A SIMULATION-BASED ANALYSIS

OF THE IMPACT OF IN-SOURCING A MAJOR PROCESS ELEMENT

ON THE COAST GUARD

HH-60J DEPOT MAINTENANCE PROCESS

THESIS

AFIT/GAQ/ENS/03-03

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Raymond R. Hill (Chairman)	date
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Steven E. Vigus

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Abstract

Leaders at the United States Coast Guard's Aircraft Repair and Service Center (ARSC) in Elizabeth City, North Carolina recently formalized their planning and analysis functions by adding a dedicated branch to their command structure. The Planning and Analysis Branch intends to apply computer modeling and simulation to study the impact of process changes to the various Programmed Depot Maintenance (PDM) lines. This research considers the applicability of this type of modeling and simulation, using ARENA to study the current HH-60J PDM process. The contribution of this research is a methodology specific to ARSC needs, an analysis of methodology based on a discrete event simulation model of PDM lines, and a specific case study demonstrating the methodologies. The response variable of interest is average PDM process time as a function of either in-sourcing or out-sourcing labor for a major process step. The research includes development and evaluation of a macro-level process model using ARENA 5.0.

A SIMULATION-BASED ANALYSIS OF THE IMPACT OF IN-SOURCING A MAJOR PROCESS ELEMENT ON THE COAST GUARD HH-60J DEPOT MAINTENANCE PROCESS

I. Introduction

Background

In an effort to reduce costs and improve service to its customers, leaders at the U.S. Coast Guard's Aircraft and Repair Service Center (ARSC) in Elizabeth City, North Carolina have recently added a Planning and Analysis Branch. Traditionally, process analysis and optimization were performed on an as-needed basis either by managers and supervisors from a variety of in-house work units or by an outside contractor. The standup of the Planning and Analysis Branch signals a high-level commitment by ARSC to bring state of the art modeling and analysis techniques and tools into greater use for in-house decision making.

The Planning and Analysis Branch is currently considering a change to the Programmed Depot Maintenance (PDM) process for the Coast Guard's HH-60J search and rescue helicopter. Vibration-induced cracks in one or more of the HH-60J's main beams, essentially the airframe's structural skeleton, frequently require replacement of the entire main beam. This has historically been done by on site at ARSC by an outside contractor on an as-needed basis. ARSC is considering purchasing the necessary tools and jigs and hiring additional workers to perform these repairs organically, without the contractor.

The equipment costs associated with adding beam replacement capability are relatively simple to define. However, the true benefit of adding workers requires considering of the value of their contributions to the entire PDM process. This study seeks to better understand how each of the two beam replacement strategies, organic or contracted, might affect the overall performance of the PDM process.

Programmed Depot Maintenance

The Coast Guard's aircraft maintenance program consists of three major types of maintenance actions. Unit-level maintenance, referred to as organizational-level maintenance, involves routine repairs and preventative maintenance performed by Coast Guard technicians at a Coast Guard Air Station. Some unit-level repairs require extensive back-shop work and may involve special tools and expertise that are usually associated with intermediate-level maintenance.

The second type of maintenance action is major modification, commonly referred to as a mod. Mods include system upgrades or large-scale repairs to add capabilities or correct deficiencies in an aircraft. Mods are sometimes performed by unit personnel, but are more commonly performed by special maintenance teams either at ARSC or at the Air Stations.

The third type of maintenance action, programmed depot maintenance (PDM), is the focus of this research. PDM is a thorough overhaul of the aircraft, generally consisting of the removal of all major components, inspection of the airframe and removed components, complete reconditioning of aging parts, reassembly and repainting of the aircraft. For all U. S. Coast Guard HH-60J helicopters, this work is performed at ARSC. Aircraft completing PDM are restored to a like-new condition.

Programmed Depot Maintenance Cycle

PDM schedules are planned to avert aircraft failures associated with high accumulated flight times. The probability of failure of aircraft systems is often described by a bathtub shaped probability distribution (Figure 1). Ebeling describes the cycle as a piecewise function characterized initially by burn-in failures, then by random mid-life failures and, finally, by late-life wearout failures (1997, 31). The high-incidence failures early in the cycle can be identified and corrected through a series of initial test flights. The failure rate then decreases dramatically and tends to stabilize until the aircraft accumulates enough flight time and/or system cycles to enter the region of increasing failures.

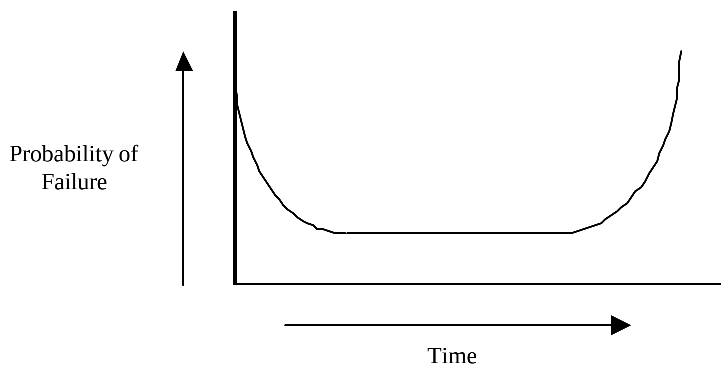


Figure 1. Reliability Bathtub Curve
(Adapted from Ebeling, 1997)

An aircraft PDM avoids the steepest part of the curve which represents the aircraft age at which failure rates increase significantly. The PDM concept assumes that a properly overhauled aircraft will have reliability characteristics similar to new aircraft. A PDM interval is the elapsed time between start of consecutive PDMs for a given aircraft.

By managing PDM intervals, ARSC strives to continually return each aircraft to like-new condition, avoiding increased failure rates associated with older aircraft. For the HH-60J, the target PDM interval is five years. This equates to a flow rate (work in process) of 5 aircraft with a nominal process time of 146 work days, based on an assumed 245 work days per year for the work force. A significant increase in process time would require an increase in flow rate in order to meet the fleet-wide target PDM interval. This relationship is illustrated by Figure 2.

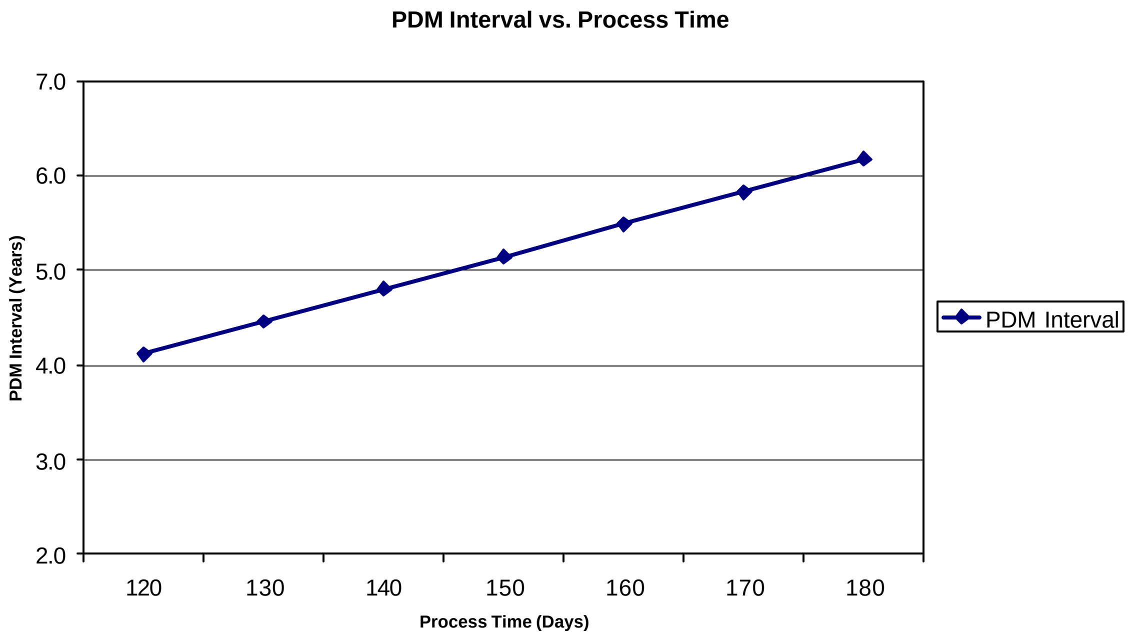


Figure 2. Effect of change in process time on WIP

In practice, work in process (WIP) is limited by available floor space inside ARSC's PDM hangar and by operational commitments. The Coast Guard operational concept for the HH-60J is based on a fleet of 42 aircraft, 5 of which are in PDM at a given time. Figure 3 illustrates the resulting relationship, where work in process is held constant at five units and changes in PDM cycle times affect the PDM interval.

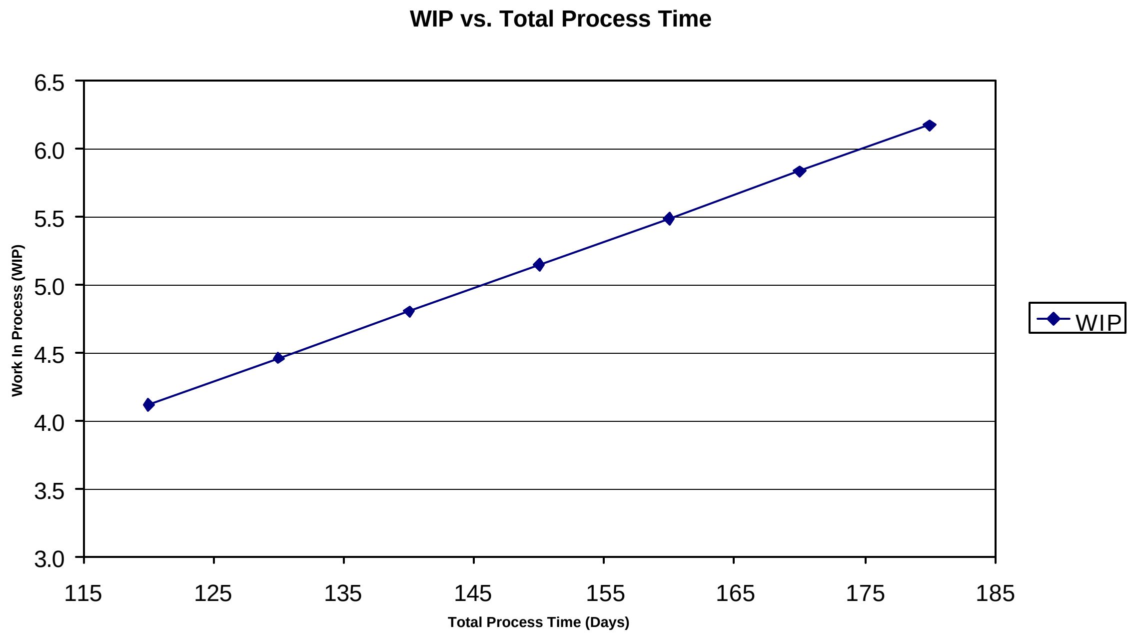


Figure 3. Effect of Total Process Time on PDM Interval

As these models illustrate, a reduction in PDM cycle time benefits ARSC either by reducing requirements for WIP, by shortening the time between PDM cycles, or by some combination of the two.

Problem Statement

The existing beam replacement process for Coast Guard HH-60J helicopter relies on an outside contractor to provide labor, special tools and assembly jigs. ARSC is considering purchasing the necessary equipment and hiring additional workers to perform beam replacement in-house using organic resources. An increase in the workforce may provide additional benefits that extend beyond completion of required beam replacements. The complexity of the PDM process makes it difficult to correctly predict the full impact of additional structures workers. ARSC decision makers need to better understand the effects of beam replacement labor resources on aircraft process time.

Research Questions

This research is designed to answer the following questions:

- Is an ARENA model the appropriate tool to conduct this research study?
- How well does the ARENA model represent the effects of changes in labor resources for ARSC's HH-60J PDM line?
- Will an increase in structures shop labor likely reduce PDM process time as compared to having beam replacement work done by a dedicated crew of contract workers?
- What improvements can be made to the model or data sources to develop a better ARENA model for future research?

Summary of Current Knowledge

The overall PDM process is well defined. Historical process times for HH-60J PDM are available as well as a complete history of aircraft arrival and completion times. The flow chart in Figure 4 depicts an aggregate view of the HH-60J overhaul process.

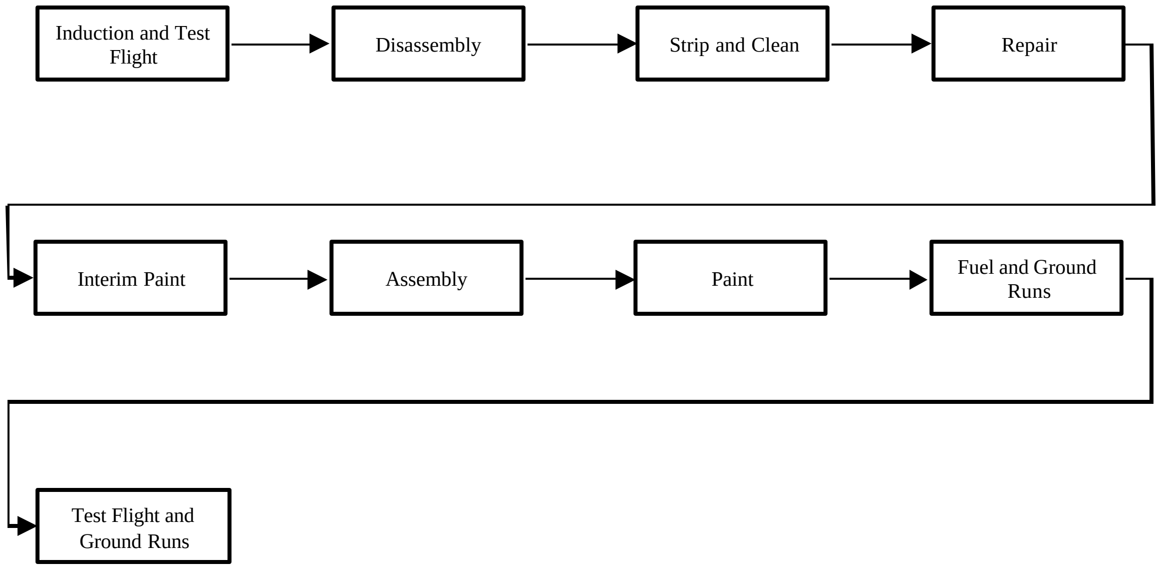


Figure 4. Basic HH-60J PDM Process

Within ARSC's databases, labor hours are charged to each PDM aircraft by work center and type of work performed. The current categorization of labor expenses is designed to meet ARSC's internal cost accounting practices. The data that align best with the requirements for this research are macro process times and labor hours. These labor hour data are difficult to attribute to detailed work tasks. ARSC's emphasis on macro-level hourly charges mean that any actual data is more appropriate for an aggregate-level model versus a detailed, task-oriented model.

According to ARSC analysts, computer modeling is a new organic analysis tool for examining the HH-60J PDM line. The modeling, methodology, simulation analysis techniques, and beam-replacement focused case study in this research will be a basis for future modeling and analysis efforts within ARSC.

Assumptions

The simulation model that serves as the primary research tool for this thesis depicts a macro view of the PDM process. Within each macro process step, there are actually detailed sub-processes that consume resources of time, labor and materials at varying rates. A macro-level simulation model assumes that each discrete process step can be aggregated into a high-level process step for modeling simplicity. Interviews with line managers at ARSC suggest that this approach is appropriate because line supervisors are empowered to adjust the sequence of specific tasks within an aggregate process step to keep the overall PDM project on schedule. Without aggregating tasks, accurately depicting all possible task sequence combinations would be difficult, and impractical, to build, particularly since we want to model the entire PDM process, not just some piece of the process.

Resource tracking modules within the computer model assume aggregation of labor within each work center. This means that any task which requires labor from a given work center can be performed by any craftsman in that work center. It also means that modeling of labor hour divisions may not exactly match actual task requirements. That is, a task scheduled to be performed by one person for two hours may be executed in the simulation by assigning two persons for one hour each. In some cases this may give an optimistic view of system capabilities. In practice, the manner in which craftsmen are routinely redirected to assist fellow workers to keep project work flowing suggests that this approach is appropriate.

Scope

This study focuses on the likely outcome of two different ARSC staffing policies for conducting beam replacement step during PDM. The primary measure of interest is total process time for any aircraft completing PDM. However, a major objective of the research is also to explore how well simulation methodology in general and our specific model serves to provide insight into the PDM process.

Thesis Overview

A literature review of simulation theory and modeling experiments provides a precedence for computer modeling of the PDM process. A recent AFIT project by Shyong (2002) studied the effects of inventory levels on cost and process times for depot level repair of a turbine engine component. Shyong used the ARENA modeling tool, as does the ARSC analysis branch. Thus, the decision to use ARENA for this project was the practical choice.

The simulation model built is a macro model of the PDM line for H-60J airframes. This model views the process as a single overhaul line that receives helicopters from Coast Guard units, performs the required overhaul steps, and outputs rebuilt aircraft. Some aircraft will require replacement of one or more main beams as a part of the PDM process. The simulation model accommodates this process difference by routing individual entities according to work required. It also collects time statistics for each entity that passes through the process for later analysis.

Simulation theory requires two reviews of a model: verification and validation. Verification is a review of the computer code and process structure to confirm that the model is constructed correctly with respect to the actual structure of the process being modeled. It also confirms that there are no errors in the basic programming flow, syntax, or data entry. Validation is a common-sense review of the model to confirm that outputs produced by the simulation match the real world (Kelton, et al, 2002: 43).

In the verification phase, AFIT experts review the ARENA model code for errors. The logical structure of the macro model is reviewed by the ARSC sponsor to ensure that it matches the flow of the real-world system.

Validation involves model runs using process times and induction intervals based on historical data. Because actual labor resource requirements for each sub-process step are not clearly defined in the data, it is impossible to completely cross-check the behavior of all model elements against the real-world system. Validation of this model relies on a judgment by researchers that its behavior is consistent with what is expected from the real-world system. Because the computer model structure parallels the verified macro model logic, validation of the computer model also includes confirming that the ARENA model logic matches the macro model logic.

A two scenario experiment is run with the verified and validated model to predict the effects of two different staffing policies for the beam replacement process step. Scenario one assigns the required labor to a dedicated team of five contract workers who work on beam replacement exclusively. Scenario two increases the ARSC structures shop workforce by five workers, allowing them to work on other PDM tasks when not engaged in beam replacement work. The average process times for PDM aircraft in each scenario are compared to determine whether scenario two, organic beam replacement, decreases average process time.

Analysis of results includes evaluation of the results of the process time study as well as an assessment of the ARENA model as a suitable research tool for additional studies of the PDM process.

II. Literature Review

Introduction

This literature review briefly summarizes some of the published works that support the basic premises, methodology, and conclusions of this research. It begins with background information on Coast Guard HH-60J helicopters. It then defines each of the two measures of effectiveness: time and schedule. Next, it reviews the applicability of various scientific approaches to evaluating depot maintenance processes. Finally, it considers the applicability of the selected research approach, simulation, and defines key terms and concepts used in computer simulation.

Coast Guard HH-60J Programmed Depot Maintenance

The United States Coast Guard operates a fleet of 42 HH-60J "Jayhawk" helicopters located at twelve Air Stations throughout the United States. These aircraft are stationed at coastal units and are used for a variety of missions including search and rescue, law enforcement and marine environmental safety. Coast Guard personnel perform day-to-day maintenance at each aircraft's base of operation, forward deployed site, or shipboard. These maintenance actions range from minor inspections to replacement of large subassemblies such as engines or transmissions. Generally, major maintenance actions and system upgrades that involve extensive disassembly of the airframe or excessive labor are performed at ARSC in Elizabeth City, North Carolina. ARSC planners use a master PDM schedule to sequence the complete overhaul of each aircraft in the fleet based on each aircraft's time since last PDM. Generally, each airframe returns to ARSC every five years for PDM. A major driver of this five year

PDM interval is the airframe corrosion that develops due to the harsh Coast Guard operating environment.

The scheduled process for completing PDM requires 128 days. This schedule allows for repairs and upgrades to electrical, mechanical, avionics, and structural components and systems as well as all normally required corrosion control and paint work. Most of the work is performed in-house by a team of coast guard active duty and civilian craftsmen.

Measures of Effectiveness

The primary measure of effectiveness considered in this research is process time. Gilbride (2002) examined the PDM outsourcing decision process and found that process time is valued by the Coast Guard and should weigh heavily in the selection of the best source for PDM work. This is consistent with the expressed priorities of ARSC, the sponsor of this research.

Process time means task duration and is related to output rate as given by the following formula:

$$pt = \frac{1}{r} \qquad (1)$$

where pt is process time, and r is desired output rate. (adapted from Krajewski and Ritzman, 2001: 470) The PDM process time is the basis for the overhaul schedule, and determines the length of time a given aircraft will be unavailable for operational service. The relationship between operational availability and maintenance cycle time is described by the formula:

$$A_o = \frac{MTBM}{MTBM + MDT} \qquad (2)$$

where *MTBM* is the mean time between maintenance and *MDT* is maintenance down time (Blanchard, 1998:127). In the PDM environment, PDM process time is the MDT used to calculate operational availability. As process time decreases, MDT decreases, and operational availability increases.

Theory of Constraints

A popular approach to optimizing performance of a sequential process is to identify the most constrained resource and focus improvement efforts there. The term *constrained resource* suggests something in limited supply such as raw materials, machine cycle rate, manpower, etc., and is commonly referred to as a bottleneck. Throughput of the bottleneck must be improved in order to improve throughput of the entire system. (Goldratt, 1990: 5)

Roser et al. (2001: 949) examined various approaches to identifying bottlenecks in a process and concluded that doing so is no trivial matter. They found two prominent techniques for analyzing processes for bottlenecks: measuring wait time before process steps, and calculating overall utilization of the resource. In each case, the resource generating the highest value is the bottleneck. They point out that this approach is limited in that it concentrates on machine utilization and virtually ignores the effects of other elements such as supply and demand, and human workers. They offer a more robust model for identifying bottlenecks by considering these and other factors.

Modeling Approaches

While modeling tools for decision making are varied and many, they can each be categorized as either prescriptive, predictive, or descriptive. Ragsdale (2002: 8) offers two criteria for evaluating into which category a model fits: form of the function f(*), and values of independent variables:

Table 1. Modeling Techniques
(Ragsdale, 2002)

Category	Form of f(*)	Values of Independent Variables	Modeling Techniques
Prescriptive Models	known, well-defined	known or under decision-maker's Control	Linear Programming, Networks, Integer Programming, Critical Path Modeling (CPM), Goal Programming, Economic Order Quantity, Nonlinear Programming
Predictive Models	unknown, ill-defined	known or under decision-maker's control	Regression Analysis, Time Series Analysis, Discriminant Analysis
Descriptive Models	known, well-defined	unknown or uncertain	Simulation, Queuing, Program Evaluation and Review Techniques (PERT), Inventory Models

Applying these guidelines, a model of the PDM process is classified as a descriptive model. The cause and effect relationships between process variables and system outcomes are well known, and variability in process times makes the values of independent variables uncertain. As we note from Table 1, simulation is an appropriate tool for this type of model.

Vashi and Bienstock (1995: 197) focus specifically on logistics applications when describing three popular modeling approaches: optimization, heuristics, and simulation. They analyze pros and cons of each and encourage the potential application of multiple approaches to the same problem.

The first approach, optimization, prescribes a best, or optimal, combination of values for variables over a given range to maximize the objective value of some mathematical programming model. For a given range of values, this should prove to be the most effective approach. However, when the exact range of values for variables is unknown, and the model produces some optimal solution for that solution space, that solution may not necessarily be the optimal solution for the problem at hand. A second limitation involves large solution spaces that can require unreasonable computer processing times to produce a solution. In these cases, the computer program will stop its search according to a predetermined heuristic. This limiting approach carries no guarantee of finding the true optimal solution but may be the only viable approach when applying optimization to complex problems such as the PDM process.

The second approach, heuristics, applies a "rule of thumb" to the decision process. Often these heuristics are based on user experience and can often lead the decision maker to a reasonably good solution. There is, however, no guarantee that this solution is the optimal choice. The approach is also somewhat limited because it is based on previous experience. It is unlikely that an innovative new solution will be found unless the heuristic model itself provides some mechanism for generating innovations.

The third approach, simulation, was selected for use in this research. Simulation addresses the special requirements of a complex processes, not only by allowing for variability, but also by facilitating stochastic analysis. The PDM process is affected by changes in process times, lead times, arrival times, inventory levels, etc. Computer simulation allows researchers to model stochastic processes and to analyze the effects of various policies, not only on the objective function, but also on each intermediate variable, and derive probability distributions for a range of results versus a single predicted output value.

Related Logistics Research in Modeling and Simulation

There are numerous examples of successful application of simulation to aspects of the depot maintenance process. Shyong (2002) evaluated the effects of various spare parts levels and queuing policies on process time and cost for the overhaul of the F101 LPT rotor at Tinker Air Force Base. His detailed model of both front- and back-shop activities met verification and validation criteria and identified potential savings in both time and cost for this step in the overhaul process. More importantly, his research demonstrated the value of simulation in evaluating cost and time improvement opportunities in other engine overhaul sub-processes. (Shyong, 2002)

Mooney (1997) studied turn around time by experimenting with a model of a single critical hydraulic control part. His model predicted process times for repair of this component at the Naval Aviation Depot. By modeling the effects of various changes in the process flow, he was able to identify process improvements to generate savings in cost and process time. (Mooney, 1997)

Schuppe et al (1993) modeled the addition of two major process tasks to the C-141 airplane PDM process. They applied simulation to predict the effects of the increase in work tasks on existing PDM schedules and resources (people, hangar space, test equipment, tooling, and money). The simulation predicted that the new process steps would result in a shortfall of production needed to meet customer requirements. The team identified a few sub-processes as bottlenecks requiring additional attention as likely sources of process improvement.

Computer Simulation Concepts and Methods

Kelton et al (2002: 8) report that simulation leads all other operations research tools in popularity. The almost ubiquitous presence of powerful desktop computers in business offices places the necessary computing power for simulation studies within reach of most managers.

Early non-computerized simulations and modern analytic models were limited in their complexity by the user's ability to process data. This limitation was usually addressed by generalizing the performance of elements of the model and by making assumptions about interactions of entities and values of variables. When dealing with complex systems such as a PDM line, these simplifications can render the model ineffective. Computer models can be built as complex or as simple as necessary to provide the necessary level of detail for the system elements being studied.

Models of large-scale systems quickly become very complex, taxing programming resources and computer processing power. Increases in desktop computing power and the availability of high-level simulation languages now allow researchers to experiment with large, detailed models that were previously impossible to work with. (Law and Kelton, 2000: 2)

Model Verification and Validation

Verification of a model is the process that confirms the model faithfully represents the conceptual model (Kelton, et al 2002: 42). This involves reviewing the logic with system experts and considering the effects of possible inputs and interaction within model elements. A properly verified model accurately represents the system concept that, in turn, represents the elements of the real world system under study.

Kelton, et al (2002: 43) associate validation with a comparison of simulation results against observations of the actual process. The range of results from a valid simulation should encompass results from the real-world process. However, many simulations model rely on abstraction of the model for simplicity or are designed to study the results of scenarios for which there are no real-world examples. Law and Kelton (2000: 86) address the case where there is no existing system for comparison. They recommend having analysts and experts review the model for correctness and reasonableness of the model outputs.

III. Methodology

Introduction

This chapter discusses the research methodology. It explains the basis for selecting simulation modeling as a research vehicle and describes the process used to define and develop the final model. It then describes the specific functions of major model elements, model logic structure, and methods used to collect and analyze output data. It also reviews the verification and validation process that was employed.

Selection of Computer Simulation as the Research Vehicle

A variety of tools are available to study the behavior of a system. Law and Kelton (2002) offer a discussion of these options and an illustration (adapted as figure 5) that shows how these methods relate to each other and the type of system to be studied. One decision that a researcher makes is whether to experiment with the actual system or to experiment with a model of the system. For a complex system such as the Coast Guard helicopter PDM line, experiments with the actual system are impractical due to the long cycle times. Actual cycle times for the process vary, but considering a nominal 146 day cycle time, with five units in the PDM process, it would take over a year to collect data on 10 aircraft PDM cycles. For this reason, experimentation with a model of the system was selected.

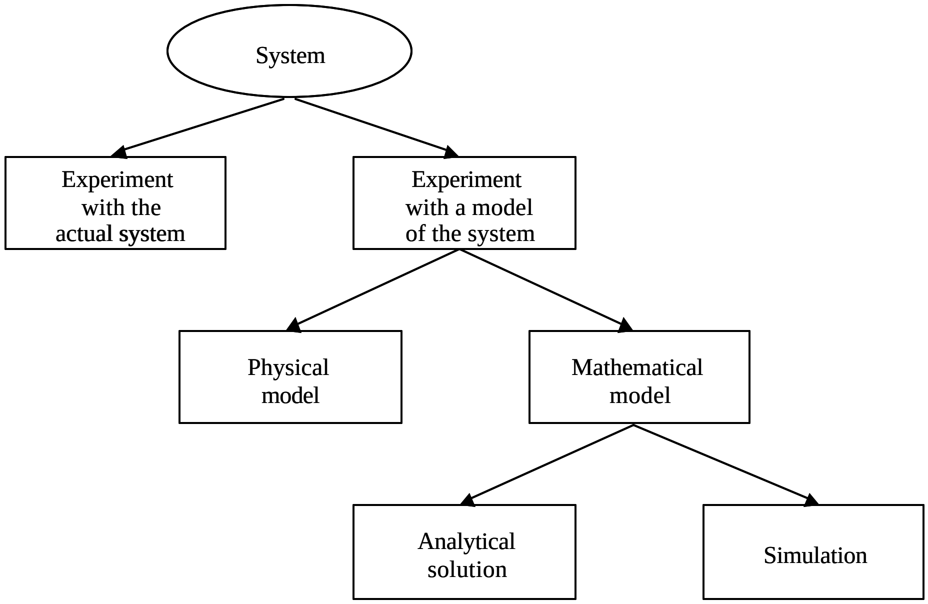


Figure 5. Ways to study a system

Adapted from Law & Kelton (2002: 4)

Among modeling options are physical models and mathematical models. Physical models generally employ some type of scale model to examine the effects of changes in the physical system components. In this study, the variables of interest focus more on event scheduling than on the physical plant layout. For this reason, a mathematical model is best suited to representing system behavior.

Within the category of mathematical models are analytical solutions and simulation. The former approach requires a complete understanding of the exact relationships between processes and functions that comprise the system. It also requires that the system be simple enough to allow researchers to develop accurate mathematical formulae to describe the interaction of system elements and calculate the value of all output variables of interest. Stochastic process techniques offer a viable option.

However, complexity of the PDM process and the complex interactions between system elements over time seemed to indicate that simulation is the best approach to system modeling.

Conducting a Simulation Study

Researchers have applied slightly different procedures for developing and conducting simulation studies. Shyong (2002:29) based his design and analysis process on the models presented by both Montgomery (1991:9) and Altiok and Melamed (2001: 6), resulting in a proces that is uniquely adapted to simulation of the details of a specific element of the PDM process, specifically the repair of the low pressure turbine component of the F101 turbine engine. Law and Kelton (2002:84) offer a model which follows the same general flow but which includes a feedback path that suggests reviewing previous process steps after verification and validation. This research follows Law and Kelton's model (figure 6).

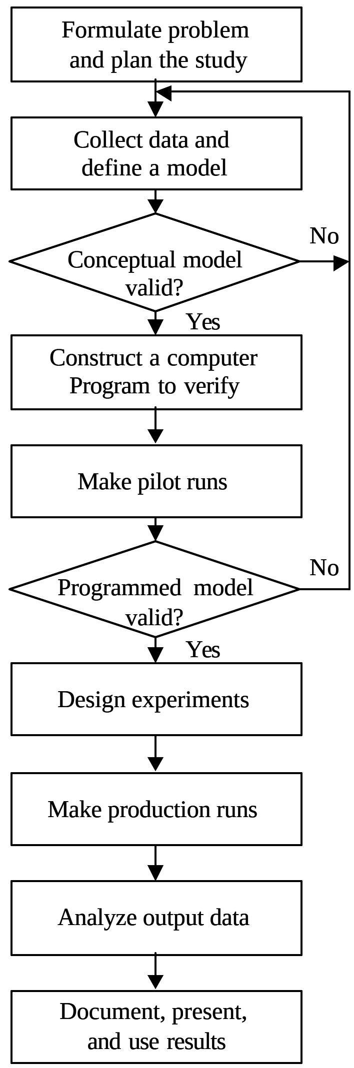


Figure 6. Steps in a Simulation Study
(Law and Kelton: 2000:84)

Formulating the Problem and Planning the Study

The objective of this simulation study is to consider the possible effects of beam replacement staffing and scheduling policies on the overall process flow time for HH-60J PDM. The basic process model will be modified to create two models, each representing a staffing strategy.

The first model, scenario one, simulates the current policy of bringing in a team of contracted technicians who work exclusively on beam replacement for those aircraft requiring this work. In ARENA, the resource for this work is Beam Contractor.

The second model, scenario two, adds to the in-house team of structures technicians who can work on any process tasks requiring structures workers. Beam replacement work takes priority over other structures tasks in this scenario.

Collecting Data and Defining a Model

Line supervisors for the HH-60J PDM line provided detailed maintenance schedules for their respective processes. These schedules were based on point estimates of process times for each major task. From these master schedules, an equivalent logic flow diagram was generated to define the predecessor relationships between concurrent tasks. Some sequential tasks that involved a single work shop were combined to simplify the model logic. Similarly, some tasks were broken into sub-tasks, designated as initial and final, to allow partial completion of one task to function as a predecessor for another task. The resulting macro model is included as Figure 7. Supporting sub-models of this macro are included in Appendix A.

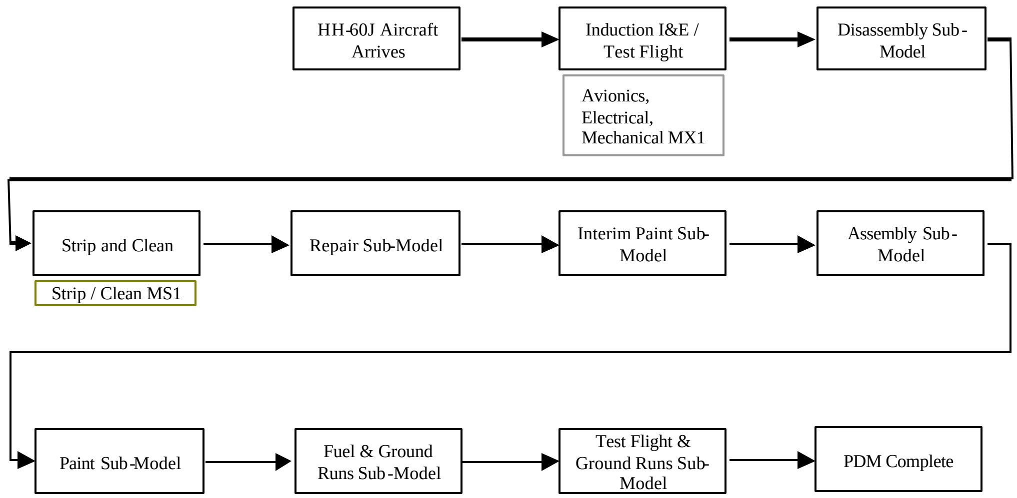


Figure 7. HH-60J PDM Main Model Logic Flow Diagram

For modeling purposes, the PDM process is viewed as a series of sequential task groups. The model assumes that workers complete the induction phase first, then move on to disassembly, strip and clean, repair, and so on. Within a major task group, tasks can be completed sequentially, simultaneously, or both. These task groups are modeled in ARENA as sub-models. Figure 8 shows the tasks and logic that comprise the Disassembly Sub-Model.

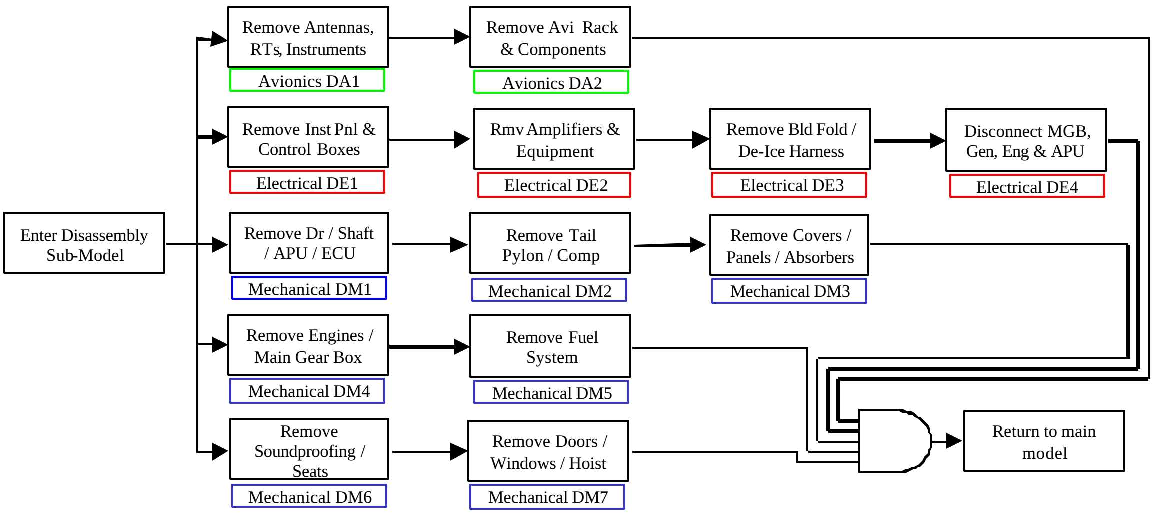


Figure 8. HH-60J PDM Disassembly Sub-Model Logic Flow Diagram

For the example in figure 8, task DA2 (Remove Avi Rack and Components) commences after completion of task DA1 (Remove Antennas, RTs, Instruments). Tasks DA1, DE1, DM1, DM4 and DM6 may be performed simultaneously if adequate labor resources are available. The five-input AND symbol indicates that all five predecessor tasks must be completed before completing this sub-task and starting the next step in the macro PDM process (the task groups in Figure 7).

When converted to ARENA logic, the same sub-model is represented by the logic flow illustrated in Figure 9. The initial branch to five parallel process steps is accomplished by using the duplicate block from ARENA's Blocks menu. The duplicate block creates four duplicate entities plus the original. Each of the five entities then proceeds through the logic independently until being combined back into a single entity at the Batch block. Once divided, each entity represents a portion of the work to be performed in the Disassembly Sub-Model. The Batch block performs the AND function by blocking entities from flow back to the main model until all required sub-model work is complete.

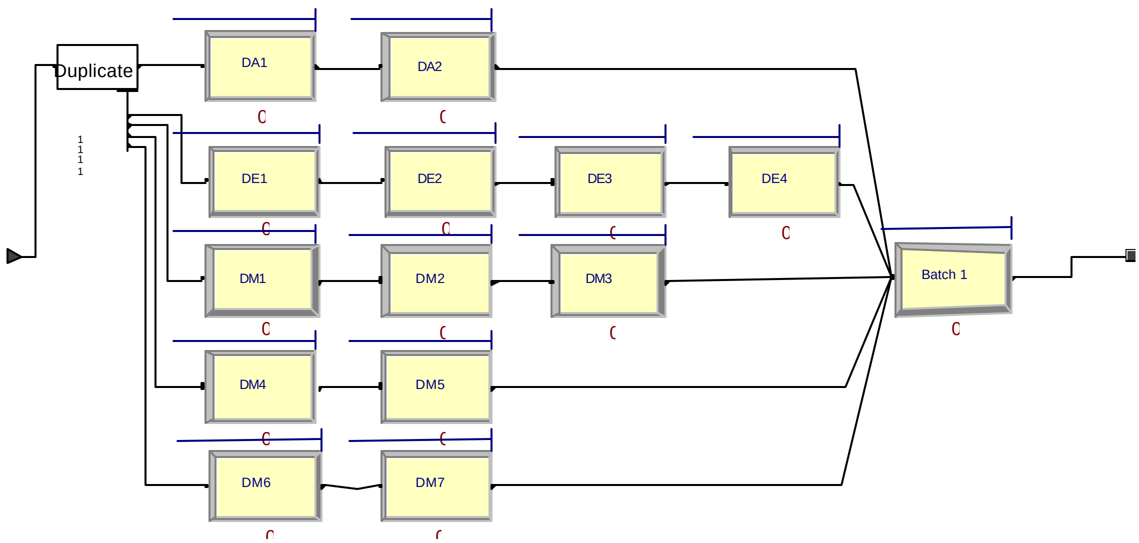


Figure 9. HH-60J PDM Disassembly ARENA Sub-Model

The arrival of aircraft to PDM is scheduled based on availability of production resources. In actual ARSC schedulers coordinate with Air Stations so that a single aircrew can deliver a completed aircraft to an air station and pick up the next unit for induction. This capacity-driven arrival sequence is modeled in ARENA as two Create Entity blocks and a Seize block (Figure 10).

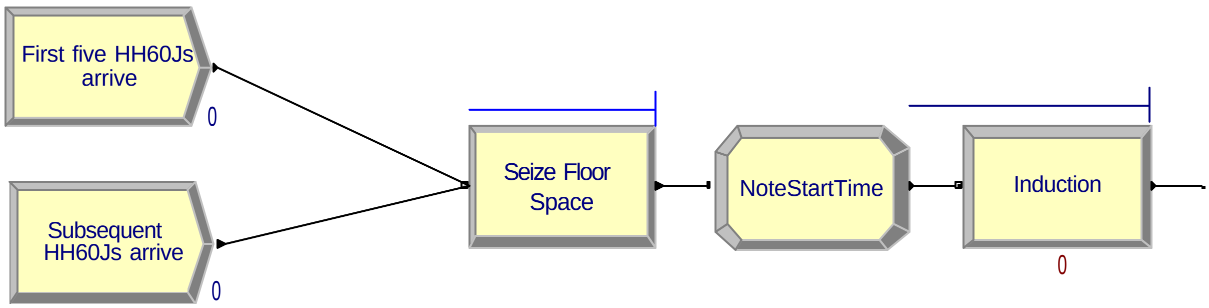


Figure 10. HH-60J Entity Creation and Release Logic

The first five entities are generated according to a constant inter-arrival time schedule to evenly load the PDM production line. Subsequent entities are generated after the fifth entity and stored in the Seize Floor Space queue until the resource Floor Spaces becomes available. By limiting Floor Space to five, this block limits work in process to five.

Validating the Conceptual Model

ARSC staff reviewed the logical model for logic flow and predecessor relationships between task elements. Changes to the model were incorporated prior to construction of the ARENA model.

Constructing and Verifying the Computer Model and Making Pilot Runs

An ARENA model of each process line was developed using the validated logic flow diagrams and process times. Sub-models were developed independently and tested as stand-alone modules to verify correct operation before being integrated into the main model. A master data dictionary was used to verify the correct assignment and use of element names and assignment of resources. An element-by-element review was conducted to verify that each ARENA data field matches the corresponding data dictionary entry. Proper interaction of sub-models was checked by observing ARENA-generated animation.

The labor hour data that are currently available for the HH-60J PDM process are not categorized by individual work center and work task. Labor hour data are further obscured by the combination of front shop and back shop tasks involved in the PDM process. Individual workers may be assigned to front shop activities, back shop activities, or both. Our model only focuses on front-shop activities. This model deals with the floating labor pool by assuming that line supervisors schedule workers with a priority on front shop tasks to meet production schedules. Fluctuations in front shop process times will result in fluctuations in available back shop labor. For the existing PDM process, it is assumed that manpower is staffed to allow for routine fluctuations without negatively impacting the completion of back shop work.

ARSC's current policy for beam replacement is to bring in contracted workers, just for the duration of the replacement, then to release the workers. An alternative, adding in-house resources, assumes that the current structures shop manning level has historically met production requirements, cannot accommodate the additional labor demands of beam replacement.

To determine the appropriate structures shop manpower level, a response study was conducted using ARENA's Process Analyzer. Initial manning levels were suggested by ARSC analysts and served as the started point for the response study. Based on multiple runs of 30 repetitions each, manning levels were determined for each shop, producing a mean process time of 131.45 days. Structures worker manning was set at 11, a level that provided a minimum process time that is sensitive to a decrease in number of structures workers. This simulates a staffing level where the addition of a major task such as beam replacement would impact manpower available for other tasks, either in the front shop or in the back shop.

The beam replacement step was added to the model by inserting one Decide block and one Process block (Figure 11). The modeled probability of replacing a beam (76%) is based on historical data provided by ARSC. The beam replacement block is placed in series with the repair process flow to model a 25 day increase in process time due to beam replacement.

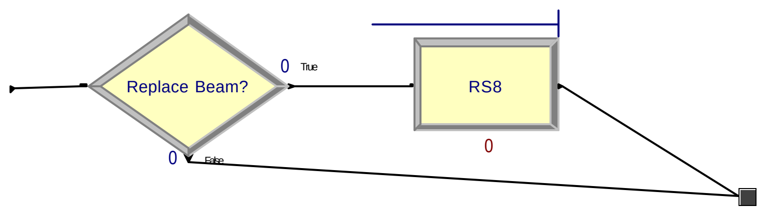


Figure 11. HH-60J PDM Beam Replacement Logic

Validating the Programmed Model

The graphical interface in ARENA allowed construction of a model that very closely resembles the logic diagram reviewed by ARSC. ARSC analysts validated the logic for beam replacement by reviewing probability and process time assumptions. The remaining ARENA logic was verified by comparing ARENA with the corresponding logic element in the logic model. The process times and resources were then compared to those recorded in the data dictionary and the original project schedule from which the data dictionary was developed.

Designing Experiments

The study utilizes two experiments. Each experiment focuses on one of two staffing policies. In the design phase, values were determined for each of four parameters for these experiments: initial entity arrival interval, warm-up time for simulation, duration of simulation, and number of simulation repetitions.

Entity arrival interval only applies to the first five entities. When one of these entities completes the PDM process it triggers the start of a release of a new entity from the queue. Process output intervals were inspected visually for balanced inter-arrival times and total process times using an ARENA plot of process time versus completion time for a single 10,000 day simulation (Figure 12). A 20 minute arrival interval produced an output pattern that evenly distributes initial inter-completion times and minimizes bunching of entities completing the process.

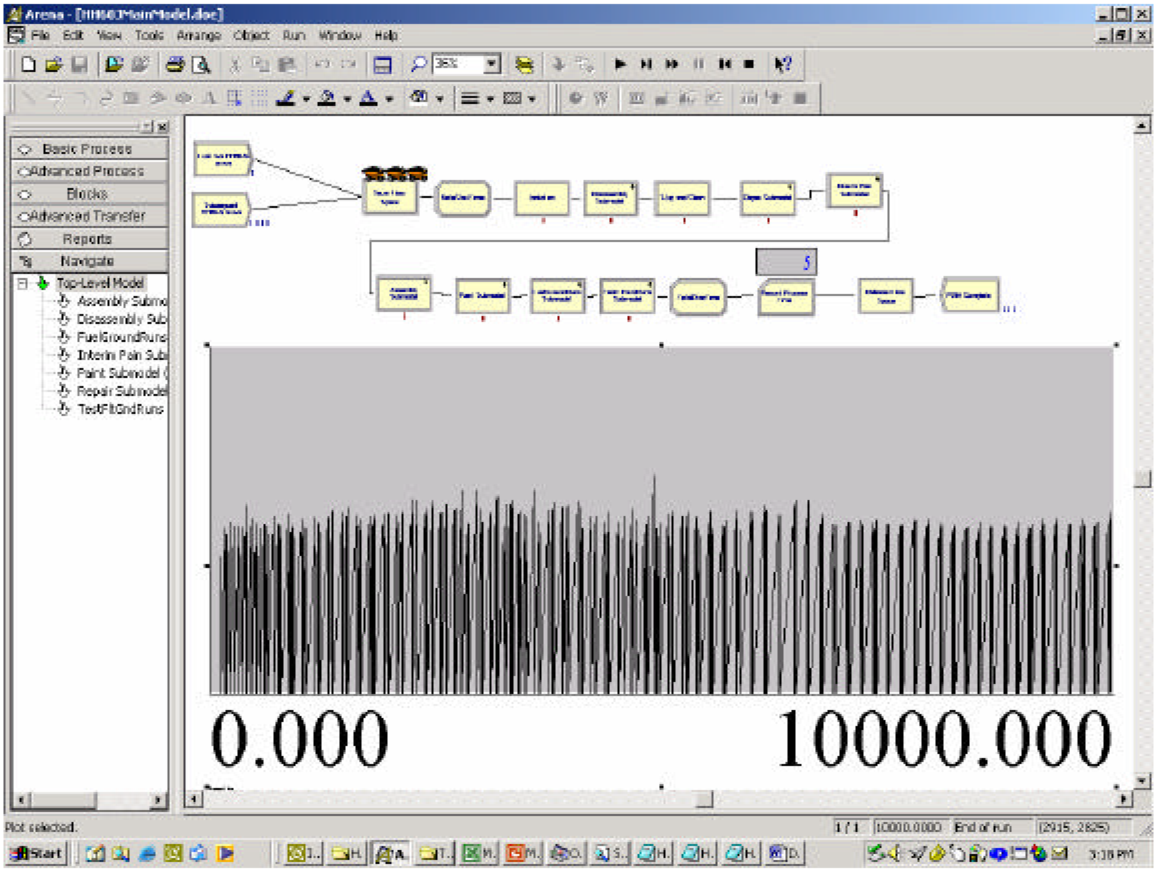


Figure 12. HH-60J PDM Entity Process Output Intervals

Warm-up time was similarly determined using a visual inspection of the plot of entity total process time versus entity number (Figure 13) The process time pattern becomes stable as soon as the process is fully loaded with five entities. Based on this observation, the warm-up time was set to 150 hours to delay data collection until the process is fully loaded. This inspection method for determining warm-up time is offered by Kelton, et al (2002: 288) as an appropriate technique for determining when steady state appears in a simulation.

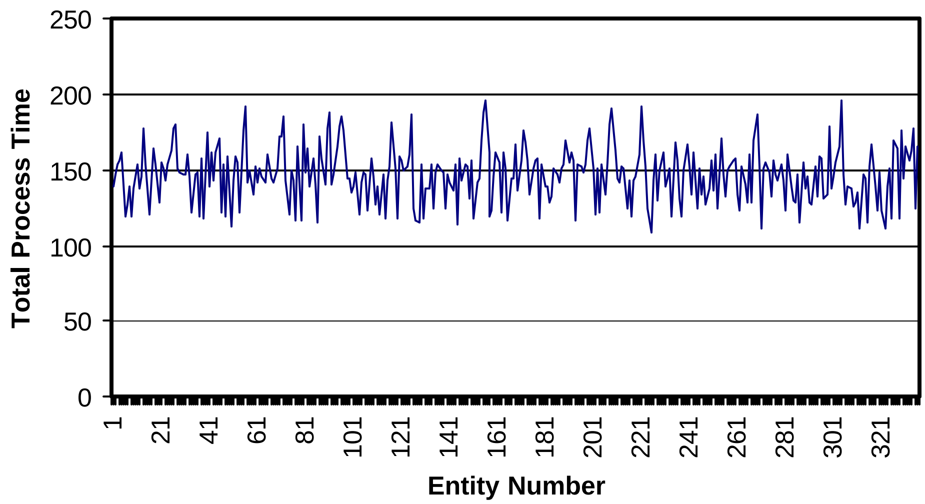


Figure 13. HH-60J Entity Process Times

The duration of the simulation was selected based on available computing power. The 10,000 hour simulation used for the previously described testing requires approximately 15 seconds of computing time. This allows the experiment to be run within the time domain that initial testing was done.

To estimate the number of repetitions required, results of the initial 30 repetition runs were used. Scenario 1 produced an average process time of 147.14 days with a sample standard deviation of 0.83 days. Scenario 2 produced an average process time of 145.92 days with a sample standard deviation of 1.45 days. A target 95% confidence interval of 0.5 days (with a corresponding 0.25 day half-width) was selected for the final production runs. Initial estimates of scenario standard deviations were used to estimate replications required to achieve the specified precision.

Law & Kelton (2000) offer a formula for calculating a point estimate and confidence interval for the population mean, given the results from *n* independent replications of a simulation.

$$CI = Xbar(n) \pm t_{n-1,1-a} \text{ SQRT} [s^2(n)/n] \qquad (3)$$

The results from scenario 1 produced the largest sample variance. This worst-case scenario was used as the basis for calculating the baseline confidence interval:

$$CI = 145.92 \pm 1.96 \cdot \text{SQRT}[2.10/30] \qquad (4)$$

$$CI = 145.92 \pm 0.52 \qquad (5)$$

This confidence interval exceeds the target interval of ± 0.25 days. The original formula provided a basis for solving for *N*, number of repetitions required, based on the results of 30 repetitions:

$$N=[(1.96 \cdot 1.45)/ 0.25]^2 \qquad (6)$$

$$N=129.2 \qquad (7)$$

Based on this result, the theoretical minimum number of repetitions to achieve the desired confidence interval of ± 0.25 days is 130. Law & Kelton (2000: 513) emphasize that this is only an approximation of the number of required replications and that this formula is offered as a tool to manage computing resources when unnecessary replications will waste limited computing resources. The actual computing time for 30 replications of this simulation is under ten minutes. Thus, we increased the number of repetitions to 140, increasing the likelihood that the simulation will achieve the target confidence interval for average process time.

The use of common random numbers was considered as a means to reduce variance in comparing two systems. This study considers two modeled alternatives that include the same number of process steps, suggesting that it might be a good candidate for synchronized random-number allocation. Kelton, et al (2002: 484) describe synchronization as a method of inducing correlation between two or more models so that a more accurate comparison can be made between them. As entities pass through the ARENA model of the PDM process, they experience delay times based on the defined probability distributions for these times. The actual value drawn from each distribution is determined by the random number data stream. With 66 process blocks in the PDM ARENA model, the sequence of entity flow through the model is substantially affected by the interaction between these random draws. If all entities passed through the model in the same sequence, then assignment of random number streams to each process block could synchronize the random numbers used in two models. However, the decide block that redirects some entities to beam replacement also provides a means for entities to pass each other in the process and for any specific aircraft to follow different processes within each scenario. This disruption of entity sequencing means that a direct comparison of average process times by entity is not practical.

Production Runs

Two scenarios were selected. Scenario 1 models a process with five dedicated contract workers assigned to work on beam replacement exclusively. Scenario 2 models a process with five structures workers assigned to work primarily on beam replacement, but assigned to work on other available structures tasks when not actively working on beam replacement. Beam replacement work takes priority over other tasks for these workers.

Each scenario was run for 140 replications of 10,000 hours each with statistics collected on average process time for each replication.

IV. Results

Introduction

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

Hypothesis and Hypothesis Testing

The experiment involves a hypothesis test designed to examine whether staffing the beam replacement process step with general structures shop labor will provide an improvement in process time, as compared to having a dedicated team of beam replacement contractors perform the work. Given outputs from simulations of the two alternatives, the test is:

H_o: P_1-P_2=0

H_a: P_1-P_2? 0

Where: P_1 = Average process time for scenario one and

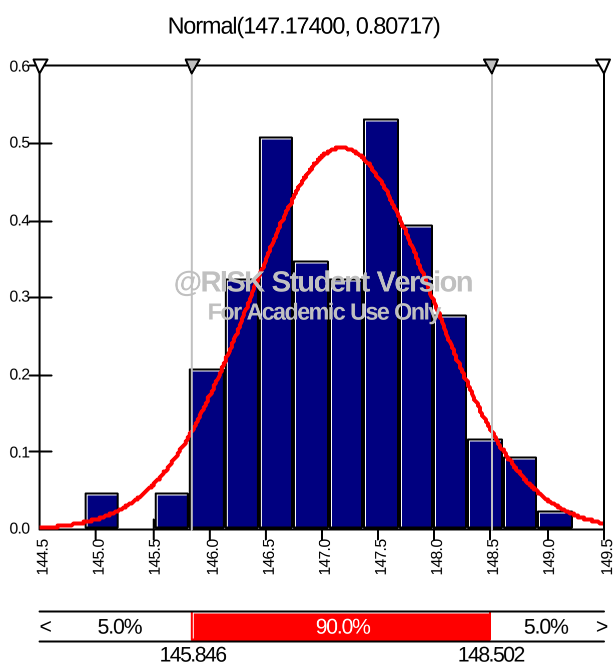
P_2 = Average process time for scenario two.

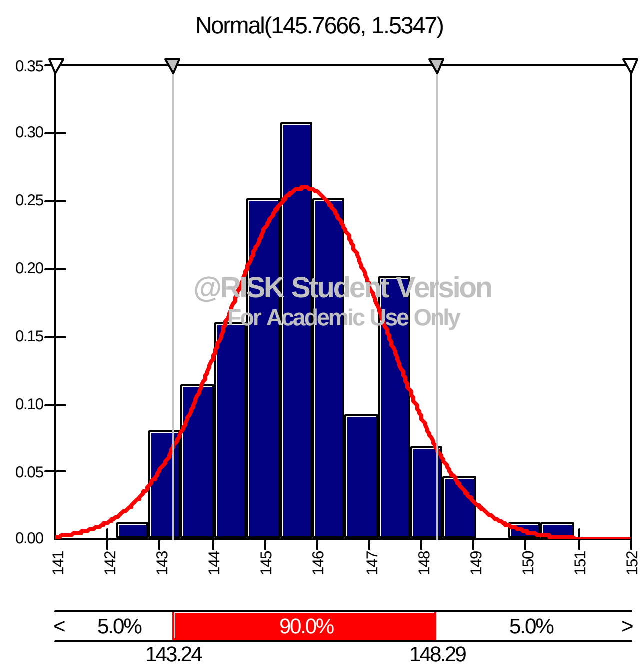
The null indicates no difference in process times between scenario one and scenario two. If the test rejects the null hypothesis, then the alternate hypothesis, there is a difference in process times between scenario one and scenario two, is presumed to be accepted. If the hypothesis test fails to reject the null hypothesis, then no conclusion regarding the alternate hypothesis can be made, other than our analysis failed to depict any difference in process time.

Test for Normality of Outputs Means

The Central Limit Theorem states that the distribution of means of independent, random samples from a population follow a normal distribution. The output from of scenarios one and two were tested for normality using the Fit Distribution function in @Risk . Both samples sufficiently follow the normal distribution (see Table 3).

Table 2. Entity Process Time Goodness of Fit Test Results





	Scenario 1 Goodness of Fit (Normal)	Scenario 2 Goodness of Fit (Normal)
Chi-Squared Test Value	6.157	11.54
P Value	0.9080	.4831
Rank	1	1

Testing for Equal Variances

Outputs from scenarios one and two produced variances of 0.65 and 2.36, respectively. Excel's two-sample test for equal variances was employed to evaluate whether there is any statistical difference in output variance between the two scenarios. The resulting output is shown in Figure 4:

Table 3. F-Test Two-Sample for Equal Variances.

	Scenario 1	Scenario 2
Mean	147.18	145.77
Variance	0.65	2.35
Observations	140	140
df	139	139
F		3.61
P(F=f) one-tail		1.21E-13
F Critical one-tail		1.32

The F statistic for this test exceeds the F critical value, supporting a conclusion of unequal variances of the scenario outputs.

Hypothesis Testing

The paired t-test was employed due to the unequal variances of the scenario output. This test produces a confidence interval for the difference of means. If the confidence interval contains zero, then the test fails to reject the null. The added value of this test is that it provides a description of the difference of the means, which can be used to describe the difference in outputs between the two scenarios.

The paired-T test does not require equal variances but it does require equal sample sizes. It also accommodates positive correlation between the two samples. Although the experiment was not specifically designed with synchronized common random numbers, ARENA's random number assignment process will likely result in a high degree of correlation. Law and Kelton (2000:560) note that many simulation packages allocate random numbers in a manner that requires specific action by programmers to defeat the high degree of commonality and synchronization between scenarios.

Excel was used to conduct the paired-T test with the following results (Table 5):

Table 4: Paired-T Test for Difference of Means

Mean	1.41
Standard Deviation	1.77
Standard Error	0.15
95% Confidence Level	0.29

With a confidence interval that does not contain 0, the null hypothesis is rejected, supporting the conclusion that the difference in mean outputs between scenarios one and two is statistically significant. The confidence interval also describes the expected range for difference in mean process times between the two scenarios as 1.12 to 1.70 days.

V. Conclusions

Introduction

This research employs modeling and simulation to predict the impact of in-sourcing the replacement of main beams by ARSC's PDM line. The primary measure of effectiveness for this study is average process time.

Conclusions

Results of the literature review summarized in Chapter II and the experiment described in Chapters III and IV support answers to the four research questions presented in Chapter I:

1. *Is an ARENA model the appropriate tool to conduct this research study?*

A review of current literature supports the use of computer simulation for this type of study. Much of the previously published research applied simulation to experiment with a small, well-defined element of the larger system. Based on the results of these experiments, researchers considered how their result could be applied to better understand the behavior of system as a whole. This research approaches the study from a macro view, directly observing the simulated interaction of major system elements.

The ARENA interface simplified review of the model by process experts. It allowed direct comparison of the model logic to a conceptual logic flow diagram developed base on ARSC-provided schedules and plans. Similarly, the spreadsheet view of process variables within ARENA allows researchers to easily compare programmed values with those recorded in the data dictionary. Given that simulation is well established as a tool for this type of research, ARENA proved to be a good choice for this study because its interface minimized the time required to verify and validate the model.

2. *How well does the ARENA model represent the effects of changes in labor resources for ARSC's HH-60J PDM line?*

The model allows researchers to consider the complex interactions between process elements with variable process durations. Because ARSC's process labor data is not currently formatted for direct use by this type of model, the exact values of resulting process responses represent only a predicted trend. However, the model will accommodate more detailed process time and resource requirement data. As better data become available, the model's prediction capability will improve.

The difference in variance between scenarios suggests that additional study is warranted to better understand how ARENA's resource allocation logic affects process time in the simulation. When structures shop resources are not required for beam replacement work, they can be assigned to other structures work tasks. It is possible for a required structures resource to be assigned to a long-duration task before an entity arrives for beam replacement. In this case, the resource is not released from the current task to work on beam replacement until the task is completed, causing the beam replacement step to be delayed. This ARENA-imposed limitation may be the source of increased process time variation in scenario two.

3. *Will an increase in structures shop labor likely reduce PDM process time as compared to having beam replacement work done by a dedicated crew of contract workers?*

Results of the simulation experiment support the conclusion that shorter process times would likely be achieved by increasing structures shop manning. In the simulation, this manning increase cut average process time by 1.4 days as compared to having the work performed by a contractor. As discussed in the response to research question two, this value does not directly represent a 1.4 day improvement in the real world process. Rather, it simply predicts a statistically significant reduction in average process time. Further research with detailed data may help to better understand the magnitude of the expected improvement.

Practically speaking, analysts would likely seek process improvements that deliver greater reductions in process time. A process time reduction of 35 days could decrease the fleet's PDM interval from five years to four years with a constant WIP of five aircraft. Although the model used in this research lacks the necessary detail to accurately support a decision to reduce PDM intervals based on an untested process change, it does suggest that this modeling approach has the potential for greater insight into the effects of such process changes.

4. *What improvements can be made to the model or data sources to develop a better ARENA model for future research?*

The process model developed for this research is a starting point for further research. The current model is designed to study the impact of a single decision variable. The basic process structure could serve as the basis for development of models to consider other process decisions. These might include modeling the effects of adding additional process steps, constraining facility resources, or increasing work in process.

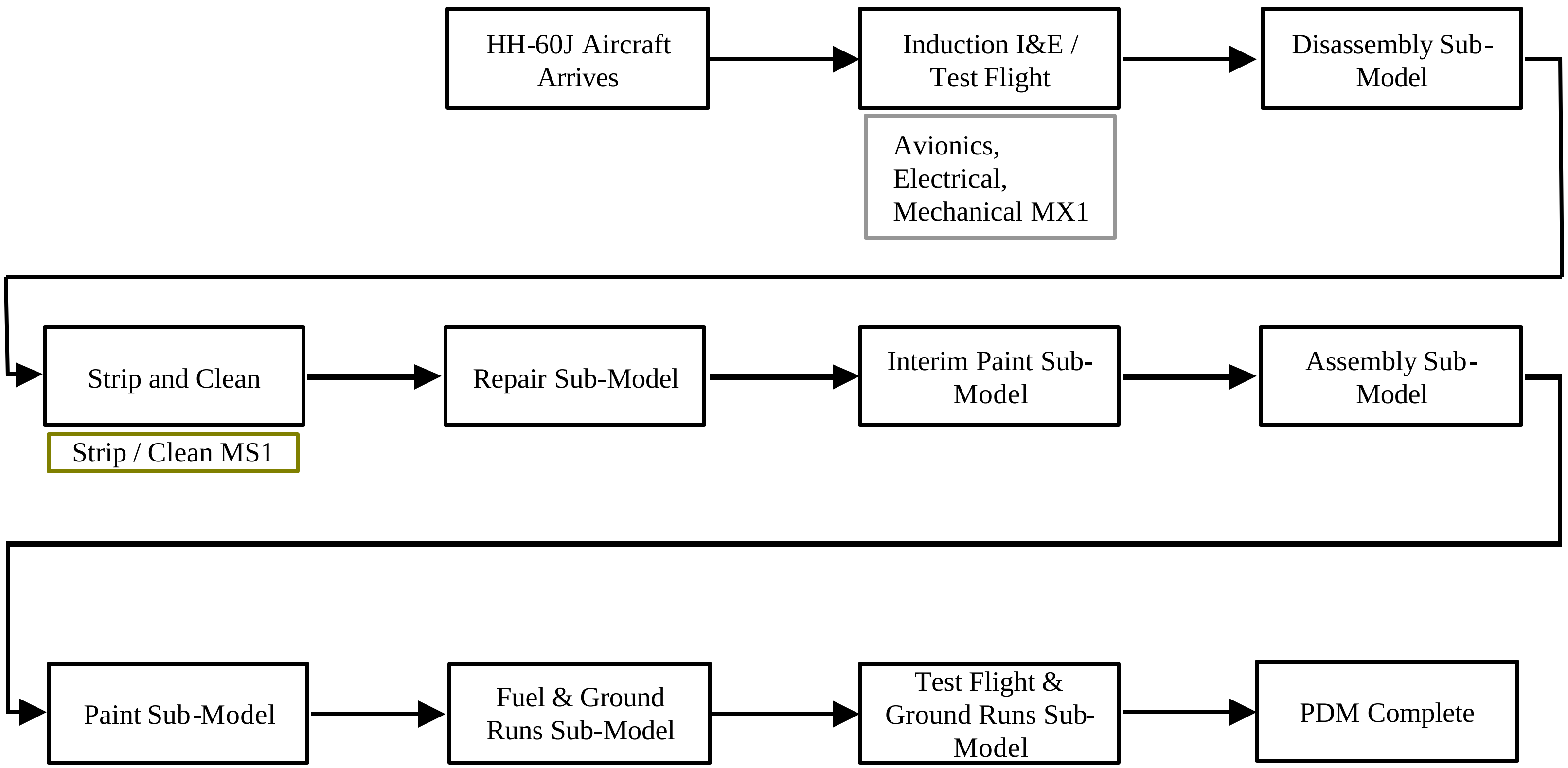
Any changes to the model or its intended use will require verification and validation for the intended use.

To improve the predictive capability of this model and future variants, the following data should be updated with the most current information available:

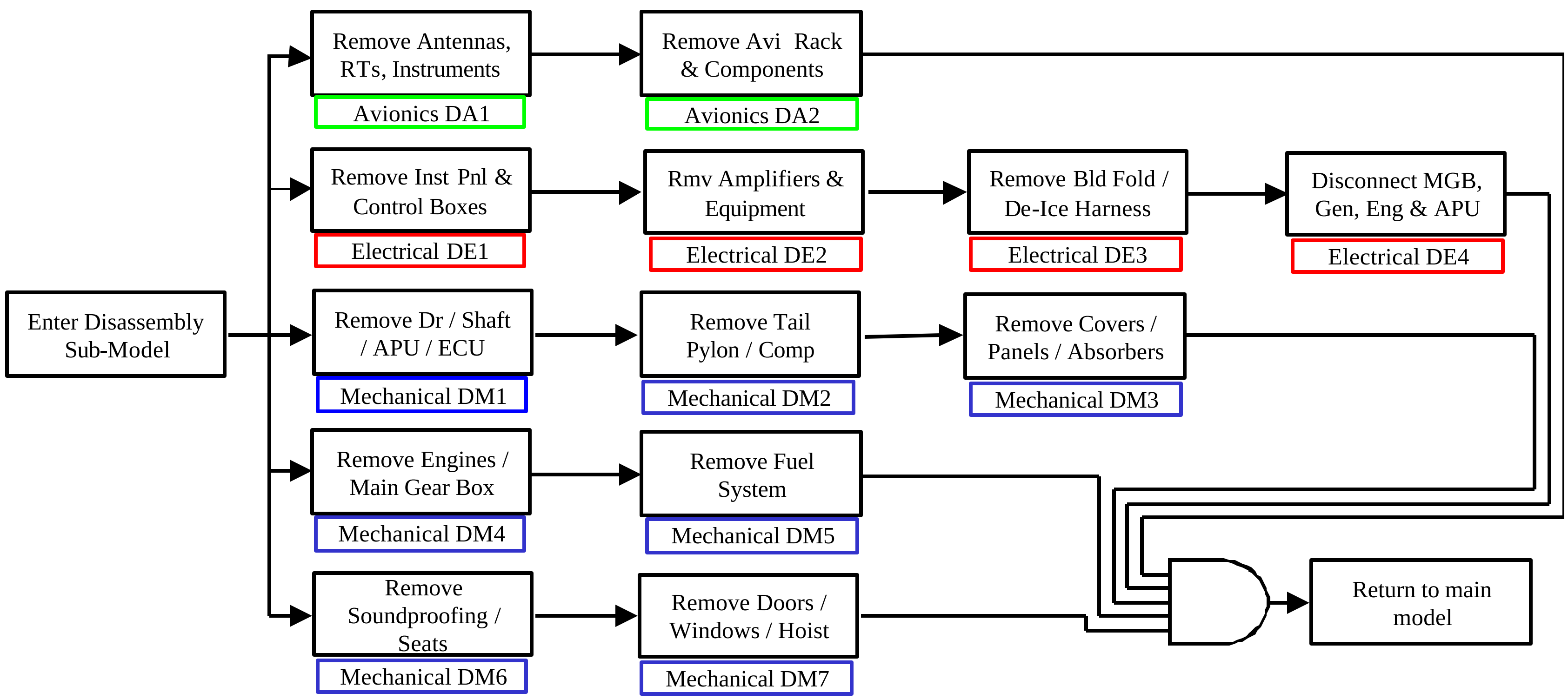
a. Process times for each process element with updated probability distributions.
b. Manpower requirements for each process element, categorized by work shop when multiple shops are required for a task.
c. Availability of workers for front shop work, categorized by work shop.

Appendix A. HH-60J PDM Logic Flow Diagrams

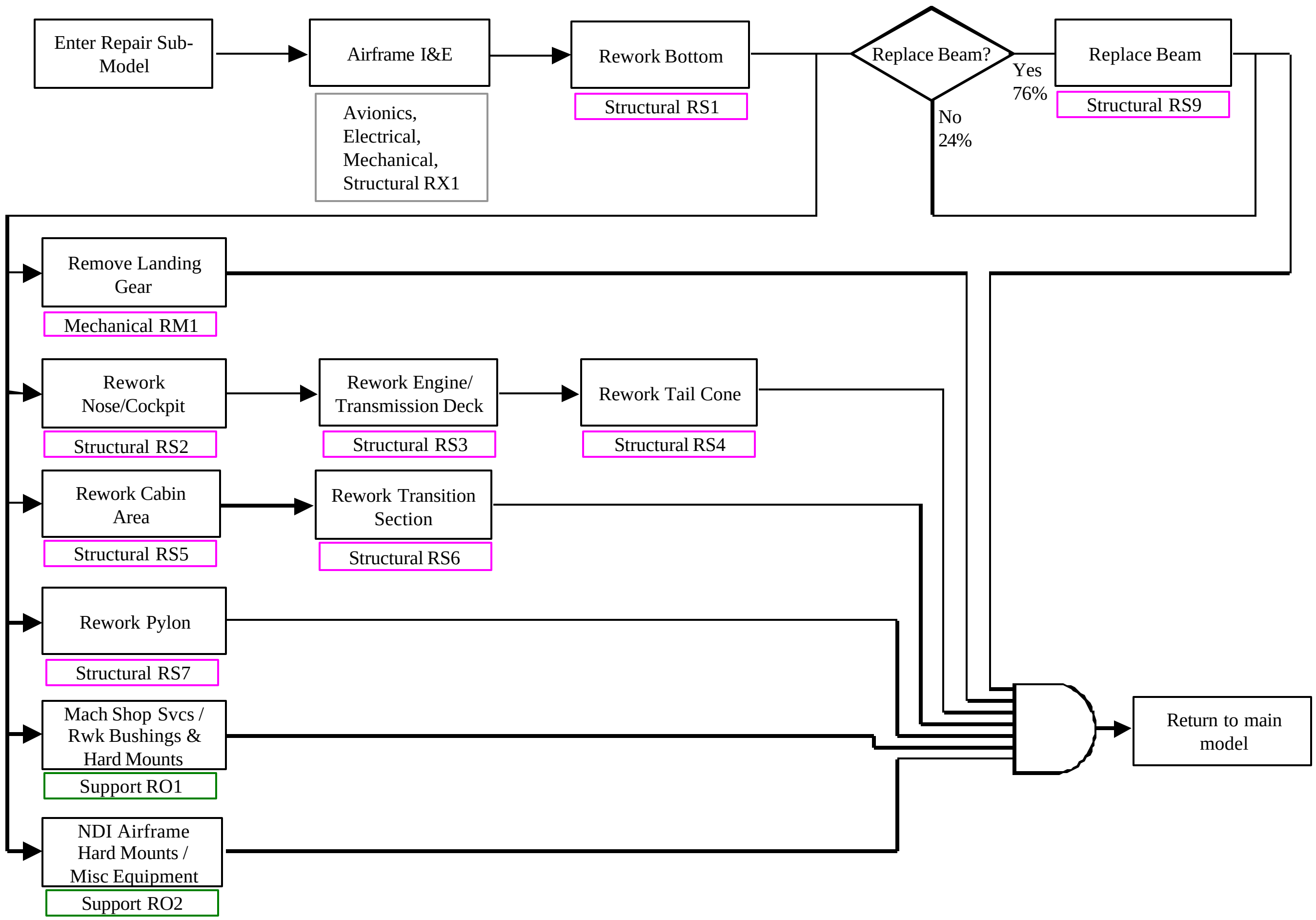
Appendix A-1. Main Model – Logic Flow



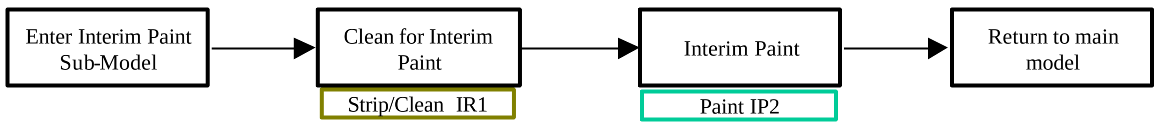
Appendix A-2. Disassembly Sub-Model – Logic Flow



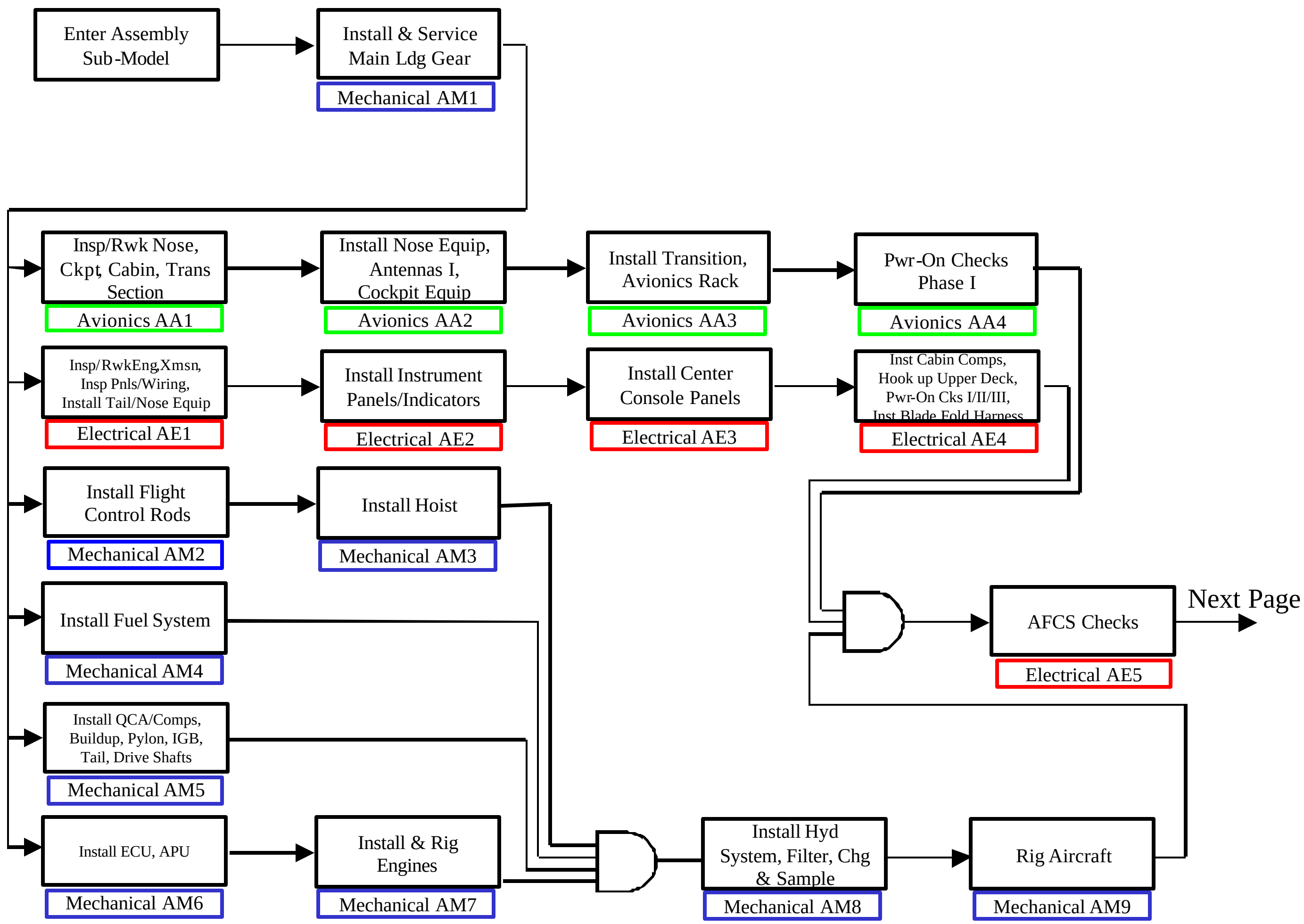
Appendix A-3. Repair Sub-Model – Logic Flow



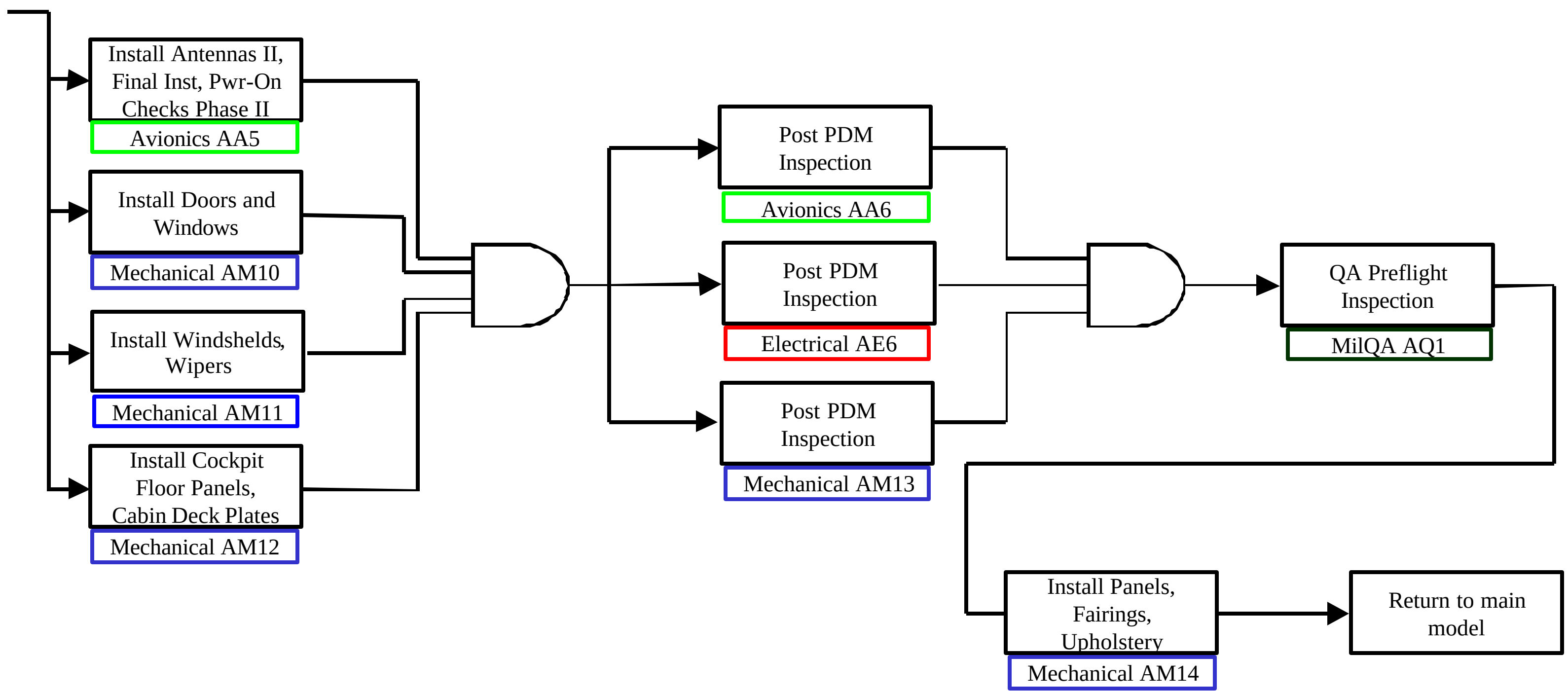
Appendix A-4. Interim Paint Sub-Model – Logic Flow



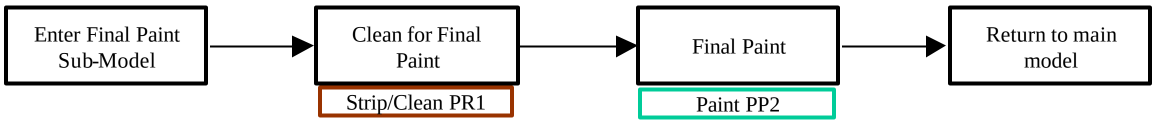
Appendix A-5. Assembly Sub-Model – Logic Flow



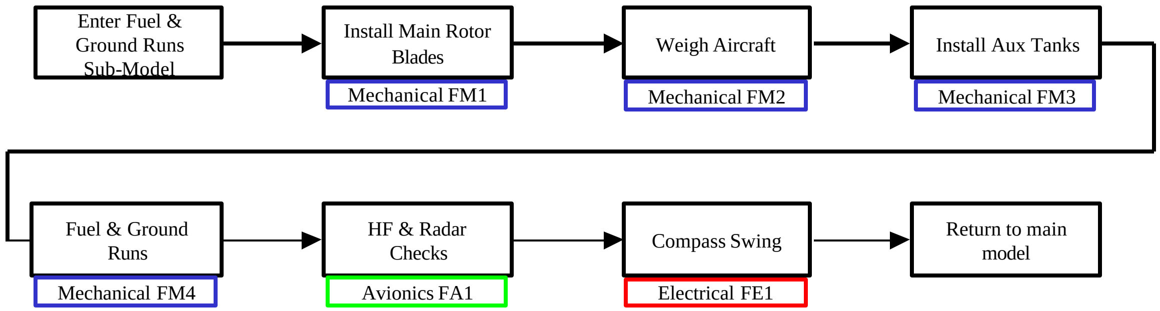
Appendix A-6. Assembly Sub-Model – Logic Flow (Continued)



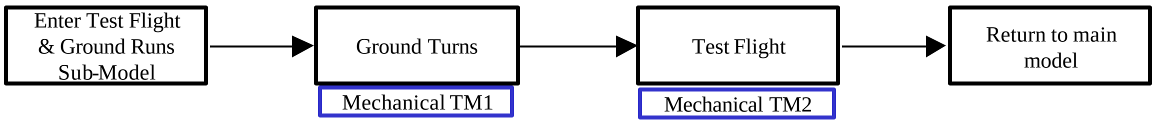
Appendix A-7. Final Paint Sub-Model – Logic Flow



Appendix A-8. Fuel & Ground Runs Sub-Model – Logic Flow

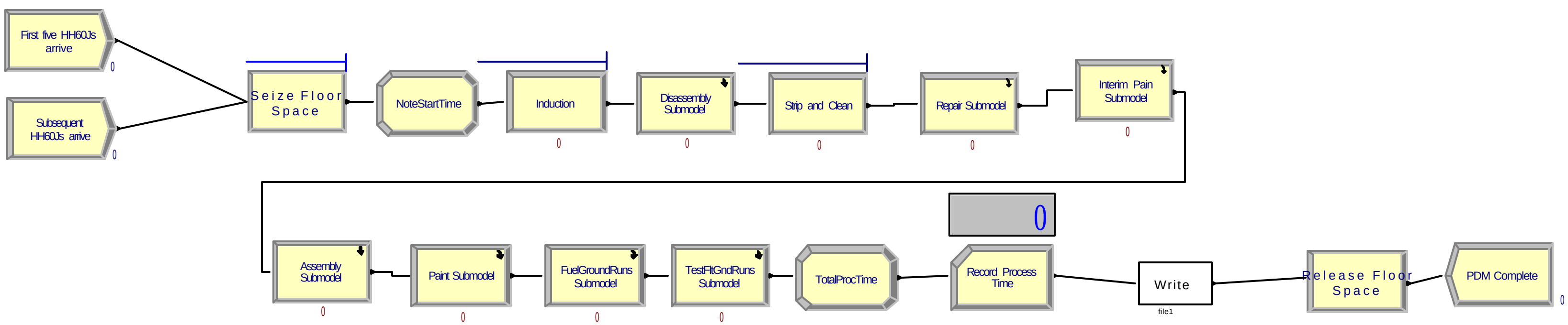


Appendix A-9. Test Flight & Ground Runs Sub-Model – Logic Flow

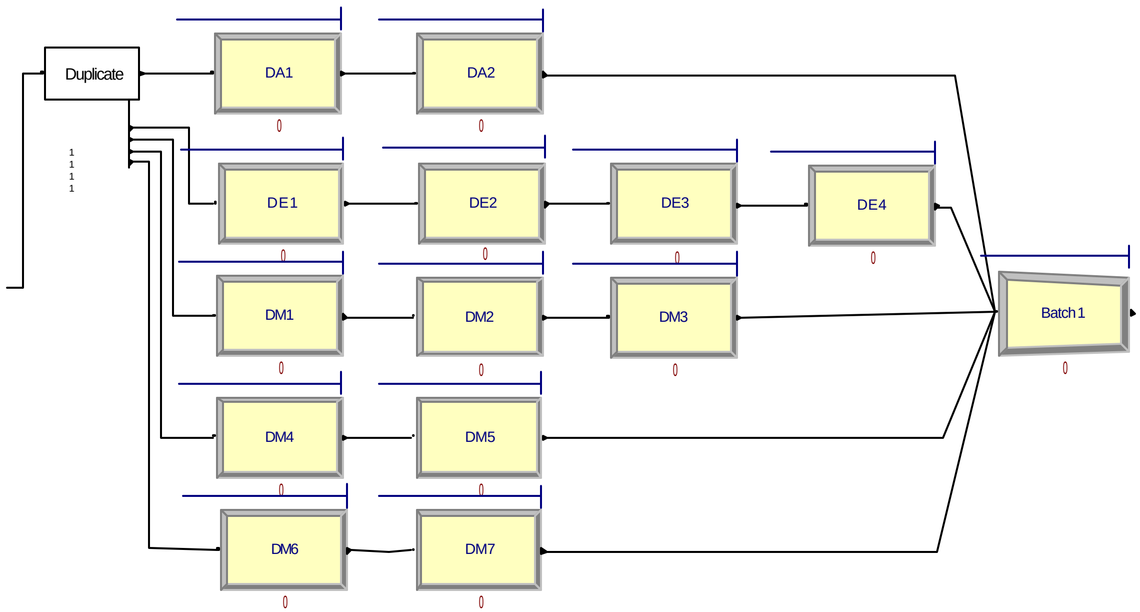


Appendix B. HH-60J PDM ARENA Logic Diagrams

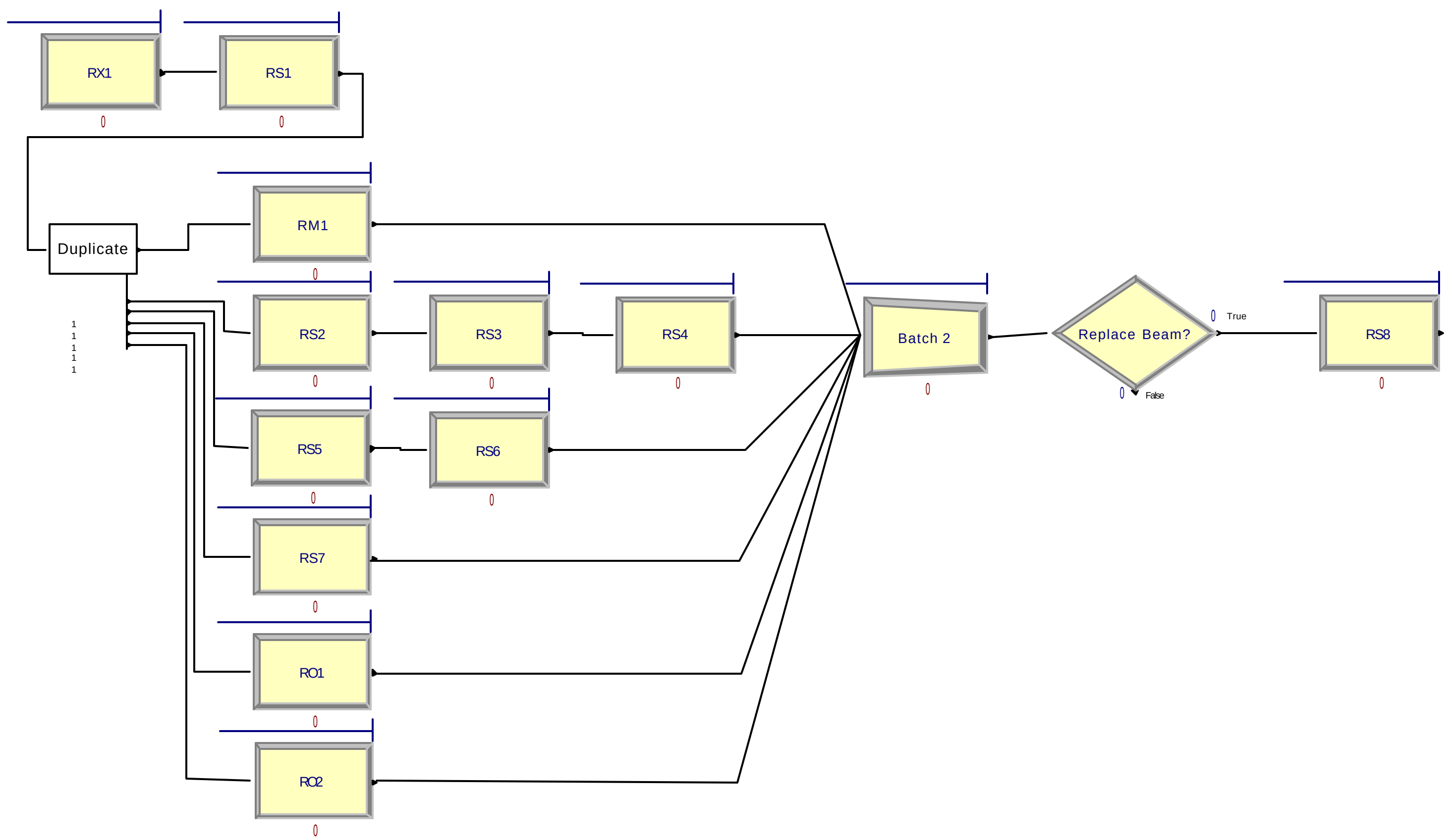
Appendix B-1. Main Model – ARENA Logic



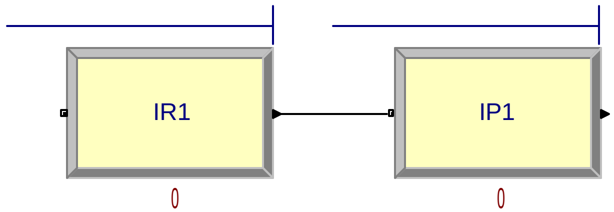
Appendix B-2. Disassembly Sub-Model – ARENA Logic



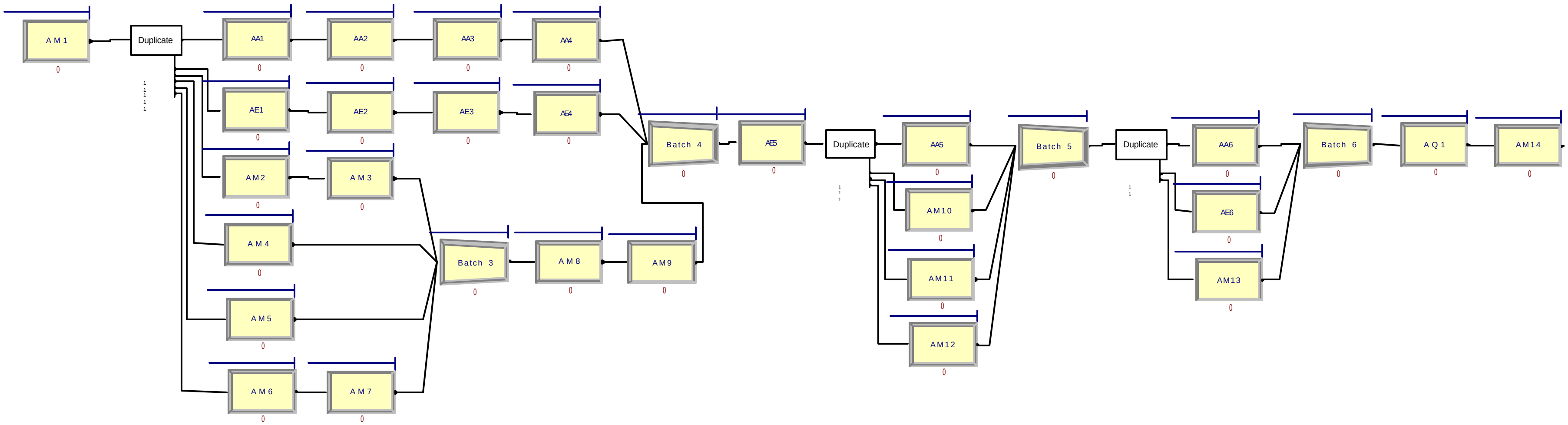
Appendix B-3. Repair Sub-Model – ARENA Logic



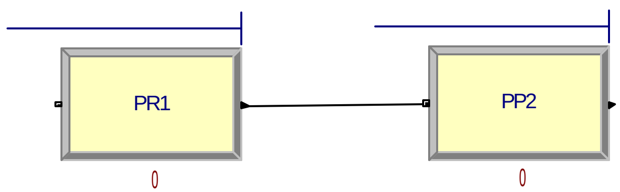
Appendix B-4. Interim Paint Sub-Model – ARENA Logic



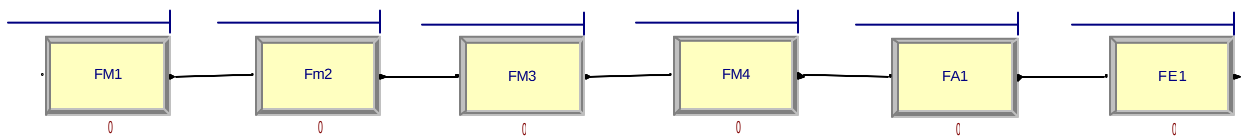
Appendix B-5. Assembly Sub-Model – ARENA Logic



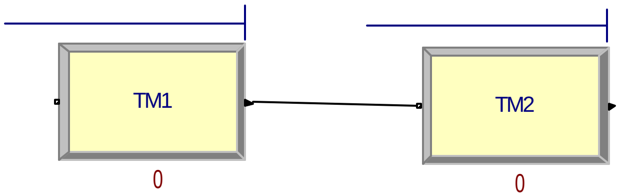
Appendix B-6. Paint Sub-Model – ARENA Logic



Appendix B-7. Fuel & Ground Runs Sub-Model – ARENA Logic



Appendix B-8. Test Flight & Ground Runs Sub-Model – ARENA Logic



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Vita

Lieutenant Commander Steven Vigus was born in Orange, California. A 1982 graduate of Saddleback High School in Santa Ana, California, he completed the Electronics Technician Vocational Training Program at Rancho Santiago Community College in Santa Ana, California in 1982. After two years of industry experience as an electronics technician and assistant operations manager, he joined the U.S. Marine Corps, where he served as an intermediate level electronics technician, attending college classes during off-duty hours. In 1988 he left the Marines for Disneyland Park, where he supervised electronics technicians for the Facilities Engineering and Construction division. In 1989 he completed his B.S. in Electronics Management from Southern Illinois University at Carbondale.

Mr. Vigus returned to military service in 1991, earning a commission from the Coast Guard's Officer Candidate School. After completing Naval Postgraduate Flight Training in 1993 he served as a Coast Guard search and rescue helicopter pilot and flight training instructor. In 2001 he was selected to the Air Force Institute of Technology's Master of Science in Systems Management program. Upon graduation in March 2003 he will be assigned to the Aviation Forces Branch, U.S. Coast Guard Atlantic Area.

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14. ABSTRACT

Leaders at the United States Coast Guard's Aircraft Repair and Service Center (ARSC) in Elizabeth City, North Carolina recently formalized their planning and analysis functions by adding a dedicated branch to their command structure. The Planning and Analysis Branch intends to apply computer modeling and simulation to study the impact of process changes to the various Programmed Depot Maintenance (PDM) lines. This research considers the applicability of this type of modeling and simulation, using ARENA to study the current HH-60J PDM process. The response variable of interest is average PDM process time as a function of either in-sourcing or out-sourcing labor for a major process step. The research includes development and evaluation of a macro-level process model using ARENA 5.0.

15. SUBJECT TERMS

Simulation, modeling, computerized simulation, modeling & simulation, ARENA, aircraft maintenance, aviation logistics, depot maintenance, PDM, Coast Guard, HH-60J, maintenance management.

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