for the part to moved from base supply to the flight and issued. This is done since the DIS will have already notified supply that a part is required and will have it waiting when the aircraft returns from the mission.

PHM

The PHM area conducts checks the same as the other ground check and air abort and failure checking areas. However, at these modules the variable used to check for failure is greater than zero. In other words, the model consider a part "failed" if its remaining life is less than some amount of time. Figure 22 shows the decision, assignment and record modules that make up this area.



If not below PHM Level take else route to decide where to return to in the model

If not below PHM Level2 see if I can return to complete day's activity

PHM:
The aircraft are check to see if they will fail in the next 10 hours or if they are close enough to the prevent maintenance time to wait

If Phase Time is close to 300 then route the aircraft to special repair

If Status bit = 3, it is end of day and need to be sent to the repair with least time

Figure 22. PHM Area

The default setting is 10 hours but, the user may change that setting. This area is designed to return an aircraft back to the ground or air abort stations if they are not below 2 hours time remaining. This variable is also adjustable at the GUI screen. This is modeled this way so that a ground or air abort does not occur and this may be the way that the real PHM is modeled. As stated in the literature search, the PHM will be equipped with sensors and reasoners to try and determine the best time for maintenance. If maintenance can be delayed because LRU life remains and it would not be a safety hazard, then operations may continue to a more convenient time.

Model Verification and Validation

The verification and validation and was done in two steps. The verification was done by the model builder. Each area was scrubbed for correct modeling, the animation was observed on several occasions to check proper aircraft flow, and the output was compared against real world data to check accuracy of the simulated output. The validation was conducted with six subject matter experts (SME) from AFRL Human Effectiveness Directorate, Logistics Readiness Branch (2002). The different model areas were reviewed by the SMEs and each process was evaluated for accuracy. The suggested changes included times for turning on the clock for the LRUs, changes to process times like preflight, service, phase, fueling, and weapon loading, and the number of sorties and length of sorties were discussed. These suggestions were incorporated into the model that was previous described.

A final verification analysis was conducted by running 10 replications for one simulated year equal to 250 hours 50 weeks times 5 days per week. The output was scrubbed for reasonableness and compared to the Hill sortie data. The outputs that were analyzed were Sorties/day, MC rates, number of spares ordered/number of items repaired, spares levels, and flying effectiveness. The results of the final verification are located in Appendix A.

Conclusion

The model for this research was built to replicate the sortie generation process and the future ALS in order to measure its effect on this important process. This chapter detailed the processes that make up the model. Sixteen aircraft enter into the simulated day in groups of four, at four distinct times. The aircraft are subject to numerous processes that first prepare them for flight, simulate taxi, takeoff, flying, and landing, and then they are serviced and debriefed all in the means of returning the aircraft to flying status. Returning the aircraft to flying status may involve repair and replacement of a certain radar LRU or as simple as troubleshooting and documentation. The ALS simulates the aircraft being monitored continuously for anticipated faults and repairs are made according to a predetermined level before the fault occurs. The main focus of the ALS has been on the PHM and assumptions were made that DIS would be fully functional. The PHM did include false alarms that were significantly detrimental to the sortie generation process since with every false alarm a LRU is removed and replaced, believing that the PHM is always correct and has fault isolated to the correct part. Lastly, the final verification runs were extremely helpful in learning a great more about the model with the review of output that will be similar to the analysis output.

IV. Analysis and Results

Introduction

The previous chapter defined the simulation model that was used for this research. This chapter defines the steps in setting up and performing our analysis. These steps include determining the appropriate length and number of replications to produce sufficiently normal output data while meeting a specified confidence interval half width. This discussion then sets up the analysis of the results from the simulation runs.

Simulation Output Variables

PACAFI 21-102 lists the logistics performance terms that a unit must report to higher headquarters. The output of this simulation model was structured after this instruction.

Table 5. Logistics Performance Measures

Identifier	Average	Half-width	Minimum	Maximum
Possessed Hrs	30000	0	30000	30000
AVG Possessed ACFT	16	0	16	16
MC Hours	24101	62.176	23750	24446
MC Rate	0.80337	0.00207	0.79167	0.8149
NMCM Hours	4151.1	40.092	3950.4	4346.2
NMCM Rate	0.13837	0.00134	0.13168	0.14487
NMCS Hours	1747.6	24.893	1590.9	1903.7
NMCS Rate	0.05826	8.30E-04	0.05303	0.06346
Sorties Scheduled	21778	18.534	21666	21881
Sorties Flown	20110	25.728	19968	20237
Hourly UTE Rate	1280.3	1.6213	1272.2	1289.9
Sortie UTE Rate	1256.8	1.608	1248	1264.8
Hours Flown	20486	25.941	20356	20639
Flying Sch Eff Rate	0.9234	7.88E-04	0.91706	0.92728
Air Aborts	586.4	9.2633	554	641
Ground Aborts	111.3	3.6937	94	130
Abort Rate	0.03572	5.11E-04	0.03339	0.03844

Table 5 lists these output variables and shows their magnitudes and associated confidence interval half widths for our baseline scenario with thirty replications. The PACAFI includes more performance parameters but it felt was that those shown in Table 5 represent variables that were important to this research. In the next paragraph these variables were scoped down to key measures of effectiveness (MOE) that would represent an analysis of an aircraft equipped with an ALS.

Key Measures of Effectiveness

Preliminary runs of the simulation model plus the baseline runs discussed in the previous chapter helped to make key decisions on the MOEs that were analyzed. These MOEs are Mission Capable Rate, Not-mission Capable for Maintenance and Supply, and Flying Scheduling Effectiveness. The Mission Capable and Not-Mission Capable rates are based on the number of hours that an aircraft spent in each of these status categories. The Not Mission Capable hours for Maintenance included both the preflight failures and the radar failures, while the Not Mission capable rate for supply tallied the time an aircraft waited for a specific LRU. The Flying Scheduling Effectiveness rate is based on the number of flown sorties divided by the total number of scheduled sorties. It was felt that these rates would offer the best way to observe the differences between the baseline system and the ALS, and also the differences between the different ALS levels that were set-up.

Results

The goal for the half width variation for the key MOEs was plus or minus 2%. The majority of the baseline runs were conducted at 250 days, which is equivalent to 50 weeks of work at five days a week with two weeks dropped for holidays. This run length combined with 10 replications provided a confidence interval half width of less than one percent, which is well under the goal that had been set. However, at just 250 days not every aircraft was experiencing the phase inspection downtime. Extending the run length to 5 years or 1250 days allowed every aircraft to go through that inspection at least once. This replication length combined with 10 replications provided confidence interval half widths on the order of 0.2 percent, well below the goal of plus or minus 2% half width.

The next step was to determine the number of replications that produced data that exhibited normal behavior. Utilizing the software tool JMP®, the Mission Capable Rate and Flying Effectiveness outputs distributions were plotted. Two aspects of this distribution were examined, first they were fit to a normal distribution and second the shape of the distribution was observed from the graph. The data from the 10 replication runs passed the Shapiro-Wilk goodness of fit (GOF) test at the alpha level of 0.05. However, the plot of the distribution did not appear to have the normal bell shaped curve, so the number of replications was increased to 20. Figure 23 shows the Mission Capable Rate distribution for 20 replications. Figure 24 show the Flying Effectiveness for 20 replications.

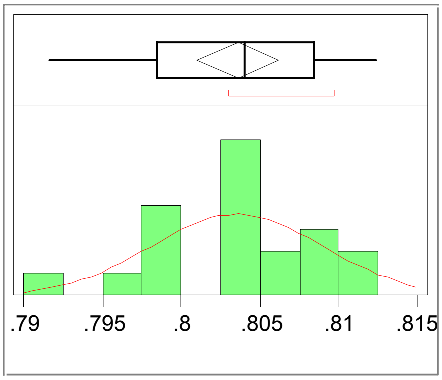


Figure 23. Mission Capable Rate Distribution for 20 Replications

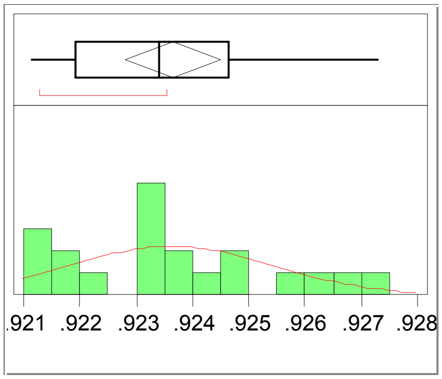


Figure 24. Flying Scheduling Effectiveness Rate Distribution of 20 Replications

With 20 replications the output again passed the Shapiro-Wilk GOF test at the 0.05 level but the distribution still did not appear normal, so the replications were increased to 30. This output again passed the Shapiro-Wilk GOF test and the graphed distribution appeared to have the normal bell shape. Therefore it was decided to use this combination of 30 replications and 5 years length. It also should be noted here that the execution time for each replication at 5 years was quite small (two minutes), therefore the increased run time in going from 10 to 30 replications was minimal. Figure 25 shows the distribution for Mission Capable Rate at 30 replications. Figure 26 shows the distribution for Flying Effectiveness at 30 replications.

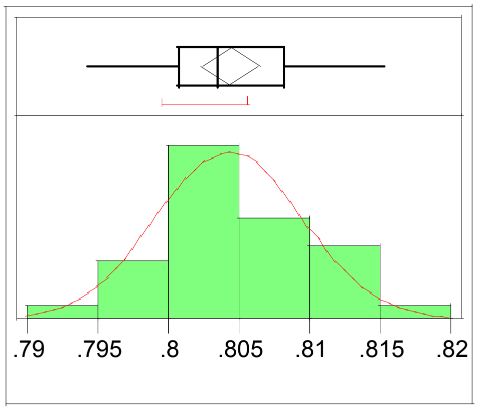


Figure 25. Mission Capable Rate Distribution of 30 Replications

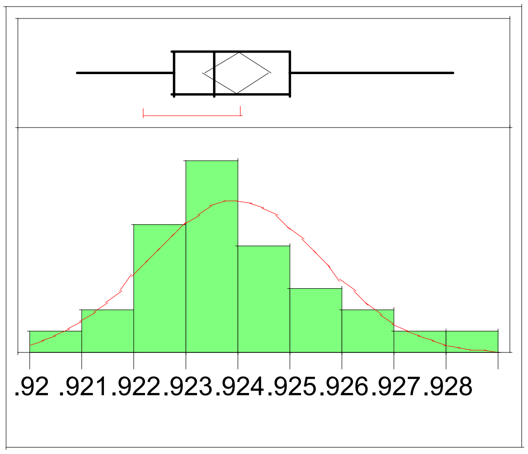


Figure 26. Flying Scheduling Effectiveness Rate Distribution of 30 Replications

Once the number of replications and replication length were determined, the critical factors and levels of those factors were determined. Examining the twenty-two (PHM on or off was not considered) possible input variables to change, it was determined that the PHM Level and False Alarm Percentage were the two factors that were most important to examine. The reasoning that leads to this decision can be broken down by the groups of variables. First the MTBF numbers were fixed because examination of improved reliability was not the goal of this research. The supply numbers were fixed since again supply was not an area of interest to investigate. Like the others, takeoff times were not of a major concern. Fixing the preflight failure level and the mean time until phase, and number of aircraft to turn helped to focus the scope to the key factors. Lastly, the baseline runs showed that the second PHM level variable had little effect on the MOEs, so it was fixed. That left the two factors that were the main concentration of the research and the runs were set up to produce output that would efficiently and effectively examine the space of the false alarm and PHM level factors. Therefore, a 3^2 full factorial design of experiments was used.

The number of false alarms are based on the number of sorties simulated. As discussed in Chapter 3, the aircraft moves through a decision module in the flying area and a false alarm occurs based on a predetermined percentage. This simulates an air abort and a LRU being removed and replaced. This is a worse case scenario since no further troubleshooting is completed to verify if this was a fault or a false alarm. This was purposely simulated this way to examine the worse case. Also, it was determined that the lowest setting for false alarm percentage would be one, meaning that false alarms were always on. This factor seems like it would have the greatest impact on the simulated sortie generation process since several actions are started once a false alarm is detected. The PHM level factor is based on a time prior to the failure of the LRU. The times can be translated as knowing when a failure was about to occur with a degree of certainty. A low setting meant better certainty of an impending failure while higher meant not as sure.

The baseline runs showed a significant drop off of key output measures of effectiveness with false alarm rates over 5%. Therefore the false alarm rate was limited to 5%. It was also felt that with an operating ALS there would always be false alarms, so the minimum percentage was set to one and the center point at three. The baseline runs additionally provided insight into selecting PHM levels. The Mission Capable rates dropped slightly with increasing PHM level. This makes sense since overall LRU life is limited, and increasing the time before actual failure when an LRU is removed from the aircraft would decrease the overall life and in turn the overall Mission Capable rate. However, this will be a trade-off that the ALS designers will need to study since in-flight and unscheduled maintenance hurts flight operations, but removal and replacement too early is more costly. The approach that was taken for this research was that setting the PHM level at 5 hours to represent the system was predicting failure to an accurate level, while a high of 15 hours meant that the PHM was not as accurate in predicting failure. This left the center point of 10 hours. Also, the minimum of 5 hours provided for no ground or air aborts Table 6 shows the two factors and the levels that were simulated.

Table 6. Simulation Factor Levels

	Low	Center	High
False Alarm (%)	1	3	5
PHM Level (hours)	5	10	15

Output Analysis

With the design of experiments presented, simulation runs were conducted and then output was analyzed. First the means of the MOEs for the nine ALS runs were graphed for each key MOE as shown in Figures 27, 29, 31, and 33. These graphs all indicate that the various MOEs do not change significantly across different PHM levels, but do vary with false alarm level. There is more discussion on this topic in the Analysis of Variance section later. Figures 28, 30, 32, and 34 shows the PHM level (5 hours) that produces the best MOE for each false alarm level with the mean for our baseline system without an ALS. For the Mission Capable rate, the false alarm level of 5% does not show any improvement over the non ALS system.

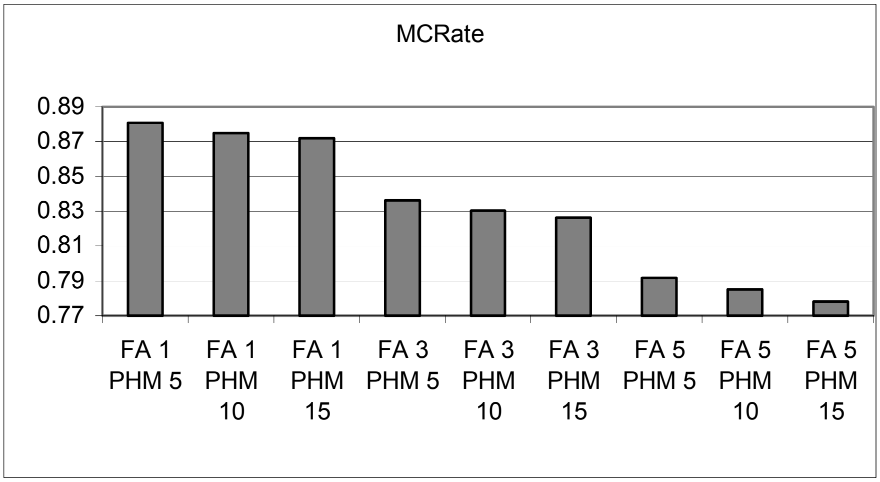


Figure 27. Mission Capable Rate ALS Runs

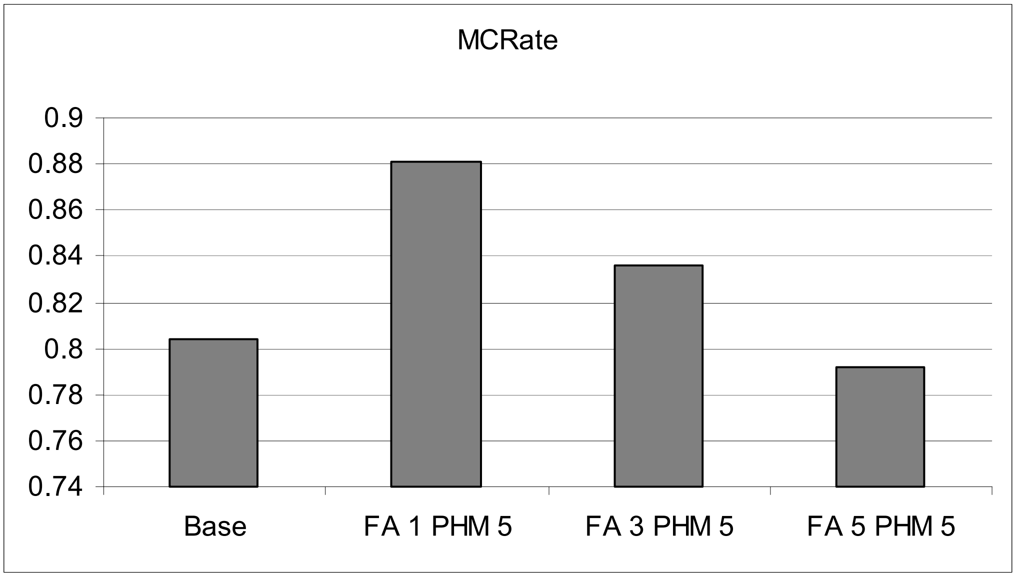


Figure 28. Mission Capable Rate Baseline and ALS Runs

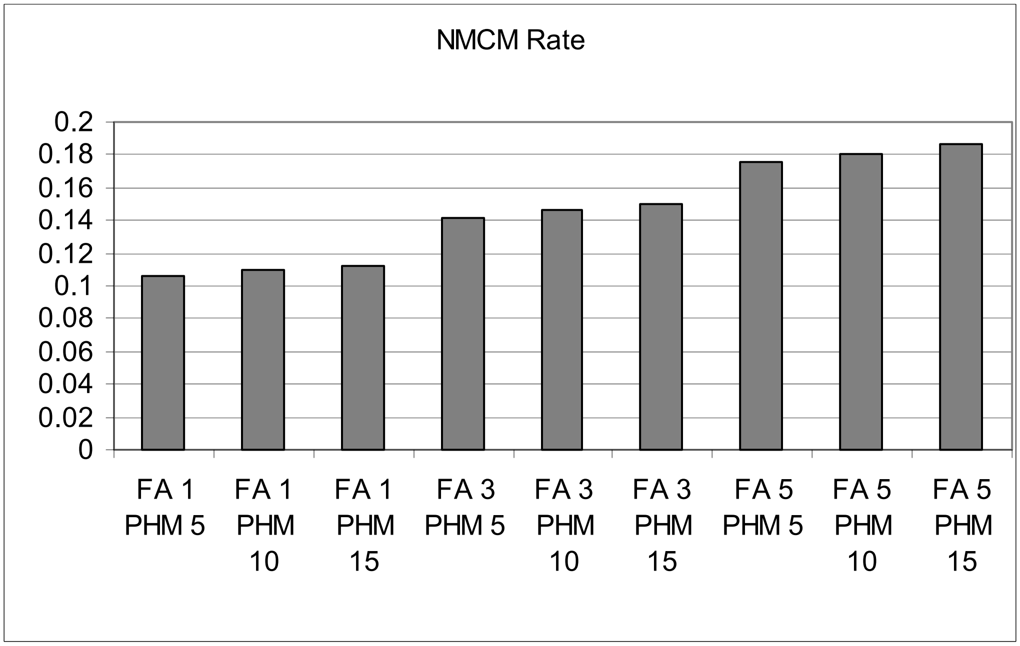


Figure 29. Not Mission Capable Rate for Maintenance ALS Runs

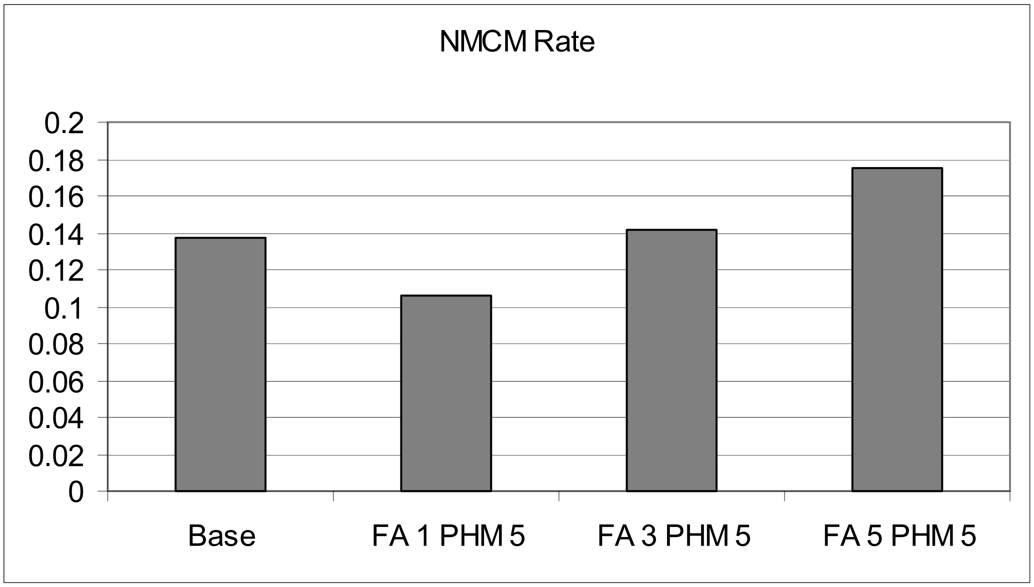


Figure 30. Not Mission Capable Rate for Maintenance Baseline and ALS Runs

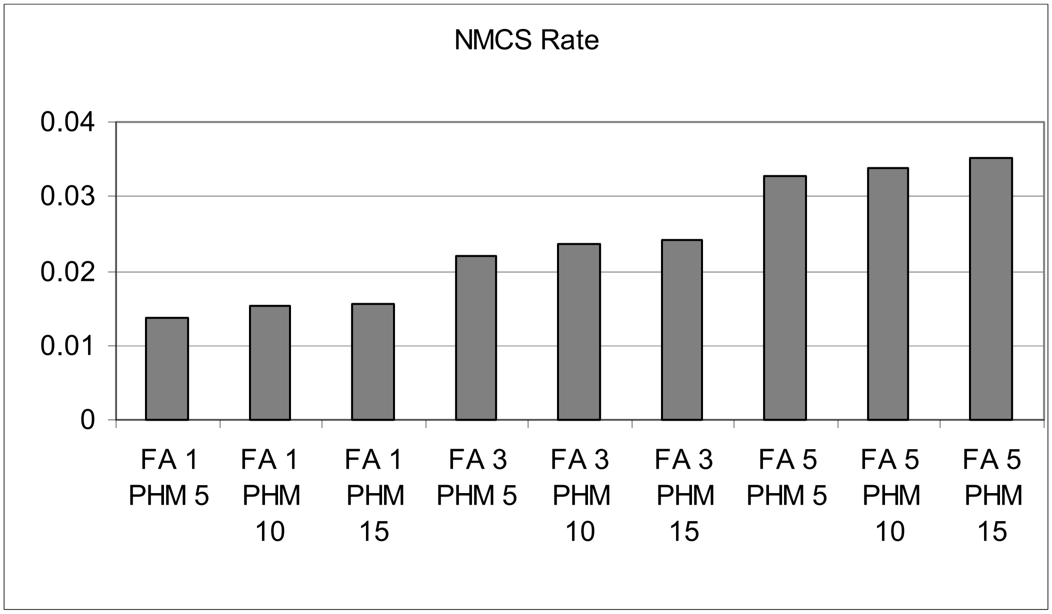


Figure 31. Not Mission Capable Rate for Supply ALS Runs

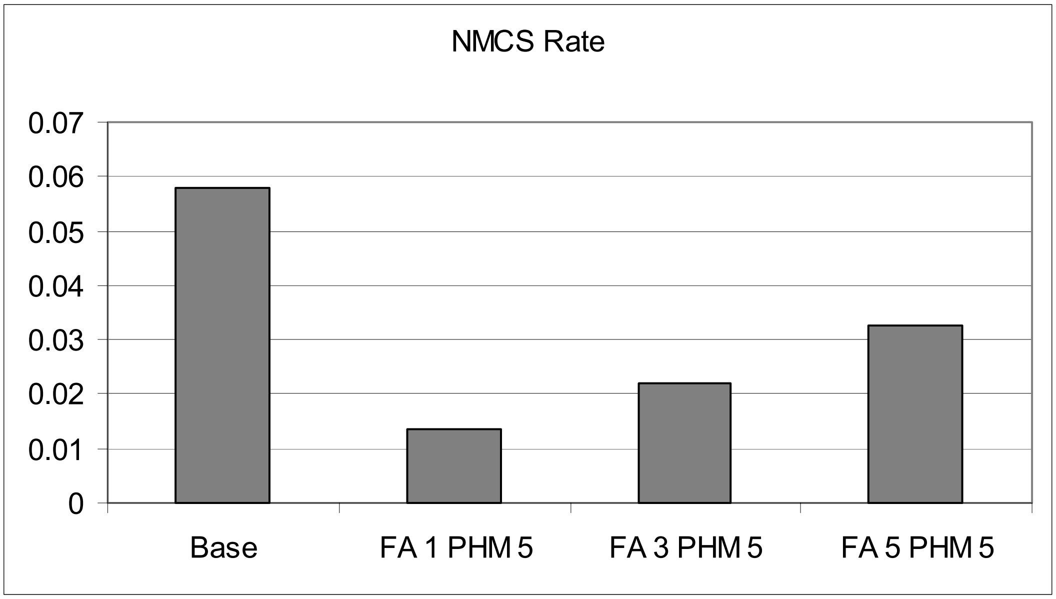


Figure 32. Not Mission Capable Rate for Supply Baseline and ALS Runs

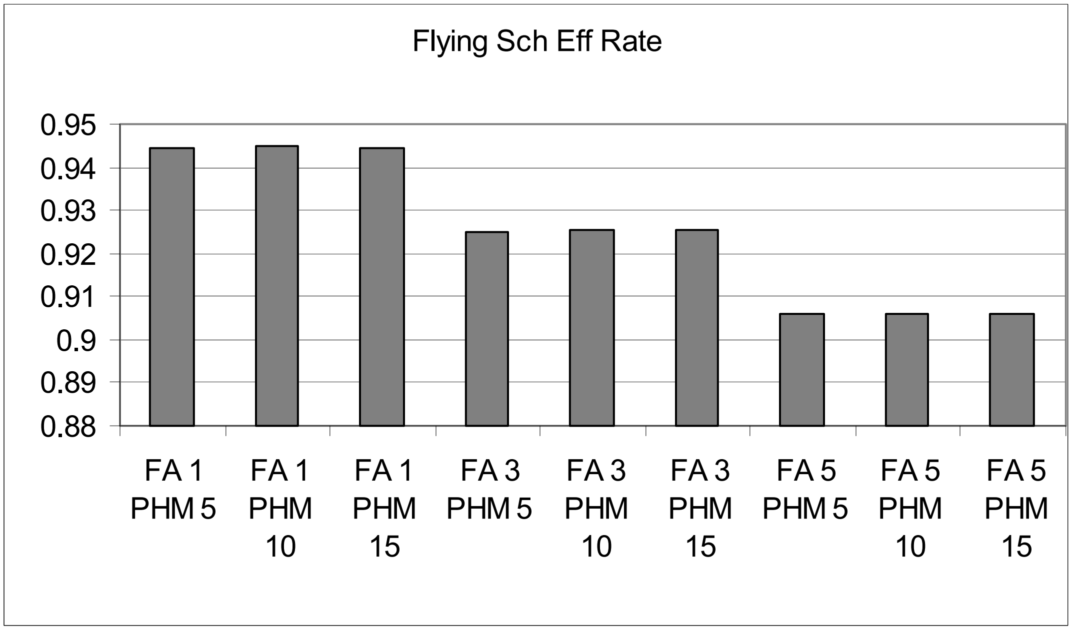


Figure 33. Flying Scheduling Effectiveness ALS Runs

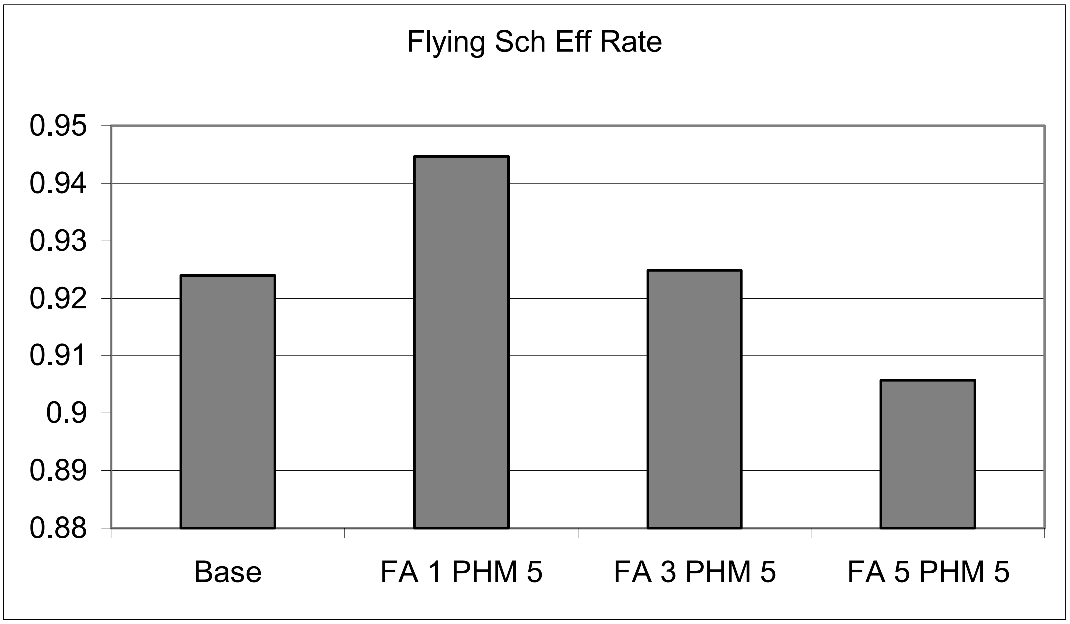


Figure 34. Flying Scheduling Effectiveness Baseline and ALS Runs

The decrease in Mission Capable Rate is driven more by the increase in Not Mission Capable for Maintenance. Comparing the scales of the two Not Mission Capable graphs, the Maintenance level is twice that of supply. Also, the ALS with 3% false alarm percentage for Not Mission Capable for Maintenance exceeds the baseline level.

Analysis of Variance

To compare the different ALS levels that were simulated an Analysis of Variance (ANOVA) (Wackerly et al; 2002) was used. This analysis would compare the different effects of the two variables that are shown in Table 6. Tables 7, 8, 9, and 10 show the ANOVA of each MOE.

Table 7. ANOVA of Mission Capable Rate

Summary of Fit

RSquare	0.98216
RSquare Adj	0.981959
Root Mean Square Error	0.005068
Mean of Response	0.830592
Observations	270

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	0.37618206	0.125394	4881.459
Error	266	0.00683296	0.000026	Prob > F
C. Total	269	0.38301502		<.0001

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio	Max RSq
Lack Of Fit	5	0.00009227	0.000018	0.7145	0.9824
Pure Error	261	0.00674069	0.000026	Prob > F	
Total Error	266	0.00683296		0.6130	

Parameter Estimates

Term	Estimate	Std Error	T Ratio	Prob>|t|
Intercept	0.8305923	0.000308	2692.8	0.0000
FA*PHM	-0.001288	0.000463	-2.78	0.0058
FA	-0.045388	0.000378	-120.1	<.0001
PHM	-0.005363	0.000378	-14.20	<.0001

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
FA*PHM	1	1	0.00019897	7.7457	0.0058
FA	1	1	0.37080544	14435.07	<.0001
PHM	1	1	0.00517765	201.5607	<.0001

Table 8. ANOVA of Flying Scheduling Effectiveness

Summary of Fit

RSquare	0.987949
RSquare Adj	0.987813
Root Mean Square Error	0.001761
Mean of Response	0.925279
Observations	270

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	0.06765676	0.022552	7269.155
Error	266	0.00082525	0.000003	Prob > F
C. Total	269	0.06848202		<.0001

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio	Ma RSq
Lack Of Fit	5	0.00000897	0.0000018	0.5736	0.9881
Pure Error	261	0.00081628	0.0000031	Prob > F	
Total Error	266	0.00082525		0.7202	

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.9252793	0.000107	8631.8	0.0000
FA*PHM	0.0000592	0.000161	0.37	0.7132
FA	-0.019387	0.000131	-147.7	<.0001
PHM	0.0001131	0.000131	0.86	0.3897

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
FA*PHM	1	1	0.00000042	0.1354	0.7132
FA	1	1	0.06765404	21806.59	<.0001
PHM	1	1	0.00000230	0.7423	0.3897

Table 9. ANOVA of Not Mission Capable Rate for Supply

Summary of Fit

RSquare	0.940318
RSquare Adj	0.939644
Root Mean Square Error	0.001983
Mean of Response	0.024024
Observations	270

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	0.01647906	0.005493	1396.975
Error	266	0.00104593	0.000004	Prob > F
C. Total	269	0.01752500		<.0001

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio	Max RSq
Lack Of Fit	5	0.00006711	0.000013	3.5792	0.9441
Pure Error	261	0.00097882	0.000004	Prob > F	
Total Error	266	0.00104593		0.0038	

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.0240238	0.000121	199.07	<.0001
FA	0.0095058	0.000148	64.32	<.0001
PHM	0.0010852	0.000148	7.34	<.0001
FA*PHM	0.0001336	0.000181	0.74	0.4612

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
FA	1	1	0.01626496	4136.473	<.0001
PHM	1	1	0.00021197	53.9067	<.0001
FA*PHM	1	1	0.00000214	0.5446	0.4612

Table 10. ANOVA of Not Mission Capable Rate for Maintenance

Summary of Fit

RSquare	0.984275
RSquare Adj	0.984098
Root Mean Square Error	0.003759
Mean of Response	0.145384
Observations	270

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	0.23520471	0.078402	5550.03
Error	266	0.00375760	0.000014	Prob > F
C. Total	269	0.23896231		<.0001

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio	Max RSq
Lack Of Fit	5	0.00004983	0.000010	0.7015	0.9845
Pure Error	261	0.00370777	0.000014	Prob > F	
Total Error	266	0.00375760		0.6227	

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.1453838	0.000229	635.60	0.0000
FA	0.0358817	0.00028	128.08	<.0001
PHM	0.0042786	0.00028	15.27	<.0001
FA*PHM	0.0011543	0.000343	3.36	0.0009

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
FA	1	1	0.23174964	16405.51	<.0001
PHM	1	1	0.00329517	233.2645	<.0001
FA*PHM	1	1	0.00015990	11.3192	0.0009

The Mission Capable Rate ANOVA shows that there exists statistical significant difference between the different effects simulated and that all factors including the interaction factor were significant at the alpha level of 0.05. The interaction factor indicates that a linear model is not appropriate for the model response surface, but the lack of fit p-value exceeding an alpha of 0.05 indicates that second order factors are not needed to describe the model. The Flying Scheduling Effectiveness Rate ANOVA is also significant. However, it differs from the Mission Capable rate ANOVA since only the false alarm factor was significant at the alpha level of 0.05. This was an interesting discovery about the PHM level indicating that changes over that factor's range would not affect the ability to produce sorties, if that was the most significant factor for a flying wing. The ANOVA for Not Mission Capable Rate for Supply showed that the effects were significant and that the two factors were significant but the interaction was not. Like the overall Mission Capable Rate ANOVA, the Not Mission Capable Rate for Maintenance results showed that each factor and the interaction were clearly significant. Also, the Not Mission Capable Rate for Supply MOE failed the lack of fit test. Investigations into the higher order terms showed that the second order terms were appropriate to fit this MOE. The results of this analysis are not shown.

Figure 27 shows the plot of Mission Capable Rate for the three false alarm and PHM Levels. The rates do not change significantly between the PHM levels but across the false alarm percentages there is a significant drop off of Mission Capable rate. Figure 28 shows that at five percent false alarms per scheduled sortie the ALS equipped aircraft performs worse than the baseline aircraft. Of course, the false alarm is modeled as the worst case possible as discussed in the previous chapter with a part removed and replaced for every false alarm. In addition to this fact there is only one LRU on base for the Antenna and the MLPRF, meaning that the entire system is stressed by this false alarm modeling.

Conclusion

This chapter exhibits the results of the simulation runs based on a baseline situation without an ALS and then the ALS two factor analysis displayed in Table 6. Figure 27 shows that an ALS equipped aircraft performs better than the baseline aircraft up to a point with increasing false alarm rates. The cross over for Mission Capable rate occurs after a false alarm rate of 3%, while the Flying Scheduling Effectiveness was no better at the 3% level. The Not Mission Capable for Maintenance rate drives the negative impact on overall Mission Capable rate. This can be tied to the number of parts being removed and replaced with a higher false alarm rate. As discussed in Chapter 3, troubleshooting, operations check, and documentation can be bypassed under an ALS but the time to remove and replace a LRU does not change. This exhibits the importance of correctly identifying the correct LRU to remove and replace. The assumption is made that the PHM correctly does that except for a false alarm.

V. Conclusion

Introduction

The previous four chapters introduced the research that was undertaken, reviewed the literature, defined the model and all the different areas established to simulate the non-ALS and ALS sortie generation process, and analyzed the output of the results. The research that has been described by these chapters investigated the impact of an ALS on the U.S. Air Force aircraft sortie generation process. This chapter will wrap up this research, list lessons learned during this process, chronicle conclusions, and discuss future research areas. It should be noted that the specific values reported for our MOEs are not necessarily representative of actual sortie generation capabilities since we are only explicitly modeling a single aircraft system. However, the improvements in our selected MOEs with the introduction of the ALS, and sensitivities of these MOEs to variations in the ALS parameters, are representative of the kinds of impact we anticipate with a fully operational ALS.

Autonomic Logistics Revisited

The Autonomic Logistics concept can be summarized as processes and tools that automate the approach to the aircraft maintenance process allowing improved sortie generation capability with less logistics needs (Henley: 2000). Under this concept aircraft maintenance tasks such as troubleshooting, parts ordering, and documentation would be fully automated allowing maintenance personnel to return aircraft to fully mission capable status more quickly with less effort.

Autonomic Logistics is still an emerging technology. Currently only the US Army and Navy HUMS possess the capabilities that are approaching an automated state. The HUMS is being installed in operational helicopters at this time.

Lessons Learned

There were numerous lessons learned during every portion of the research process. Starting with the input analysis, the time between replacement data was formulated by hand from output from the REMIS database. Tools are emerging that can perform these tasks automatically, this may be an area of future research. The model building was extremely time consuming, and starting this process early in the research helped to allow changes in the later stages of design. Documenting of the current model configuration and changes that were made to each newer version was also very helpful in the model building process. Converting Arena® output files to text readable excel files could have been easier with the utilization of the Arena® file read and write module.

Conclusion

The literature search indicated a great deal of research into the ALS concept. It also showed that discrete event simulation sortie generation models exist, however, only one paper was discovered that discussed ALS simulation outside of the research conducted at AFIT by Capt Rebulanan and Capt Malley.

The results of this research showed that the ALS equipped aircraft can perform better than a non-ALS aircraft up to a point. The analysis from Chapter 4 shows an 8% improvement in Mission Capable rate from the baseline to the best factor combination for

ALS (FA = 1 / PHM Level = 5). While the Flying Scheduling Effectiveness showed a 2% improvement at those same factor levels. At the other factor levels combinations the ALS performed marginally better or even worse then the non-ALS aircraft as shown in the Figures 28, 30, 32 and 34. The false alarm affect on the MOEs was the most interesting and a little surprising. Taking into consider that the design in this model was most likely the worst-case scenario, (part removal with every false alarm), it still provides an interesting example of an area of concern for the PHM designers. If the maintenance personnel remove and replace a part that the ALS instructs them to, then this situation creates more RTOK for events for the depot which in turn stresses the supply system. CND and RTOK have existed for many years and the rates do not seem to be decreasing. Any new logistics concept should strive to decrease these rates.

Recommendations for Further Study

A great deal of opportunities exist to make significant improvements of this sortie generation model, mostly in the PHM area. The fact that a working system still does not exist, could lead to investigations into similar system designs like the HUMS or interviews with the Joint Strike Fighter SPO on preliminary designs, trying to determine their direction so far and future thoughts of what a system may resemble. Studying the false alarms of previous systems and the actions taken by maintenance personnel could be further investigated. How the maintenance personnel react to false alarms, at what point would they start ignoring the system or how could improvements be made to gain initial confidence in the system. Research could be conducted on the process after a false alarm occurs. Issues could be examined such as do you perform a remove and replace of the LRU with every false alarm. Also should this remove and replace action be based on the percentage of sorties as it was modeled or maybe a percentage of operating time. Currently which LRU that is removed and replaced is based on an equal chance, maybe a better basis may be on the proportion of supply on base. Another research avenue may be into the PHM assumptions such as no troubleshooting and no waiting for base supply. Also, every DIS message was assumed to be received by supply. Modeling could be added that simulates dropped messages, slow message traffic, or downtimes. Other issues about the timing of DIS messaging could be investigated, when is the information required, at landing or earlier while still in the landing pattern.

One of the original goals of this research was to build the model to allow easy transition to an object-oriented model and provisions were made during the model building to allow that transition. The entities in the model were treated like objects and were assigned attributes. This could lead to possible further research using the JAVA® Silk® simulation package.

Appendix A. Baseline Runs

Rates	**Baseline**	**PHM2/5/0**	**PHM2/5/2**	**PHM2/5/5**	**PHM2/10/0**	**PHM2/20/2**
MC	0.8001	0.8584	0.8584	0.8560	0.8462	0.8361
NMCM	0.1407	0.1230	0.1234	0.1251	0.1310	0.1413
NMCS	0.0592	0.0186	0.0182	0.0189	0.0228	0.0026
FSE	0.9234	0.9368	0.9346	0.9234	0.9359	0.9359

Rates	**PHM2/20/5**	**PHM2/10/2**	**PHM2/10/5**	**PHM2/20/0**	**PHM5/5/5**
MC	0.8381	0.8518	0.8480	0.8382	0.7877
NMCM	0.1375	0.1276	0.1311	0.1380	0.1794
NMCS	0.0244	0.0206	0.0209	0.0238	0.0329
FSE	0.9342	0.9371	0.9325	0.9345	0.8916

Rates	**PHM5/10/5**	**PHM5/20/5**	**PHM10/5/5**	**PHM10/10/5**	**PHM 10/20/5**
MC	0.7787	0.7619	0.6730	0.6513	0.6273
NMCM	0.1847	0.1967	0.2595	0.2752	0.2941
NMCS	0.0365	0.0415	0.0675	0.0735	0.0787
FSE	0.9042	0.9024	0.8482	0.8548	0.8554

Appendix B. ANOVA Assumptions

Mission Capable Rate
ANOVA Assumptions
Constant Variance

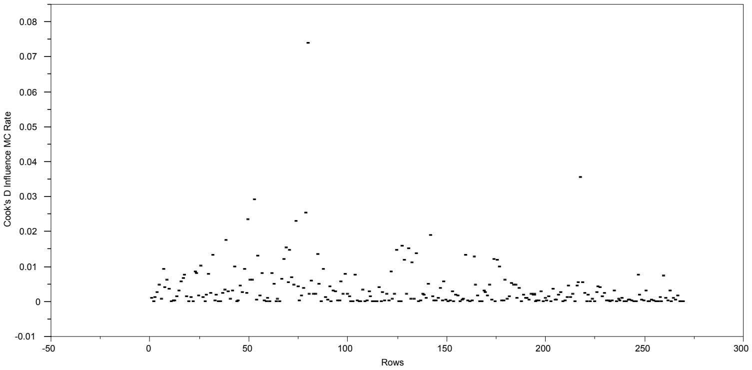
SSR	# X cols	SSE	n	Breusch-Pagan	Chi-square
3.57E-09	3	0.006741	270	1.907658683	0.992845

Independence

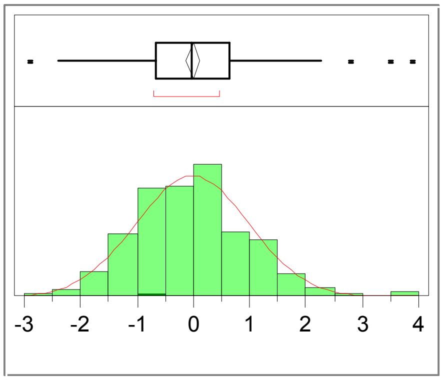
Durbin-Watson

Durbin-Watson	Number of Obs.	AutoCorrelation	Prob<DW
2.0625877	270	-0.0323	0.6539

Influential Data Points
Cook's D



Studentized Residuals



Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	0.000052	-0.119960	0.120063
Dispersion	Sigma	1.001610	0.923652	1.094053

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.984409	0.5824

Flying Scheduling Effectiveness

ANOVA Assumptions

Constant Variance

SSR	# X cols	SSE	n	Breusch-Pagan	Chi-square
2.12E-10	3	0.000816	270	7.717642765	0.5628324

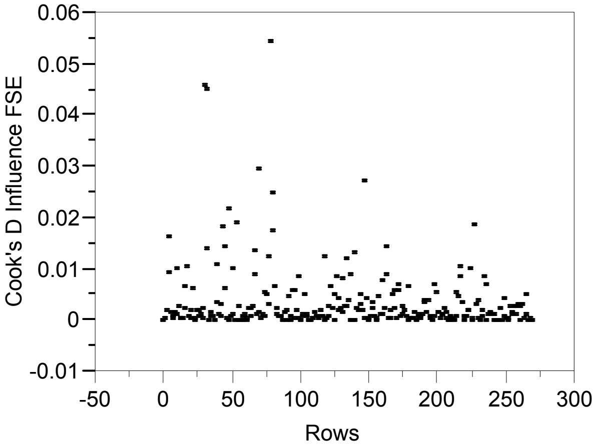
Independence

Durbin-Watson

Durbin-Watson	Number of Obs.	AutoCorrelation	Prob<DW
2.0625877	270	-0.0323	0.6539

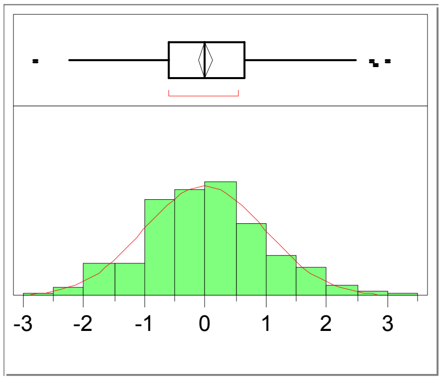
Influential Data Points

Cook's D



Normality

Studentized Residuals



Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	-0.00019	-0.120179	0.119803
Dispersion	Sigma	1.00144	0.923491	1.093862

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.983523	0.5048

NMCM

ANOVA Assumptions

Constant Variance

SSR	# X cols	SSE	n	Breusch-Pagan	Chi-square
1.86E-09	3	0.003758	270	3.20308814	0.9556957

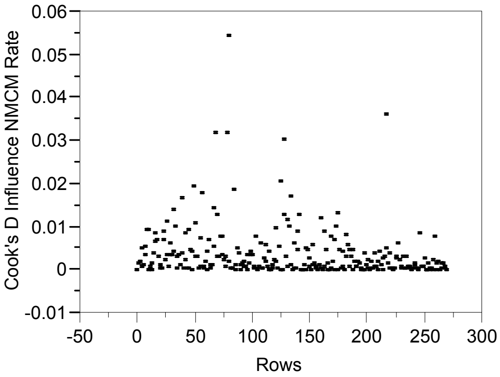
Independence

Durbin-Watson

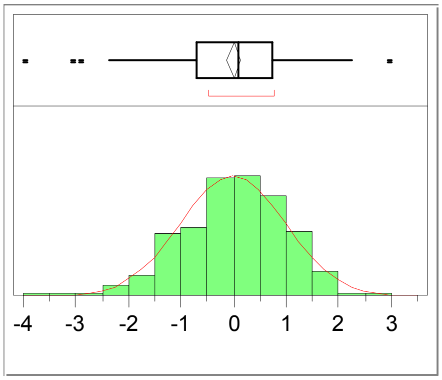
Durbin-Watson	Number of Obs.	AutoCorrelation	Prob<DW
1.9580986	270	0.0208	0.3214

Influential Data Point

Cook's D



Normality



Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	-0.00028	-0.120286	0.119728
Dispersion	Sigma	1.00157	0.923617	1.094011

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.987636	0.8304

NMCS

ANOVA Assumptions

Constant Variance

SSR	# X cols	SSE	n	Breusch-Pagan	Chi-square
5.79E-10	3	0.001046	270	12.85914476	0.1690841

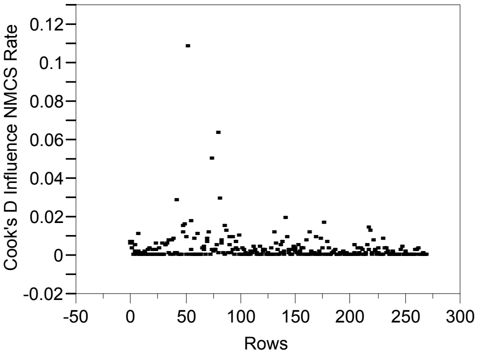
Independence

Durbin-Watson

Durbin-Watson	Number of Obs.	AutoCorrelation	Prob<DW
2.115013	270	-0.0606	0.7960

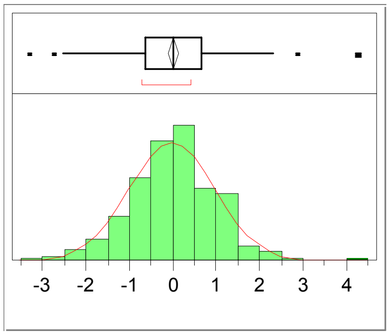
Influential Data Points

Cooks D



Normality

Studentized Residuals



Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	Mu	0.000397	-0.119641	0.120434
Dispersion	Sigma	1.001825	0.923850	1.094287

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.993117	0.9918

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Vita

Mr. Paul D. Faas graduated from Blackford High School in Hartford City, Indiana in 1978. He entered undergraduate studies at Purdue University in West Lafayette, Indiana where he graduated with a Bachelor of Science in Aeronautical and Astronautical Engineering in December 1982.

He accepted employment with the U. S. Air Force as a government civilian engineer at the Air Force Plant Representative Office, Rockwell International, Columbus, Ohio. Transferring with the Air Force to Arnold Engineering Development Center, Arnold Air Force Base, Tullahoma, Tennessee where he worked as a test project engineer. Transferring again with the Air Force to Wright-Patterson Air Force Base, Ohio, he has worked in several organizations within Aeronautical Systems Center and the Air Force Research Laboratory with the most recent office being the Logistics Readiness Branch, Deployment and Sustainment Division, Human Effectiveness Directorate, Air Force Research Laboratory. In August of 2001, he entered into long-term full-time training at the Graduate School of Engineering and Management, Air Force Institute of Technology in the school of Operational Sciences. Upon graduation, he will return to the Logistics Readiness Branch.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

The Air Force needs tools for analysis and evaluation of new logistic operational concepts. The purpose of this research was to construct a discrete event simulation model of the aircraft sortie generation process to permit what-if analyses of these concepts.

The current Air Force logistics operations system is reactive in nature, meaning that after the aircraft detects a part failure, the maintenance person must perform fault isolation procedures and then steps are taken to repair or replace the faulty item. The Autonomic Logistics System (ALS) concept changes this reactive process into a proactive one with the employment of technologies such as prognostics and distributed information network. Certain logistics tasks can be handled automatically or autonomously i.e. ordering parts, requesting maintenance specialists, and notifying maintenance control center.

The conclusion of this research was that an aircraft equipped with the ALS increased the measures of effectiveness (MOE) like mission capable rate and flying scheduling effectiveness up to a point. The research indicated that as ALS false alarms grew these MOEs decreased and eventually were worse than the baseline system. However, it is worth noting that this research simulated a worst case false alarm scenario, a part removal and replacement with each false alarm.

15. SUBJECT TERMS

Logistics, Aircraft, Maintenance, Sortie Generation, Simulation

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