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Estimating C-17 Operating and Support Costs: Development of a System Dynamics Model

Christopher D. Purvis

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ESTIMATING C-17 OPERATING AND SUPPORT COSTS: DEVELOPMENT OF A SYSTEM DYNAMICS MODEL

THESIS

Christopher D. Purvis, Captain, USAF

AFIT/GAQ/ENV/01M-10

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY
AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT/GAQ/ENV/01M-10

ESTIMATING C-17 OPERATING AND SUPPORT COSTS: DEVELOPMENT OF A SYSTEM DYNAMICS MODEL

THESIS

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Christopher D. Purvis, B.B.A., MBA

Captain, USAF

March 2001

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Christopher D. Purvis, B.B.A., M.B.A
Captain, USAF

Approved:

William L. Stockman (Chairman) — 27 Feb 01
date

Michael L. Shelley (Member) — 27 Feb 01
date

Wayne L. Foster

Wayne L. Foster (Member) — 27 Feb 01
date

Jay D. Asher

Jay D. Asher (Member) — 27 Feb 01
date

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Christopher D. Purvis

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Abstract

This research provides a justification for experimenting with system dynamics (SD) for performing Operation and Support Cost estimates. For the C-17 Globemaster III cargo aircraft, these costs could exceed $64 billion dollars. Also, many of our weapon systems are beginning to reach the end of their effective life span, and discussions about the impact of aging, on aircraft, has become a hot topic in the literature.

System Dynamics is a modeling methodology developed in 1958, but never used extensively for cost estimating. SD offers unique capabilities to the cost estimator, including the ability to model causal relationships. This capability offers the cost estimator the ability to estimate O&S costs, spares availability, and mission capable rates, throughout the life span of a weapon system. The primary goal of this thesis endeavor is to prove the applicability of SD for cost estimating by demonstrating the various outputs of a SD model, including fixed and variable costs; secondarily, showing how the results from the SD model can provide a better estimate of future costs, when compared to models in use today.

ESTIMATING C-17 OPERATING AND SUPPORT COSTS:

DEVELOPMENT OF A SYSTEM DYNAMICS MODEL

Thesis Advisor:

Lt. Col. William Stockman

Asst Professor, Dept of Systems & Engineering Management
Air Force Institute of Technology

Research Student:

Captain Christopher Purvis

Student,
Air Force Institute of Technology

ESTIMATING C-17 OPERATING AND SUPPORT COSTS: DEVELOPMENT OF A SYSTEM DYNAMICS MODEL

I Introduction

Problem

The Government Accounting Office (GAO), in their 1999 report to Congress noted: "the Department of Defense has systemic problems with management processes related to plans, finances, information, acquisition and contracts; and specific problems related to infrastructure, inventory and personnel programs" (Walker, 1999:12-13). How can this be, when there are so many systems, especially in the acquisition world, to track, analyze, and estimate costs? These "systemic problems" identified by the GAO indicate we are not doing a good job of estimating our costs.

The use of weapon systems effects inventories of parts, support infrastructure, acquisition costs, and the budget to pay for it all. The Air Force Deputy Assistant Secretary, Cost and Economics, recently established an Air Force Reinvention Team to focus on establishing a process that will produce quality cost estimates and identify the necessary resources (personnel, training, data, tools, etc.) to satisfy customers (Kammerer, 1999:1). At the same time, the Air Force Inspection Agency, during their Acquisition Management Review, revealed a need for cost/ performance/ trade-off analysis. Therefore, SAF/FM has initiated the Air Force Total Ownership Cost system to provide senior leadership visibility into these important life cycle costs.

The Assistant Secretary of the Air Force (Financial Management and Comptroller SAF/FM) reported the mission of SAF/FM as: "[to] obtain and properly apply adequate funds to accomplish the Air Force Mission by formulating, justifying, and executing budgets; improving resource allocation decisions through cost and economic analysis" (Hale, 2000). He stressed that cost and economic analysis will allow us to properly support the Air Force Mission. However, the GAO reports that the Air Force currently does not perform this analysis well. The issue may be with the current method of estimating costs, especially Operations and Support (O&S) costs, which make up the bulk of a weapon system's lifecycle cost.

> O&S costs include all costs of operating, maintaining, and supporting a fielded system. It encompasses costs for personnel; consumable and repairable materials; organizational, intermediate and depot maintenance; facilities; and sustaining investment. The O&S phase overlaps with the Production and Deployment phase. O&S costs are incurred in preparation for and after a system's fielding and continue through the end of the system's useful life (SAF, 1992:2.3)

The current method used to estimate O&S costs for weapon systems is to use cost factors and apply them to some expected level of activity. These factors are Cost Estimating Relationships (CERs), which are derived from data and fit to a line using regression techniques. One example of such a model is the Cost Analysis Strategy Assessment (CASA). CASA uses standard logistics equations to calculate costs based upon resource and user requirements. This model is complex, employing approximately 82 algorithms and 190 variables (McLendon 1999).

The Joint Operating and Support Technology Evaluation Model (JOSTE) is another model. It calculates O&S costs using systems quantities; delivery schedules; operational, reliability, and maintainability data; and labor and material rates. The Cost Tools web site[1] lists over 51 models for cost estimating. These models use some variation of the two methods mentioned above, some are rather simplistic, and others add a third dimension, probabilistic simulation, like Monte-Carlo models

What is needed is not another variation of a current cost estimating tool, but something completely different. One limitation of the current models is that they do not provide for feedback relationships. Circular relationships (feedback loops) cannot be modeled using the spreadsheet/relational database tools currently in use. Feedback loops allow modeling of continuous dynamic influences. It allows the ending state of one unit of time (fraction of a time-period) to be the beginning state of the next unit of time. This is especially important, because the decisions we make today will influence more than just one period's outcome. It will have a bow-wave effect that will continue to influence the behavior of the model, therefore allowing the user to "see" the effect of a decision made today on the system at various points in the predicted future. For this reason, what is needed is not just another variation of the same cost estimating tool, but a radically different tool, and a system dynamics model may be that tool.

Jay W. Forrester in 1958 conceived the idea of Systems Dynamics (SD). He originally applied it to companies and later to education systems. This groundbreaking approach recognized:

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[1] http://www.dtic.mil/c3i/dodim/costool.html

> “a company is not a collection of separate functions but a system in which the flows of information, materials, manpower, capital equipment, and money set up forces that determine the basic tendencies toward growth, fluctuation, and decline.” (Forrester, 1975:35)

Today, SD is used to model almost any process, from biological and environmental to financial and personal (Forrester 1968); any process where one thing (or even idea) interacts with something else. The SD approach is non-linear; it is concerned with flows, rates, and interactions (described in Appendix A). This technique simulates causal relationships in an intuitively understandable way. The application of SD in the area of cost estimating is a new science.

Value to User

In 1999, the cost analysis team for the C-17 System Program Office (SPO) became aware of the SD methodology for cost estimating. The SPO members had no experience with SD, and they did not have time or money to explore the value of such a model. They were also becoming unsatisfied with their current cost-estimating model. For instance, the current model has labor costs as a fixed cost, so flight hour changes do not effect labor costs. Experience has proven that this is not really the case. Also, the current model is a pricing model, designed for use only during the next seven years. Therefore, it did not have the capability to predict long-term cost influences, and would need replacement in a few years. Interested in the SD approach but unwilling to pay the significant cost to explore SD modeling, the SPO delayed implementation. They wanted an independent analysis of SD and so the SPO contacted AFIT, to sponsor a thesis effort. This is that effort. It will examine the applicability of SD to O&S cost estimating.

The value to the sponsor is to get an independent analysis of SD modeling, before committing significant resources to its development. The C-17 SPO hopes that by using SD, they will get a predictive model that will aid in making business decisions about logistics system performance, that will also produce accurate cost estimates based on those decisions. The goal of this thesis is to first show the applicability of SD to cost estimating, then evaluate SD for compatibility with current cost estimating requirements for the C-17 SPO. The C-17 SPO has the responsibility for development and production oversight of the C-17 Globemaster III cargo aircraft, figure 1.

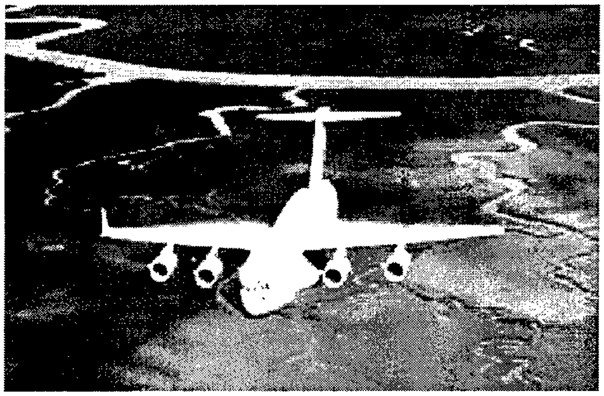

Figure 1. C-17 in Flight

> The C-17 is capable of rapid strategic delivery of troops and all types of cargo to main operating bases or directly to forward bases in the deployment area. The aircraft is also able to perform tactical airlift and airdrop missions when required. The inherent flexibility and performance characteristics of the C-17 force improve the ability of the total airlift system to fulfill the worldwide air mobility requirements of the United States.[2]

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[2] Air Mobility Command, Public Affairs Office; 502 J Street; Scott AFB, Ill. 62225-5335; DSN 576-5003 or (618) 256-5003. http://www.af.mil/news/factsheets/C_17_Globemaster_III.html

There are plans for the production of at least 120 C-17s. The current policy is to maintain a single aircraft configuration. Therefore, as new technology is developed and the design is upgraded, all the planes in the fleet will be retrofitted. Reconfiguration decisions are relatively easy early in the production phase when there are few completed aircraft. However, as the program nears completion, the decisions become harder to make, because the costs of retrofit grow with each aircraft to be retrofitted. Current models estimate the cost of retrofitting a new capability on the plane using labor and material rates, parts prices, paint, and other costs. A SD model uses relationships between various events and cost data to model a complex causal relationship. These relationships identify three areas of concern. First, what is the optimal upgrade schedule, considering such variables as parts, facilities, labor, and aircraft availability? Secondly, what is the impact on the other aircraft in the fleet from taking planes out of service to make the retrofit, or the effects of different upgrade schedules? Finally, what are the expected costs of all these different activities, under the various scenarios? The possibility that SD has the ability to answer these questions makes SD so intriguing as an estimating tool.

Understanding the potential cost and impact of retrofits on the life cycle of the aircraft fleet, would enable the C-17 SPO senior leadership to make the right decisions at the right time, with the right schedule. It would also provide a tool to determine the impacts of making sub-optimal decisions due to directives or insufficient resources. With an SD model, insight into fleet availability and the true impacts of retrofits and their costs, will foster efficient use of resources, eliminate waste, and allow decisions to be made in such a way as to reduce risk. Unlike current cost models that only forecast costs or prices, a

SD model attempts to predict future events. One example would be identifying repair facility capacity requirements to perform increasing maintenance work on an aircraft fleet as it ages, therefore facilitating the evaluation of uncertainty and risk. These benefits will allow the C-17 SPO to help fulfill the SAF/FM mission.

Therefore, understanding the need for O&S cost estimates, the reality of causal influences on systems, and the use of SD in other fields to model these causal influences, the question of the applicability of SD to O&S estimating becomes relevant. This relevancy therefore drives us to ask the following research question

Research Question,

> Can system dynamics modeling be applied to cost estimating? If so, can a model be built that is sufficiently robust, to predict accurate cost and system performance behaviors? Can it therefore provide decision-makers with a tool through which significant cost drivers can be identified, estimated and analyzed? Does this technique indicate clearer representations of cost drivers and their effects, when compared to the current pricing model? Chapter V will report the answer to these questions

Approach

The priority of this effort will be to address the question of applicability; showing how to apply the SD methodology to aircraft O&S cost estimating. Explanation of the SD model building methodology is in chapter II under "Model Development."

Before model evaluation begins, considerable work, to explore the significant influences on cost behaviors, is required. Because SD is primarily a tool used to model feedback relationships, it is important to identify those areas that have the greatest influence on the system. For instance, in general, the number of landings that the aircraft makes does not affect avionics; therefore, a detailed analysis of landings would be unnecessary in an avionics cost model. However, considering tires, landing gear, or airframe, the effects of landings might be very important. Appendix B discusses the development and testing of this initial model. It shows the importance of the variables tied to flight hours, maintenance times, and spares. From the behaviors exhibited by this model, it is evident that SD provides valuable insight into cost behaviors, therefore further investigation is warranted. The SD software evaluation is therefore the next step.

The SD methodology is an evolutionary approach. Relevant pieces will built to explore the dynamic behaviors and to evaluate whether a model can be built that addresses the various requirements of an O&S estimate (as outlined in chapter II under O&S cost estimates). In general, the model needs to be able to capture fixed and variable costs and be able to accumulate them in the cost categories identified by the Office of the Secretary of Defense Cost Analysis Improvement Group (OSD/CAIG).[3]

The key to evaluating the SD model is not necessarily the actual cost numbers presented, but the behaviors represented by the results. The C-17 cost experts and engineers (users) will evaluate these behaviors. These users will determine if the behaviors are logical and represent real world expectations. Under the SD methodology, to achieve validity, the users must accept the behaviors and corresponding results.

The final product will be a number of scenarios that explore different aspects of O&S costs. It will assume a simplified view of the C-17 as a system (a collection of parts). These parts have different aging characteristics, maintenance schedules, failure rates, and repair requirements. The plan is to model various tasks and explore the ability or failure of the SD approach to logically present results in the required format.

After these items have been "demonstrated," further modeling of the complete system will be a simple matter of duplicating the various nodes created above to further break out the combined costs and assign them to individual components. The significance of this model will be in the initial modeling work necessary to show applicability. For instance, the modeling of an upgrade task for one component would be the same for another component. The differences in induction schedules, kit costs and effects of the upgrades would be minor changes from the original upgrade task.

Thesis Overview

This chapter indicated the reasons for exploring a SD approach to O&S cost estimating. Although there are many different models for estimating O&S costs, the fact that there are so many models may indicate a perfect approach has not yet been revealed. Although system dynamics may not be the silver bullet, it is a worthwhile endeavor to analyze and discover its suitability for cost estimation, and its ability to aid in decision making. Its potential advantage is that it will give an indication of system performance and expected costs for various opportunities that the decision-maker may face.

Chapter II, Literature Review, will provide more detailed information on the requirements of O&S cost estimating, and provide an overview of system dynamics modeling. The remainder of the chapter will discuss the current method that the C-17 SPO is using to estimate these costs, and reveal inconsistencies within the model that indicate a different approach may be worthwhile.

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[3] Notice: in order to make this thesis available to all potential readers, the cost data that is used has been adjusted to avoid exposing proprietary cost data

Chapter III, Methodology, will lay out the model map used to guide the evaluation of the various properties of SD. The model map is the overall process of completing the required steps, to build a task element, through the validation of that task's expected behaviors. The model map consists of ten scenarios.

Chapter IV, Findings, will compare the model's predicted behavior against actual data where possible, and provide sensitivity analysis for decision makers, to explore the effects of dynamic influences on the aircraft, fleet and facilities.

Chapter V, Conclusions and Recommendations, reviews the findings, discuss the satisfaction of the stated objectives, recommends areas for further analysis and research, and present limitations and work-a-rounds of the SD model software

Appendix A, System Dynamics Terms Explained, will explain some of the more commonly used terms, and give examples of some SD structures.

Appendix B, Initial Conceptualization of the O&S model, evaluates some of the cost characteristics, to identify what areas need further detailed modeling. In effect, this section justifies the use of a more detailed model framework.

Appendix C, FleetSight and System Dynamics – Structural and Behavioral Analysis, explains the foundation of the software package used for the SD modeling.

Appendix D, CAIG Cost Elements, presents a more detailed analysis of the elements required for an O&S cost estimate.

Appendix E, C-17 Boeing Joint Cost Model, will discuss some of the attributes of the current model the C-17 uses to predict costs. This pricing model is used to negotiate the price of contracts to manage the C-17's flexible sustainment contract.

II Literature Review

Overview

This chapter's purpose is to familiarize the reader with a few of the key concepts that are at the foundation of this thesis effort. At the outset, understanding the system in question is important. This helps the reader understand the importance of the maintenance concept and the impact of that concept's dynamics. Understanding the size of the aircraft helps one to visualize the magnitude of some of the maintenance tasks to be performed. Furthermore, it is hoped that after examining the requirements and the importance of performing O&S cost analysis, the reader will understand the importance of attempting SD as a modeling technique. Next, the concept of aging is discussed; aging is foundational to the dynamics of this system. This is an attempt to show how other models lack the ability to consider the documented affects of aging; and the need to include these impacts in a model, to assist decision-makers in making optimal, long-term decisions. Finally, an explanation of system dynamics is given, to help the reader understand the benefits of this modeling technique.

C-17 History

After the identification of the need for a cargo aircraft that could deliver supplies and troops to forward locations, concept exploration began on the system that would eventually become the C-17. In August of 1981, a source selection decision was made awarding McDonnell Douglas Corporation (now Boeing Corporation) as the winner of the competition. The full-scale development contract was awarded in July 1982. Program Risk Reduction was begun in February 1985, and the Milestone IIIA (DAB) was completed in January 1989. Low-Rate Initial Production was initiated in Jan 1989, and First flight of the first C-17 (T-1) occurred in Sept 1991. The first squadron was established when the first of 12 production aircraft began delivery to Charleston AFB, these deliveries were completed by Jan 1995 (DOD SAR, 1999:5). Over the course of the next 5 years, additional squadrons were formed at Altus and Mchord Air Force Bases. In July 2004, the final squadron will be established at Jackson Air Reserve Base. Each of these bases has different mission requirements and maintenance capabilities (Asher, 1997:16-19).

C-17 Flexible Sustainment – History

The original support strategy for the C-17 as envisioned in 1982 was for organic (Governmental) support, when the planned aircraft buy was for 210 airplanes. However, as reductions in the planned buy occurred, due to various program issues (cost overruns, schedule delays, performance shortfalls (Davis, Phillips, Vasques, 1997:411-432), the organic support strategy came under scrutiny. In 1993, the Office of the Under Secretary of Defense (A&T) placed organic depot activation on hold until the Defense Acquisition Board (DAB) could recommend a final quantity buy decision. This decision occurred in 1995 (Kissell and Schwartz, 1999:5).

The C-17 SPO initiated a Depot Support Strategy (DSS) Study to identify the most cost effective support strategy. This study was an analysis of alternatives, to compare governmental and contractor costs in the areas of materials management, maintenance (both scheduled and unscheduled), and planning activities. The results of this study were that other than the engines, which are a commercially derived engine from Pratt & Whitney, no clear difference was identified (Bowman, 1999:5). However, due to Base Realignment and Consolidation (BRAC) considerations and the desire to maintain some organic capability, the Flexible Sustainment concept was envisioned, in the hopes of maximizing the strengths of both types of support concepts.

In 2001, this contract will be re-baselined, to reflect "total weapon system responsibility and higher level performance requirements" (Edwards, 1999:1-10). This is necessary, as the current contract is Cost Reimbursable Plus Award Fee (CP), but it will transition to Firm Fixed Price Plus Award Fee (FFP). During this transition phase, the contract will have a mix of FFP and CP elements (Asher, 2000).

Flexible Sustainment –

The purpose of Flexible Sustainment is to "encourage the program manager to use Performance-Based specifications and develop innovative, cost effective, life cycle solutions" (JACG, 1997:x). The objectives are:

> Flexible Sustainment provides Program Managers (PM) with the opportunity to reduce life cycle costs in many ways. (1) by conducting supportability analyses as part of the systems engineering process to implement the most life cycle cost-effective operational and support system. (2) by improving the reliability of existing systems and reducing operations and support (O&S) costs. And (3) by facilitating technology insertion throughout the life cycle. Implementation of Flexible Sustainment initiatives will enable DoD components the opportunity to reduce life cycle costs and provide needed funds for modernization and recapitalization (JACG, 1997:1)

Lightning Bolt 99-7 was the first primarily Logistics oriented Lightning Bolt Acquisition Reform Initiative. This lightning bolt addresses the issues of the need for fundamental changes in the way warfighting systems are supported. Because of decreasing resources, technological complexities, and the need for rapid response support capabilities, doing support the old way was no longer optimal. The commercial sector has made vast improvements in their supportability techniques, and in the spirit of adopting commercial best practices, we need to re-evaluate the role of industry and organic support (Cothran, May: 1). In this regard, we can move, from complete contractor support, to complete organic support along a continuum. Finding the optimal spot on this continuum is difficult, because so few systems have explored the benefits of these partnerships with industry. The C-17 is one of those systems.

In many areas, the management of the C-17 has endeavored to reduce costs and efficiently allocate resources. SD is another example of this effort. It fits with the stated goals by facilitating the analysis of the current system, providing opportunities to explore life cycle cost reductions, and predicting supportability decision outcomes.

C-17 Flexible Sustainment – Future.

Because of the monumental task of adapting this new maintenance/support concept, Flexible Sustainment will be phased-in over an eight-year period. Boeing has been in the Transition phase. This phase has a dual purpose. First, to allow Boeing to gradually take on the responsibility for building capability to support the system, becoming responsible for peculiar depot maintenance support activities, on-site technical support, Engine Contractor Logistics Support (CLS), and some airframe depot-level material management. Second, to give the Air Force time to change, define, refine, and implement new regulatory and statutory language (Kissell and Schwartz, 1999:20).

The next phase is the Proof of Concept Phase, which should begin in FY 01. This phase is characterized as the period when the Air Force will evaluate the Flexible Sustainment concept, and plan for a long-term depot support decision. The contractor will have assumed depot-level material management, peculiar depot maintenance support activities, sustaining logistics and engineering functions, on-site technical support, and engine CLS responsibilities.

The third phase is the Assessment Phase, which will begin approximately in FY 03. During this phase, the Air Force will assess the various metrics to evaluate the success or failure of this maintenance concept. This analysis will determine what long-term strategy will be used after C-17 production ends. The final phase, Implementation, will implement the long-term strategy identified during the Assessment Phase for all depot maintenance and material management activities. Figure 2 shows this phasing.

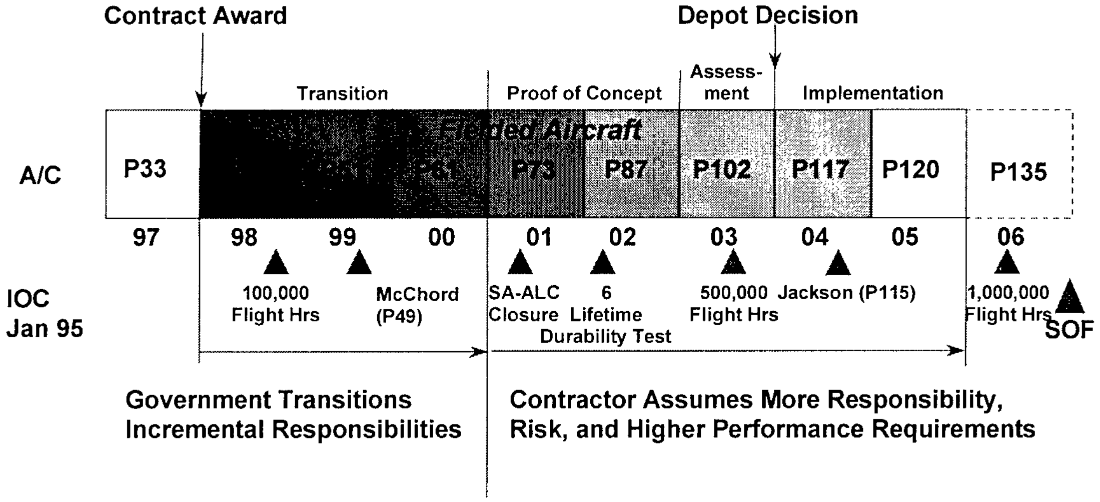

Figure 2. Contracting Acquisition Timeline (Bowman, 1999:21)

Knowing that the maintenance responsibilities will be transferred to a contractor, greater insight into the costs incurred is needed. As the program moves towards Contractor Logistics Support (CLS), it also moves towards commercial practices. The relevance of this situation, is that under commercial practices, the DoD is not entitled to cost data. As this data becomes unavailable, the ability to perform cost estimates the old way will disappear. The Air Force will need to have a position from which to negotiate. They will also need to be able to compare the cost estimates identified by the contractor and estimates identified for organic support. It is imperative then that we capture these cost behaviors while we still have access, and develop models that have less reliance on data intensive regression analysis. SD is such a modeling technique.

The following sections will explain requirements for O&S cost estimating. Appendix D explains how the C-17 is performing those cost estimates for the Flexible Sustainment concept.

O&S Cost Estimating Requirements

Air Force Instruction 65-508 implements the various directives for cost estimating, and "establishes documentation requirements and review procedures for all cost estimates and provides specific instructions on cost analyses for Air Force management and financial decisions" (SAF/FMC, 1997:1). It evolved from Title 10, United States Code statues, from which the DoD 5000 regulations were implemented. These regulations mandated the requirement to perform life cycle cost estimates.

These estimates were particularly important, because they identified how much the weapon system would really cost over the life of the system. Estimates are, that by the time a mission-need-satisfying system/concept was determined, 70 percent of the costs are locked in. In fact, before one production representative article is produced, 90 percent of the total system costs are locked in (DSMC, 1997:3). So, understanding what these costs are going to be, and estimating the full program costs for the next 30 years becomes increasingly critical, especially in the light of shrinking defense budgets. Figure 3 illustrates these "committed vs. actual" costs timelines.

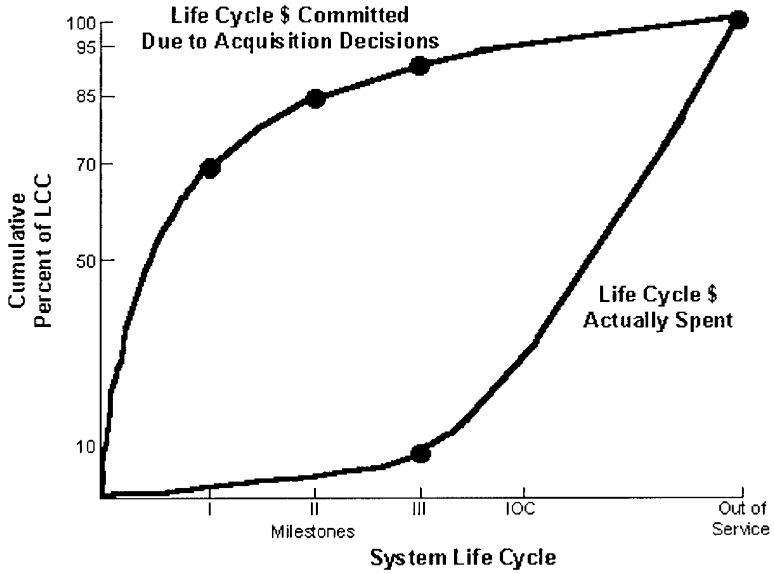

Figure 3: Early Decisions Affect Life-Cycle Cost

With this information, and the concept that 60 percent of a program's life cycle costs are incurred in the Operating and Support phases, see figure 4, the criticality of O&S cost estimating is evident (DSMC, 1997: 4), (OSD,CAIG, 1992:2-2), (SAF, 1992:2.1).

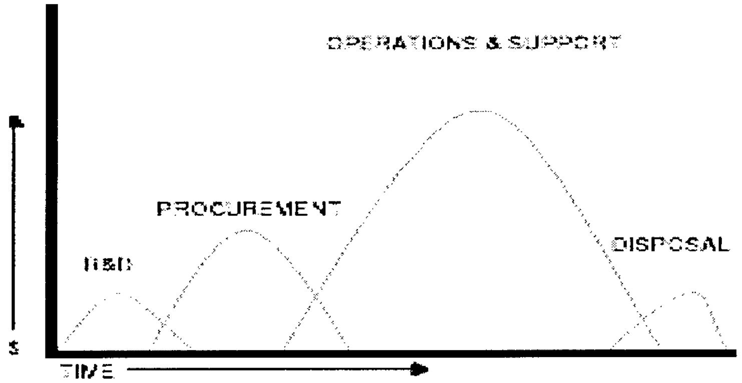

Figure 4. Comparison of cost areas

To improve on the quality of these cost estimates, the Secretary of the Air Force (SAF) established the Air Force Cost Analysis Improvement Group (AF CAIG). This group is chaired by the Deputy Assistant Secretary of the Air Force (Cost and Economics) (SAF, 1997, 3).

CAIG O&S Process Criteria.

The CAIG established minimum criteria for all cost estimates: completeness, reasonableness, consistency, documentation, and credibility (OSD, CAIG, 1992:3-2). Completeness is identifying and including key cost drivers and ensuring that costs are consistent across fiscal years. Reasonableness applies to factors, ground rules, appropriate methodologies, and the correct use of historical data. Consistency is using the correct inflation indices, deployment schedules, program documentation and assumptions. Documentation includes data sources, cost model elements, and detail, such that the estimates can be replicated from the documentation. Finally, credibility, is the model validated and are data types (budget/actual) identified?

When these elements are deficient, usually the estimate is insufficient. The deficiencies must be corrected before the nest milestone decision. These deficiencies fall into five categories: insufficient documentation; omitted or incomplete cost elements; programmatic information missing; inconsistency with previous estimates; and lack of standard format for presenting results (OSD, CAIG, 1992:3-3). Chapter IV will explain satisfaction of these criteria, and how deficiencies are avoided in an estimate, while using the SD methodology.

C-17 O&S Estimating – Current Methodology

The following information pertains to the C-17 Joint Cost Model, developed in coordination with the C-17 SPO, Defense Contract Management Command, Boeing, DCAA, and various Supplier personnel in 1997. The purpose of the model was to establish a process and provide a tool to determine the cost of Flexible Sustainment (Asher, 1997: 9). The model works as follows (figure 5): labor modules and material modules feed their various data elements into a spreadsheet that applies cost estimating relationships to those data inputs. These values are then used to determine Overhead and General and Administrative costs (G&A) using a Forward Pricing Rate agreement. All these elements are sent to another spreadsheet that calculates the factors and prices of these elements from the contractor submitted BOEs (Basis of Estimate). The spreadsheet formats the data into various reports and proposals.

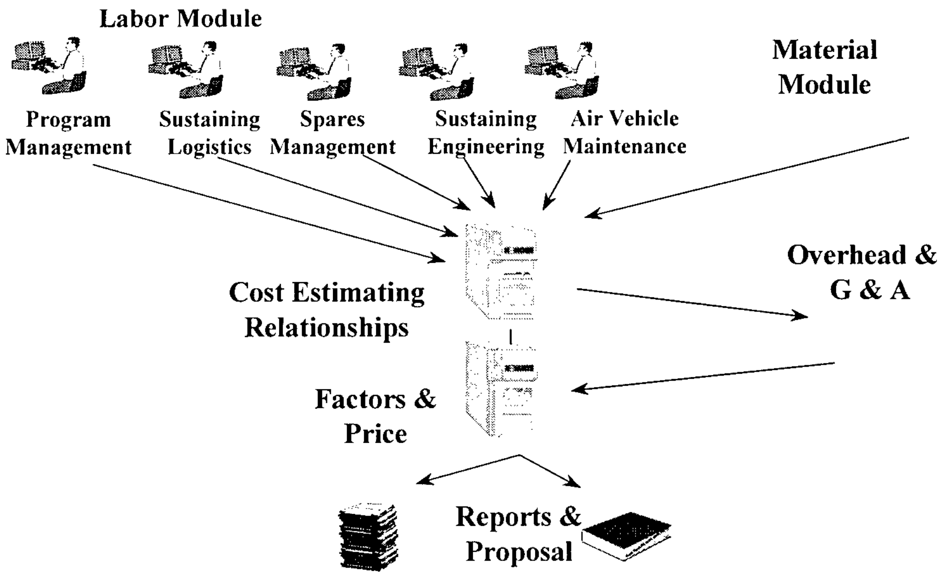

Figure 5. Joint Cost Model Process Flow

This contract is undergoing negotiation to enter the next phase. These negotiations will change the methodologies used to price this new contract. The contract type, Cost Plus (CP), will transition to Firm Fixed Price, becoming a commercial pricing structure. Appendix E contains the details of the current C-17 cost structure.

Since labor costs are fixed, they are easily estimated and contracted for using a Firm Fixed Price Contract. For the next few years, the C-17 will still be in production, and the supply of spares and the availability of facilities to do repairs will be plentiful. However, in the materials area, due to lack of consensus, a CP contract was required for Consumables, Investment Spares, Repair of Reparables, and Support Equipment (Asher, 2000). The issue becomes more complex the farther we move down the continuum to an old fleet. What are the expected effects on spares, consumables, and facilities as the fleet ages? What decisions made now, will minimize our future risks in the areas of cost and performance? Is there an impact on the system due to aging of the system?

Effects of Aging on Systems

An article appeared in the August 14, 2000 edition of the Air Force Times. It reported how the GAO had identified a deficiency in the airlift fleet. Specifically they found that some aircraft, such as the C-5 Galaxy were only available 55 percent of the time. The major contributing factors cited were a lack of spare parts, higher than forecasted repair times, the increasing number of aircraft that need depot maintenance, and the age of the aircraft (GAO, 2000, 1). They identified that the tanker fleet was suffering the same fate. In fact they found that on average the cargo fleet was 29 percent and the tanker fleet was 19 percent below the predicted mission-capable rates made just five years earlier (Rolfsen, 2000: 20).

> Aging is a general factor that affects all weapons systems. Older aircraft and engines not only require more inspections and maintenance but also increase downtime for maintenance. Both the service life (flying hours) and the chronological age contribute to structural fatigue, corrosion cracking, worn out systems, and obsolescence. Each of these issues causes a large workload that directly affects aircraft availability due to increased depot maintenance days, field maintenance (inspections and repair), and operational restrictions (GAO, 2000: 38)

Even the OSD CAIG admonishes the estimator to take into consideration changes over the life span of the system.

> The procurement O&S characteristics of a system (reliability, repair rates, test effectiveness, etc.) change over the system's lifetime. When estimating annual O&S costs of deployable units (i.e., annualized costs over the steady-state period), a mature system should be assumed. Systems exhibit mature performance after they are fully operational; however, the performance results may not be the same as identified in the system specifications. When developing a time-phased estimate, the expected rate of maturity (e.g., reliability growth) should be considered (OSD, CAIG, 1992:3-22).

In an apparent contradiction to this information, an AFLC technical report was released in 1983 which concluded there was no evidence that maintenance costs increase dramatically as an aircraft ages (Foster and Hunsaker, 1983: ii). Their study was to look at available literature on the subject then try to replicate the hypothesized Bathtub Curve of expected aging characteristics. Their study examined a number of different aircraft models over a period of eight years. For instance, they compared the C-130D to the C-130H. They thought the older model would experience higher costs, but what they found was that there was only about a 5 percent to10 percent difference in the depot maintenance costs. They used this information to conclude there was no significant differences in costs due to aging. However, the biggest difference in plane age was only 17 years (C-130B to C-130H), in one case the age difference was only 3 years (B-52D to B-52G). The period they evaluated was 1975 to 1982, and they gave no history to support the idea that operationally the planes were being used extensively. It was during this period that the "hollow force" occurred, before the "Reagan Buildup." It may be that at the end of the Vietnam Crisis, that the planes and military were not being maintained to as high a standard as before, and maintenance requirements were relaxed. Without the history, this data is meaningless. They did not include any documentation that the aircraft may have had different missions, and therefore different maintenance requirements (the mission of the C-130HA is very different from the C-130HC). Roger Steinlage, senior cost analyst at AFMC/HQ discussed this problem of lacking the history to complete the story that the data is telling.

One further problem with Foster and Hunsaker's data, is that the oldest aircraft (B-52D) was only 28 years old, it had not reached the end of its expected service life of 30 years. They cite an article by Everett Beals "When Should You Trade Your Car." This author tracked the costs of his 1963 Dodge. He expected to see at some point a dramatic increase in the cost of repairs, but none was forthcoming. However, after reviewing the data, the reader quickly notices that Beals only tracked costs for seven years, one could conclude that the car had not reached the end of its service life. Beals concludes that although he cannot forecast a point in which maintenance costs start to increase dramatically, he can foresee that at some point parts will be difficult to come by. I would suggest that it is at this point where maintenance costs will skyrocket.

There is the additional concern of obsolescence. Beals alludes to it, in the fact that he suggests that parts may be hard to find in the future. The C-17, which is still in production, has experienced this problem already. The manufacturer changed the Multi-Functional Display (MFD), which was a Cathode Ray Tube component, to a Light Emitting Diode display. In that instance, the MFDs in the current aircraft became obsolete. There are minor differences in these components, and the C-17 leadership had to make a decision to upgrade the fleet, or buy enough of the old components to meet future expected demand, before the old components became unavailable. As time goes on, more components, especially avionics and higher tech components will start to experience this same effect (Asher, 2000). Therefore, two aging problems can occur, obsolescence and failures due to fatigue.

The Bathtub Curve theory tries to explain failure rates in a system. The theory is that on a brand new item, the system will experience "Burn-in" failures. These failures are attributable to getting the bugs worked out. After some period, the system is fixed and then the failures that are occurring are random or chance failures. This period is the start of the expected service life of the system. At some point in the future, the system will reach the end of its service life, and it will begin to experience an increasing amount of failures. These failures are wear-out failures. These failures are normally distributed about the mean of the end of the service life. Therefore, they show an increasing rate of failure beginning about the end of the service life, and climbing exponentially (Gill, 1987, 100). Figure 6 shows an example of the Bathtub curve.

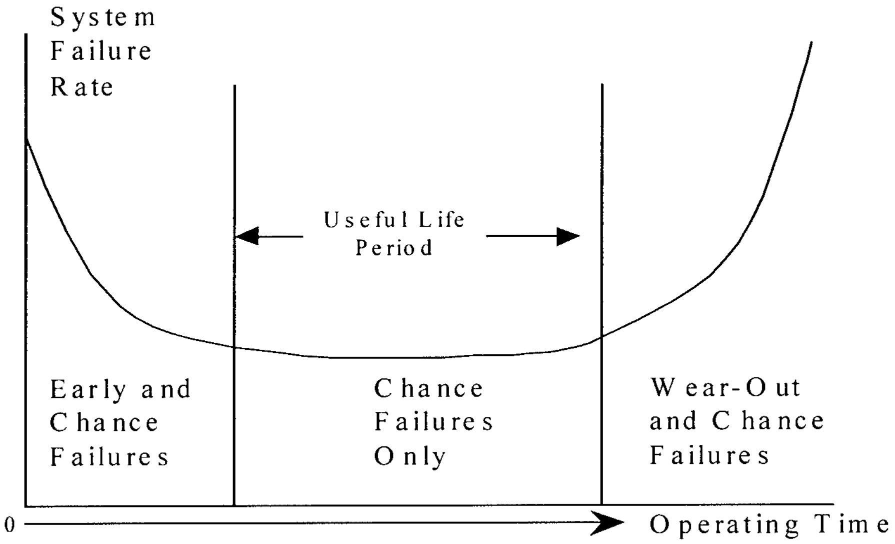

Figure 6. The Bathtub Curve

The difficult issue is that regardless of what the engineers design, knowing what the service life is, cannot be determined without extensive testing. It is easy to determine and test the expected service life of a light bulb designed to last 1000 hours, but it is entirely different to estimate the life span of an aircraft with a design life of 30,000 hours.

Having established that the effects of aging are reasonable, and establishing the fact that the Air Force is worried about them, using them in our model is the next logical step. Moreover, this ability to model the effects of aging is one advantage SD exploits. The different scenarios will show how different assumptions on the influence of aging can affect costs.

Introduction to System Dynamics

The approach used to explore the applicability of using SD to generate the O&S cost estimates, will be the development and application of various tasks and hypothesized component dependencies using a SD system dynamics modeling tool. Ten scenarios are developed, each with increasing complexity. These scenarios conceptualize and quantify the operational environment, failure and detection processes, maintenance activities, and the aging properties of the C-17. Through the application of the SD model, the outputs will validate the usefulness of the software. The primary concern will be with the cost and performance behaviors represented by the model, whether they represent logical and expected behaviors, as evaluated by C-17 engineers and cost analysts.

As mentioned briefly before, system dynamics is both an old, and a new way of looking at processes. Jay W. Forrester originally conceived the idea in 1958. In 1961 he published his ideas in a book titled Industrial Dynamics (Forrester, 1961). He defined this new technique as, "the investigation of the information feedback characteristics of systems and the use of models for the design of improved organizational form and guiding policy" (Coyle, 1996: 9). Industrial dynamics is synonymous with system dynamics. These concepts have been in use for over 30 years. However, due to the shift in thinking required to build the models and other barriers to systems thinking (Richmond, 1991:3-7), system dynamics is in many regards a new tool, whose application is providing new insight into processes and system behaviors.

The main thrust of SD is to view an event as the result of some behavior. It analyzes how the whole process works together, how systems influence and provide "feedback" to other processes in the system, resulting in some "event." For instance, in a production facility, the level of finished goods inventory is the result of many events. SD would look at the whole organization as a system made up of interacting parts, and the "causal interactions" between these parts. Customer orders, labor rates, productivity, materials availability, capacity, and cost of capital, all combine in a holistic environment to achieve the "event," the level of finished goods inventory. Furthermore, this is only one piece (node) of the bigger picture. For each area, we would develop another node to determine the behavior of that system. For instance, customer behavior (buying our product) is a product of how many potential customers are available; how many know about, would use, or have bought our product. We start with a pool of potential customers (those who do not yet own our product), as they buy our product, they become actual customers, depleting our pool of potential customers. Eventually demand for our product will drop, as potential customers become actual customers. As this causal loop is occurring, similar loops are occurring in materials (we are a potential customer to someone else), labor, and supplies. In many cases, the nodes will be similar enough, that they can simply be duplicated with only minor adjustments. SD builds a model to describe all these interactions.

Model Development –

There are two phases in developing a SD model (Wolstenholme, 1990:3-5), the qualitative and quantitative phases. Phase 1 is a qualitative hypothesis-generating step, in effect, building a potential model. This phase includes the generation of the Reference Mode and the causal loop or influence diagrams that are characteristic of SD models (Shelley, 2000: 35-53), (Coyle, 1996: 10-12). These diagrams; are developed with the help of experts involved with the processes in question. These experts translate the thoughts and assumptions about the real system into an easily conceptualized, physical picture. This helps the players understand the "feedback" that occurs between system events, and thereby providing insight into "why" events occur.

> A systems approach to problem solving requires having the perspective to deduce important system variables, and the relationships between them. Understanding then evolves from modeling the system, and seeing how the variables change, over time, as the problem parameters are changed. System Dynamics provides a method for developing such understanding" (Clark, 1988: i).

Essentially, by taking the intuitive picture of what occurs in the system (system behaviors) and illustrating them, the whole system becomes easier to understand and easier to communicate to others. Appendix B walks through this process. It follows the building of an initial model to test for key cost drivers, and serves as the impetus to model, with more complexity, those areas that have the greatest impact on costs. This approach is used because we want to model the system, not build a 100 percent accurate representation of every cost element (Karnopp and Rosenberg, 1975, 4).

Phase 2 will be the quantitative-evaluation step; it encompasses the formulation, testing, verification and validation, and implementation steps (Shelley, 2000: 64-78), (Forrester and Senge, 1980:209-227). During this phase, various estimating techniques are used to determine causal direction flow; the strength of the causal relationships; and the parameters of those relationships. This is done for each of the variables that have a significant impact on the total flow as determined through sensitivity analysis. For instance, the variables of flight hours, mean-time-between-failures, and mission type will affect various components of the C-17 differently. The goal is to find these relationships, and apply the various factors and constants to enable the model to accurately simulate the system. Many of these factors have already been determined, and are used in the C-17 Joint Cost Model. The key will be building the proper SD structure, and performing sensitivity analysis to determine if more accurate factors should be developed for model implementation.

Model Implementation –

After investigating key cost drivers, the final step will be to implement these drivers under different scenarios, to test for logical results. Cost factors from Boeing's "Basis of Estimates" (BOEs) will be sanitized and used to populate the various cost drivers, from which the software will determine the operations and support costs for a specified period. These BOEs are the cost factors that Boeing has currently supplied for the basis of their current support contract for the C-17 (the Flexible Sustainment Contract). As such, they represent what Boeing is charging for particular activities

Wolstenholme points out that to predict the future with current models, you must assume that things are not going to change in the future; that is, your basis of estimate will remain static. In the short run, that is a fair assumption, but over the long run, it is not. SD relies on the fact that things will change. It facilitates strategy evaluation and decision making about how to best change, enhance and improve the current system. The idea is that because the system will, the estimate must consider these changes. Exact calculation of stocks and flows (modeling components defined later) are not necessary, as point accuracy is not the goal. The goal is development of the model and verification of the reasonableness of the behaviors it represents, for the data simulated.

Finally, model validity is achieved when the general behavior characteristics of the model and its ability to generate accepted responses to set policy changes, is accepted by the user (Wolstenholme, 1990:58). He reports:

> In many fields of enquiry, the validity of a model often refers only to whether it can accurately reproduce past statistical data as observed in the real system. Although it is considered important in System Dynamics that a model can reproduce a reference mode of behaviors, this is seen as only one of a range of tests of validity....For System Dynamics models, which attempt to create scenarios based on assumptions about multiple relationships and policies, such emphasis on the past is seen as less important.... Validity is seen as a more complex concept, which centers on user confidence in the model. This confidence stems from an appreciation of the structure of the model.... ***Validity is achieved in the sense that it structurally represents the reality described and produces an accepted response to a given input, that is, a smooth transition when subjected to a proportional control policy***. [Emphasis, mine]

This is not a one-time event. Unlike regression analysis, which relies on R^2, Durbin-Watson tests, and other non-intuitive signals to suggest validity (McClave, Benson, Sincich, 1998: 429-799) the SD approach is to build confidence in the model builder and user, that the model is beneficial. Forrester and Senge highlight 17 tests that will help build confidence first in the model builder, then in the user that the model is valid (Forrester and Senge, 1980, 209-227). The final test of validity would be acceptance and implementation by the user of the model, for decision-making purposes.

Conclusion

This chapter provided background information in four areas: O&S cost estimating requirements; the current method used by the C-17 SPO for cost estimating; effects of aging on systems; and an introduction to system dynamics. It also addressed the history of the C-17 and explained the maintenance concept of Flexible Sustainment, used to support C-17. It also addressed the need for a tool to aid decision-makers in making optimal, long-term, decisions. Finally, a brief summary of system dynamics was given, to help the reader understand the benefits of this modeling technique.

Chapter III Methodology

Overview

This chapter will outline the method used to develop the various scenarios to test applicability of SD for estimating the C-17 O&S costs that the decision-makers will be able to impact. These scenarios will be developed using a system dynamics simulation modeling package, at the request of the C-17 SPO cost analysis team. This chapter will discuss the modeling process, present some of the analysis to be performed, and explain some limitations of this model.

Modeling Process

The SD modeling methodology is an iterative process[4]. Ten steps are developed during this model evaluation process. Each step takes the model builder closer to validity, that is, confidence that the tool has applicability to the effort being tested. These steps provide a chance to test and verify the behaviors of the model, in an evolutionary sense, proving the general before continuing to build detail. All discrepancies and seemingly illogical results need reconciliation before attempting the next step towards a detailed model.

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[4] Appendix G explains some of the terminology unique to the FleetSight software, if the reader is interested.

Analysis

The first step in building the model is to plan the process, the development of the Study Map. This study map guides the modeler through an iterative model building process, that is, build one area, test it, confirm its behavior, then add to it. The purpose is to slowly build complexity, and continually verify the model's structure and behavior. Each of these scenarios tests one area of the model. A successful test indicates that the SD would be able to model any similar tasks. If SD can be shown to logically present these areas, it can be reasonably assumed that a complete O&S estimate could be produced by duplicating the various tasks, and combining them into one model. The scenarios that will be tested are as follows.

Step 1. Verify C-17 Aging

In this phase, the purpose is to verify that the aging curve is logically displayed. The issue is whether the aircraft moves through the different ages (new, mid-life, and old) in a smooth and logical manner, compatible with the expected aircraft age. This first step is the foundation of the model. If the aircraft does not progress logically, then the aging influences tied to the various lifecycle points of the aircraft would be illogical, and would fail to match expected behaviors, rendering the model useless.

Step 2. Acquisitions and Retirements

In this phase the historical and planned acquisition of aircraft and hypothetical aircraft retirements are planned and simulated. At this point, the historical numbers are compared with the simulated data. This portion verifies that the mechanics of model are working correctly, to add assets to the fleet. The same check as step 1 is also performed. At this point, the model is tested for mechanical consistency. The modeler should see the fleet move through the same aging profile as identified in step one. It should show the logical influences of adding new aircraft at the beginning of the cycle, and the influences of eliminating old aircraft. Specifically, adding a new aircraft should bring the average age of the fleet closer to the "new" category; and, a retirement of an "old" aircraft should have the same effect on the average age.

Categorical factors represent aircraft age. A new product has a factor of three, mid-life is a two, and a one represents old. Therefore the average age of the fleet is calculated by taking the previous factors, multiplied by the number of aircraft in that category, summing that total, then dividing by the total number of aircraft in the fleet. Due to the dynamics of the software (uses a fifth order exponential decay function), when the average age of the fleet is 1.25, the fleet is considered used up. No prediction of behavior is made after this point, as the predictability of a "used up" fleet is unknown.

Step 3. Maintenance

In this scenario, a maintenance activity and its corresponding labor and materials requirements are input, and readied for simulation. Aging characteristics are then determined. These characteristics are an attempt to predict the effect of aging on the maintenance task. The aircraft maintainers have suggested that as an aircraft ages, it takes longer to do a particular task, and that task may have to be done more often. For instance, corrosion checks are performed more frequently on an older aircraft. Therefore, as the aircraft ages, the frequency of this task increases. At the same time, when doing these tasks, the possibility of braking fasteners and stripping or sheering bolts increases. Therefore, it begins to take longer to perform the task compared to when the aircraft was new. The possible influences for these impacts vary from "no impact" to "severe." The expert's opinion of the proper strength guides the influence used. The strength can by adjusted to test the sensitivity of the system to possible exogenous influences.

This scenario has two purposes: to verify the mechanics of this next level of detail; and to establish a hypothesized baseline for the program, to explore and compare the effects of a Service Lifetime Extension Program (SLEP).

Step 4. First SLEP

This step implements a SLEP, and provides the opportunity to check model behavior against expected behavior, and compare the behavior against the data from step 3. The program should start a second SLEP at the point where the remaining expected service life of the fleet reaches 10 percent.

Step 5. SLEP TWO

This step is used to determine that the model can correctly implement multiple upgrades to the system. The behavior that this SLEP exhibits should match the behavior from the first SLEP. This step also provides an opportunity to start using the model to test availability, timing and cost trade-offs.

Step 6. New Acquisition and Retirements

This step goes back to the first SLEP, and explores the behavior of the system if new aircraft are purchased, instead of performing a new SLEP, and also checks the behavior if older aircraft are retired. This is a particularly important step to the C-17 as they are approved to purchase up to 60 more aircraft, should funding become available. As mentioned in the previous chapter, due to aging issues, the Air Force's cargo fleet is 29 percent below needed capacity. One way to overcome this deficit is to purchase more cargo aircraft. Being able to explore the dynamic behavior and make trade-off decisions on buy vs. repair opportunities should prove an invaluable tool for decision-makers.

Step 7. Component Upgrade

In this scenario, the plan is to input the Work Breakdown Structure (WBS) for a component, simulate an upgrade on that component, and explore the impacts on costs and mission effectiveness. This step will be the first scenario to explore the impact on the aircraft and fleet, of an individual component's failure. In this step, engines will be used to examine this behavior. The behaviors presented should logically match expected data for engine failure rates, and predicted aging effects.

Step 8. Multiple Fleets

This step further defines the details of the aircraft. The fleet will be operated and maintained in different locations. This will further allow analysis of fleet stress due to various missions. For instance, the different bases have different missions, and demands. The effects of these stresses can be simulated, to emulate those that occur in reality.

Step 9. Operations Analysis

This step builds on the model to include the impacts of personnel, training, and spares. This step examines the model's performance under various mission profiles, training deficiencies, and spares supply impacts. Behaviors should logically track with changes in maintenance tasks, delayed tasks, and increased aging.

Step 10. Dependencies

This final step completes the detail of the model. It explores the impact of various structures, subsystems, and components of the system, including interdependencies between these elements. For instance, is there an impact on the airframe if the paint is allowed to wear out, or if mission rates increase? These interdependencies can magnify the effects of aging, and account for the possibility, that as an aircraft ages, more things break, and it takes longer to fix them. These effects are known as chain reaction failures (Colorado, 1999).

> The propagating "chain reactions" failure mechanism is characteristic of complex systems with tightly coupled subsystems. This mechanism depends on the dynamics of the system itself, in that seemingly inconsequential events trigger multiple failures through an unanticipated domino effects....the real problem is not the triggering event itself, but the interaction of anomalous operating modes among subsystems that it sets in motion (White House, 1997, 21).

Limitations

The SD modeling package appears to be a capable tool. One issue however, is that this capability is new, and examples are hard to come by. Because each user is able to define their project the way they want to, no two models are identical. This is the first effort by the Air Force to use this tool; therefore, we are breaking new ground, and consequently cannot rely on lessons learned from other Air Force users.

Other drawbacks are that this is a proprietary tool, and the flow diagrams cannot be altered for differences in structure between systems. Therefore, a more generic model is developed. At this level, it may not be a disadvantage, but, in the future, there may be other factors that the decision maker wants to model that this tool will not be able to incorporate.

The advantage to using this software program, as opposed to a different modeling package, is that the knowledge of System Dynamics is not required. After this model is built, it will be able to be altered and re-run without the user needing to understand the SD programming language. Also, because the flow diagrams cannot be altered, the main limitation to SD is eliminated, which is the tendency to create overly complex models.

Conclusion

This chapter explained the steps involved in building the components of a SD model, that will generate the O&S cost estimates. The inputs and structures were also presented. Finally, some of the limitations to this modeling effort were explained. The next chapter will present the analysis of the results of these scenarios.

Chapter IV Findings

Overview

This chapter will present the detail of the scenarios listed in the previous chapter. Particular attention will be made to compare the model's predicted behavior against actual results. Where possible, sensitivity analysis will be made, primarily by varying the strength of forces applied to the causal dependencies. This is done as an aid to decision-makers, to help explore the possible effects of various dynamic influences on the aircraft, fleet and facilities. As an example of the benefits of this tool, two comparisons are made to the SPO's current pricing model, to further accentuate the benefits of SD modeling. The goal of these scenarios is to show that indeed SD can logically model the influences, tasks, and components of the C-17; therefore, implying the applicability of SD to build O&S estimates. Specifically, to build a complete model, cost outputs should be malleable to the OSD/CAIG categories. They should capture costs in a logical manner, including, fixed, flight hour variable, and age variable costs. Also, the aircraft's behavior should be logically represented. These behaviors include delivery to the fleet, operational missions, maintenance activities (scheduled and unscheduled), upgrade requirements, failures, and stress and aging factors.

1.0 Aging (Scenario 1)

This scenario determines if the aircraft goes through the aging categories in a logical manner (New, Mid-life, Old). This scenario traces the aircraft, over a 40-year period. Figure 7 shows the graph of the C-17's life span. The curve matches the expert opinion of how the aircraft would age. Specifically, its "New" characteristics would fade quickly, but its "Old" characteristics should increase slowly. Therefore, we would expect to see an S shaped curve, characterized by exponential decay, smoothed by the fifth order decay factors implemented by the software programmers. That is, the rate of aging slows as the aircraft reaches the end of its useful life.

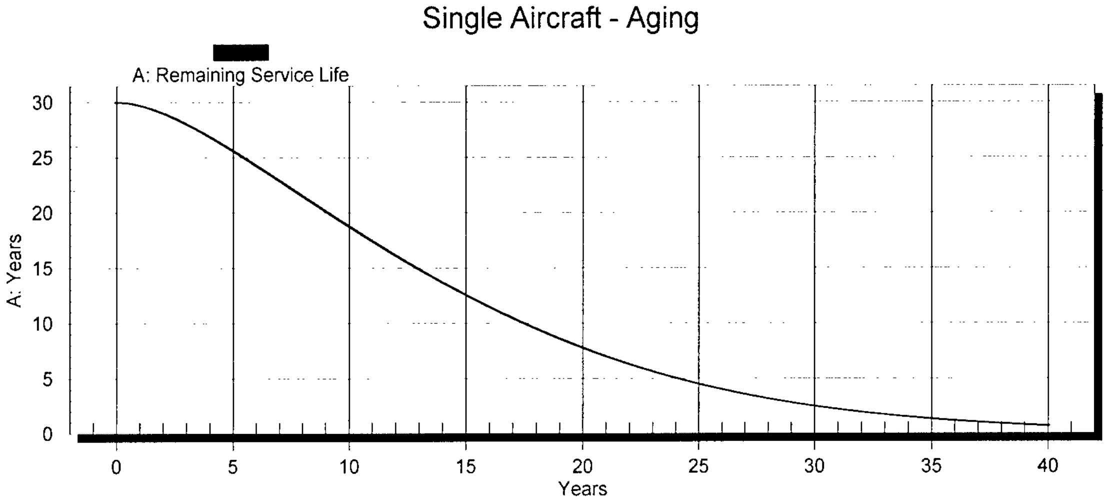


Figure 7. Single C-17 Aging, with expected life-span of 30 years

The exponential decay function allows for a smooth aging of the aircraft into the different age categories. Otherwise, a stair-step behavior occurs as the aircraft leaves one age category and enters another. This behavior is logical, because it is how things age. On a person's 21st birthday, they become an "adult," but they are really only one day older than the day before. Aircraft are the same. However, unlike people, the aircraft will never die. To achieve the smooth decay, an exponential function is used, so out past the expected lifetime, the average condition line becomes asymptotic, and the aircraft never dies. This is evident with the current fleet of aircraft. There is always some "life" left in a few of the aircraft, they may be in the "bone-yard," but often they were flown there, so they had some remaining life. This decay feature helps identify another case where the model generates a logical representation of real-world aging characteristics.

For these scenarios, assume all regular maintenance will occur on schedule. Whatever the manufacturer assumed would occur to give the aircraft a 30 year life, would be performed on schedule. This will be an overriding assumption as the modeling continues. Modeling will be done by exception, that is, if we were to model the paint task, the steady-state situation is that things will be as originally assumed. Any modeling would be to suppose what would happen if the regular assumptions are changed. For instance, what would happen if we did not paint the plane on the suggested schedule? The hypothesized answer will follow, near the end of this chapter.

2.0 A&R (Acquisitions and Retirements)

In this scenario, the planned acquisition profile of the C-17 Production Schedule is modeled. In this profile, 120 total C-17 aircraft are expected. Although there is a plan for future acquisitions, because these additional buys have not been contracted for, they have not been input in any of the scenarios

Figures 8, 9, and 10, show the results. They show, that the aircraft are acquired in the profile expected (figure 8); that the A/C move through the age categories as expected (figure 9); and finally, that the condition of the fleet matches the profile of aging (figure 10), which determines when the fleet is effectively used up (about 40 years for the fleet)

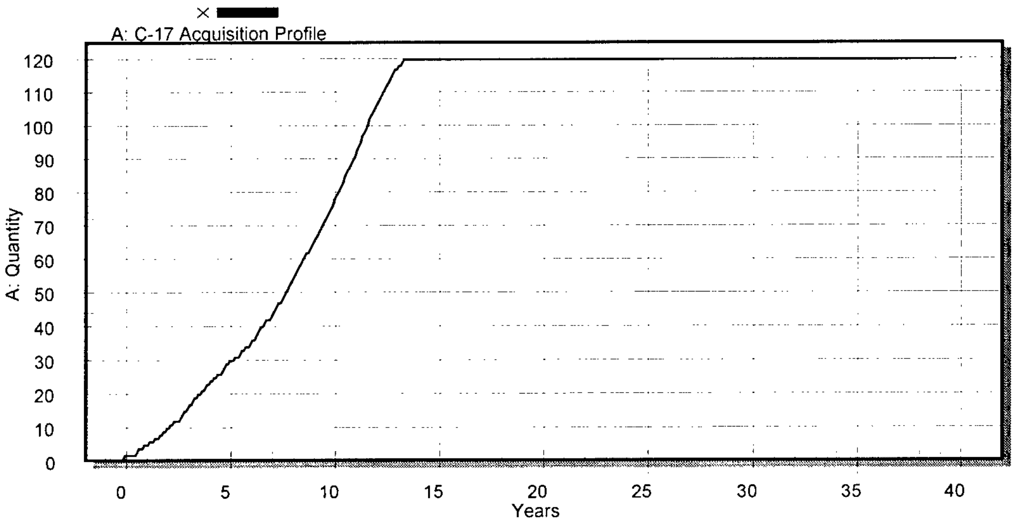


Figure 8. Acquisition Profile

Figure 8 shows the cumulative fleet size as production continues. This mechanical test shows that the software accumulates the expected number of aircraft, in the expected profile. This profile is manually input, therefore no dynamic behaviors are expected. Because failures are not modeled at this point, the fleet quantity of 120 remains static, regardless of the age of the fleet. For this scenario, these are the expected behaviors.

Figure 9 makes an important validation point. It shows that the percentages of aircraft in each age category fairly represent the expected amounts. For instance, when 100% of the fleet is new, 0% are mid-life. It is important to note that at each point, the graph shows consistent behavior, all the way to the end, when the fleet shows at the 40-year mark, that 90% of the fleet are old, and 10% are mid-life. The consistency helps build confidence that the model's structures are reliable.

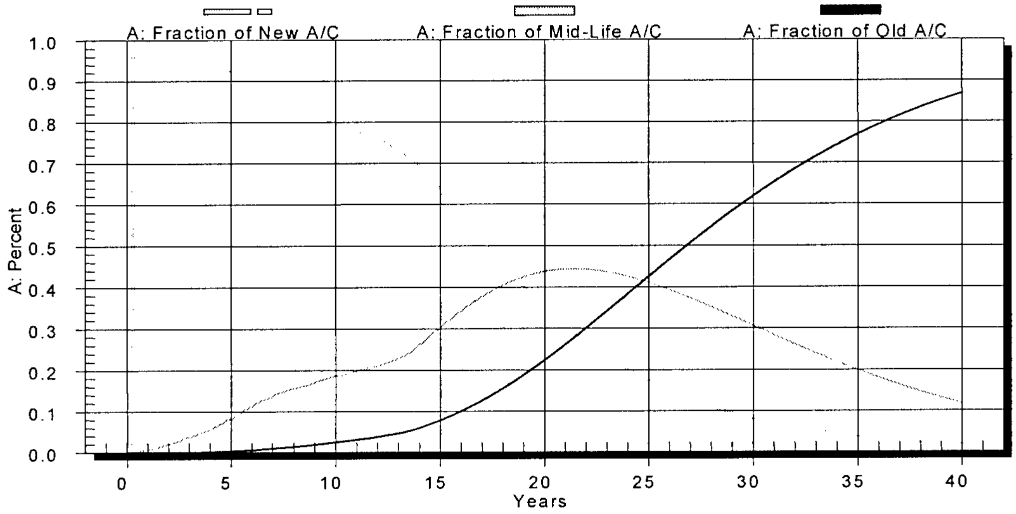


Figure 9 Ratio of C-17 Fleet Remaining Useful Life

For Figure 10, the profile presented needs some interpretation. The model uses a factor to represent average fleet age. This factor ranges from 3 (brand new) to 1 (old). One assumption is that planes never completely expire, but at some point they are so old, their reliability is unpredictable. Therefore, when the average condition of the fleet falls to a factor of 1.25, the effective life of the fleet is over.

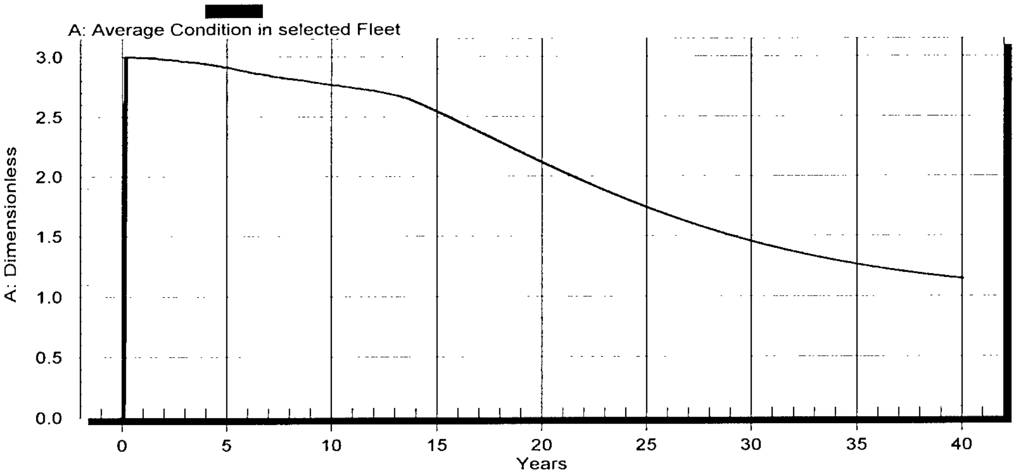


Figure 10. Ratio of C-17 Fleet Remaining Useful Life

The profile above matches this generic mode. The behavior of the curve is germane to any system with an expected life span of 30 years. This curve hold true if the A/C experiences no upgrades and that the expected service life matches the A/C's actual service life. One useful predictor is that if the aircraft appears to have a different aging profile, that is if maintenance activities begin to have shortened intervals, the maintainers would be able to adjust spares requirements before significant shortages are experienced. Alternatively, a delayed aging profile could indicate reduced spares requirements. Comparing actual and modeled behavior builds confidence in the model. Discrepancies are used to adjust the model or as advanced indicators of accelerated or delayed aging of the fleet. These situations will give the decision-makers time to affect changes, to deal proactively with, not reacting to, situations.

3.0 ACI – But No Service Lifetime Extension Program (SLEP)

This scenario defines one maintenance activity, for the fleet, modeled under scenario 2's assumptions. This maintenance activity is an Analytical Condition Inspection (ACI). This task is a careful inspection of the airframe and other areas of the A/C where corrosion is expected. Maintainers perform this maintenance task is at an interval of 5 years. This means that each A/C in the entire active fleet will have an ACI within an interval of 5 years. This maintenance task takes place at the intermediate facility labeled "the BASC" (Boeing Aerospace Service Center). For ease of modeling, the ACI Materials Kit contains all the materials needed for the inspection; therefore, each ACI needs only one kit. For a more detailed cost analysis, the components of this kit could be broken out, and modeled separately. The labor required to perform these tasks are assigned to the various labor categories, as identified by Boeing's BOEs (Basis of Estimates). The costs of the materials contained in the ACI kits come from the BOEs.

The ACI maintenance task is assigned to the Airframe WBS element. For this scenario, the BASC is the repair facility; however, a depot level facility is also appropriate. The point is that the maintenance does not occur at the flight line. This is important, because a maintenance task takes the aircraft out of flying status. In a typical manner, this would reduce our mission capable rate. See chapter 5, limitations - maintenance, for further information about the problems that this creates for the C-17.

For this model, five labor categories are identified. These categories are not the inclusive list of all labor types at the BASC, only a representative sample needed to complete this task. C-17 maintainers unanimously agree that there are no labor or material constraints on this task, at this facility. The goal here was to show how to model individual labor types and report their costs singularly and combined.

The graphs, figures 11, 12, and 13, show three things. First, the aging characteristic (average condition) stays consistent with the previous scenarios (figure11). Secondly, the completion of the task happens in a logical manner, consistent with the expected interval as shown in the kit usage (figure 12). Finally, labor is used in a manner consistent with the completion of the tasks (figure 13).

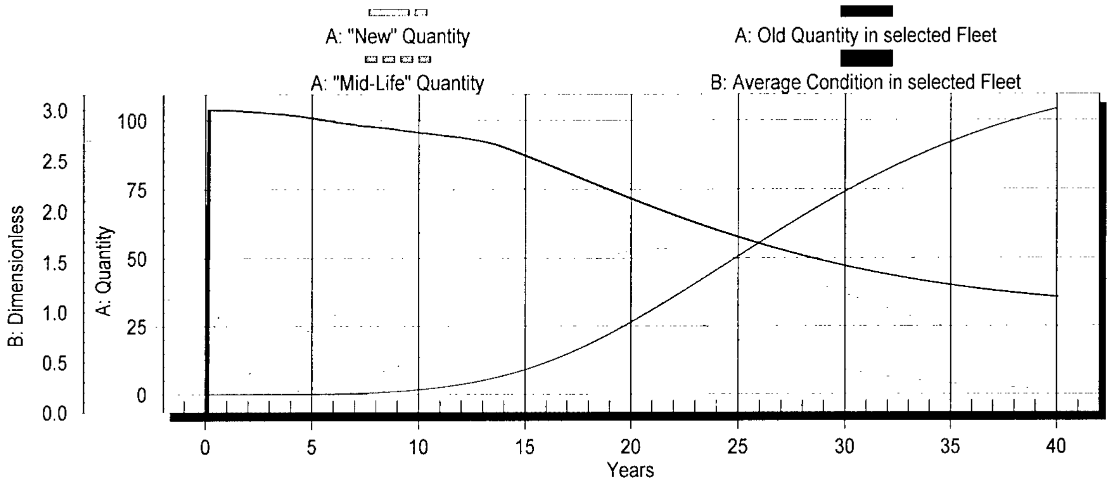


Figure 11. Aging Characteristics Profile

Figure 11 shows that the average condition is identical to scenario 2, therefore, the added detail of the inspection (correctly) does not affect the profile. Also, the "new" to "old" aging characteristics are also consistent with what was previously identified. The only difference, is instead of using the factor of "Fraction Active," actual quantities are used. The build up in the "new" category is caused by the acquisition profile. Notice that some planes in the fleet are becoming "old" as new planes are arriving in the fleet. This causes the delay in the average condition line. This further builds confidence in the model's structure, because the behaviors exhibited are logical and expected.

It is important to understand that this task is performed in the expected profile, therefore it should have no impact on the fleet's expected life span. Should we wish to model such an influence it is modeled by exception, determining the difference between the baseline and the new requirement, and modeling the hypothesized dependency. An example of this technique is the "paint" scenario explained later in this chapter.

Figure 12 shows that as the number of planes increase, the number of kits needed for ACIs also increases. In fact, the logic of the behaviors represented show the expected exponential increase of kit usage. As more planes enter the inventory, the number needing ACIs increases also, additionally, the planes in the existing fleet continue to need ACIs, so this increases the ACI demand every five years through the Acquisition period. When production ends, the fleet reaches steady state, the number of ACIs required each month levels off, but experiences some growth as the fleet ages. The expected behavior is that as the A/C gets older, it will need ACIs at a shorter interval. Therefore, the graph shows the influence of this aging factor, that as the fleet gets older, the interval shortens and so the requirement for ACIs increases. The current pricing model produces a flat line for requirements after the fleet reaches steady state. The C-17 costers admit there will probably need to an increase, but this evaluation won't occur for a number of years.

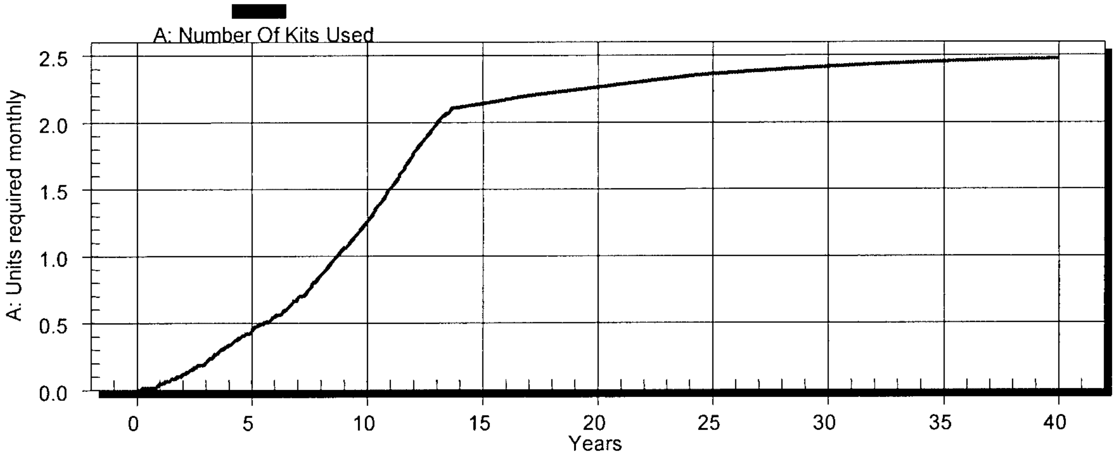


Figure 12. Material Kits Used

In the same manner, when addressing labor amounts and costs, the same behavior is expected. Additionally, a compounding influence also occurs. Aircraft maintainers agree, that as an A/C gets older, it is harder to work on. Factors such as stripped bolts, corrosion, and fatigued metal, all conspire to add man-hours to tasks that in the past were not so demanding to accomplish. Therefore, to complete a task we would expect to see an increase in the man-hours required as the fleet ages. Unfortunately, there is no scientific data to justify an exact influence, only anecdotal evidence. Obviously, the impacts are greater for some tasks compared to others. The key here was to model these influences, and demonstrate the modeling, should the maintainers believe that aging would influence that particular task. Figure 13 shows these behaviors.

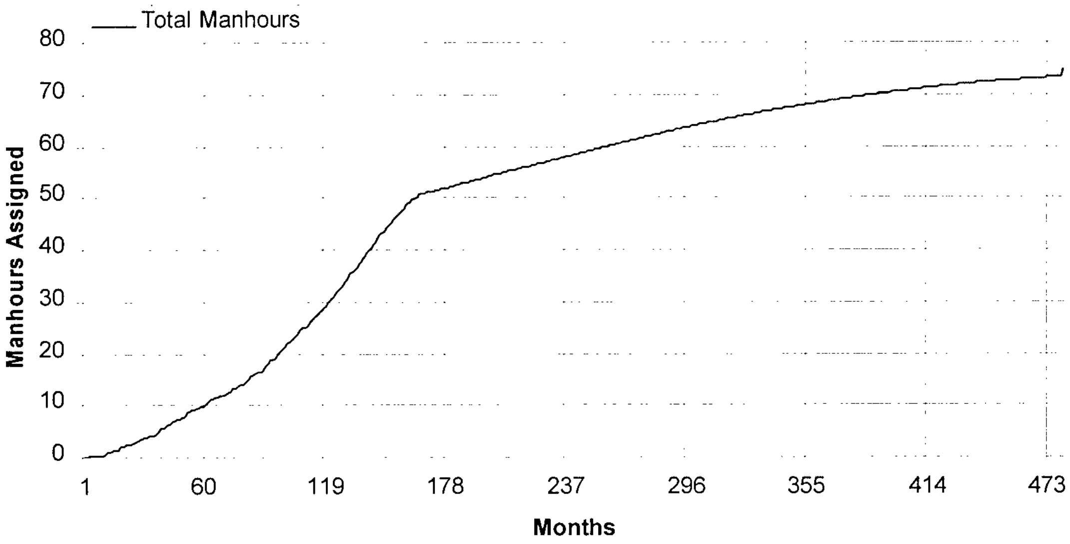


Figure 13. Labor assigned to ACI Task

As the figure shows, when compared to the materials chart, the amount of labor required increases faster than materials. The amount of kits required for the ACIs increases due to the shortening of the maintenance interval. This increases the amount of ACIs performed each year. Labor requirements increase not only because of the shortened intervals but also because it takes longer to perform the task each time it is accomplished. Therefore, if these effects are appropriate, we can model them. Either influence can be altered, not only the strength of the influence, but also the applicability of the influence. The aging influence used for this scenario was a "moderate" influence. The other possible influences were none, low, and high.

4.0 FLE Former Cracks SLEP 1

This scenario goes one step farther with the baseline established in scenario 3. It models an assembly, and simulates an upgrade on that item, to extend the life of that component. In this case, the Forward Leading Edge Formers (FLEFs) are modeled. The FLEFs have cracks in them, and if they are not fixed, the components that are attached to these hard points will experience increased vibration, and therefore, increased failures. The scheduled induction profile for upgrading this item was input according to the GRIP (Global Reach Improvement Program) schedule already in place. The GRIP schedule is the plan the C-17 uses to transfer aircraft from the active fleet to the Back Up Aircraft Inventory (BAI) so that work being done for scheduled maintenance does not affect the reported Mission Capable Rates. The FLEFs are part of the support structure of the wing, which is part of the airframe, which is an "assembly" of the C-17. Additional WBS elements (hydraulic/ Pneumatic Power, and Landing Gear) could be added to the model to account for other possible upgrade tasks and influences.

The upgrade tasks will take place at the Long Beach Depot facility. To establish this facility, the labor and materials kits needed for this task are assigned. Other kits are put in place to deal with the planned upgrades of the other components (Landing gear lifetime extension program), and an inspection kit, to bring the aircraft down if necessary for completion of one of these tasks.

The graphs, figures 14, 15 and 16, make a number of different points. First, as the upgrade takes place, the number of FLEFs in the "New" category increases (figure 14). The model assumes that the "oldest" FLEF is upgraded first. Therefore, it is from the "old" category that the FLEFs are transformed to the "new" status, figure 15. If there are not enough old FLEFs, the software takes the FLEF from the mid-life category figure 16. In this scenario, such a situation exists, therefore, the number of "mid-life" FLEFs declines to make up for the insufficient number of "Old" FLEFs to meet the upgrade requirements. The service life of the component (the FLEFs) experience a corresponding increase, due to the movement of these older FLEFs to the "new" category. The condition of the fleet also shows logical behavior in the light of this upgrade. The shift in FLEFs from the old and mid-life categories can be seen by the decrease in the quantities in these categories. There is a corresponding increase in the new category, during the time of the upgrade. During and after the upgrade, the aging process continues, so the FLEFs in the new category move into the other aging categories.

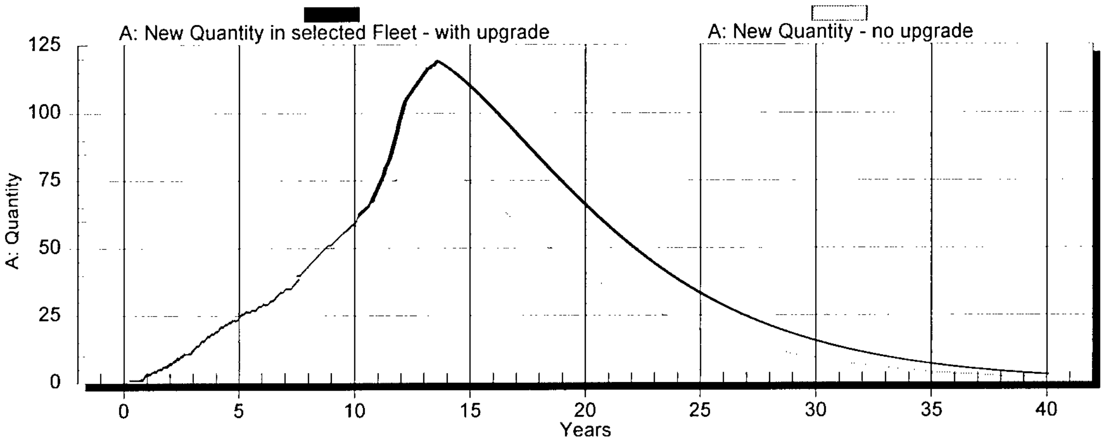


Figure 14. Effect of Upgrade on 'New' Category

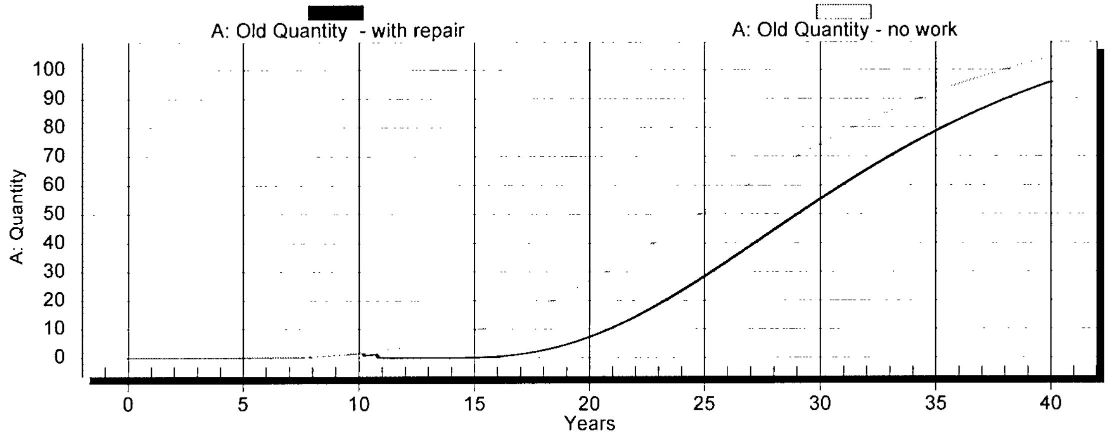


Figure 15. Effect of Upgrade on 'Old' Category

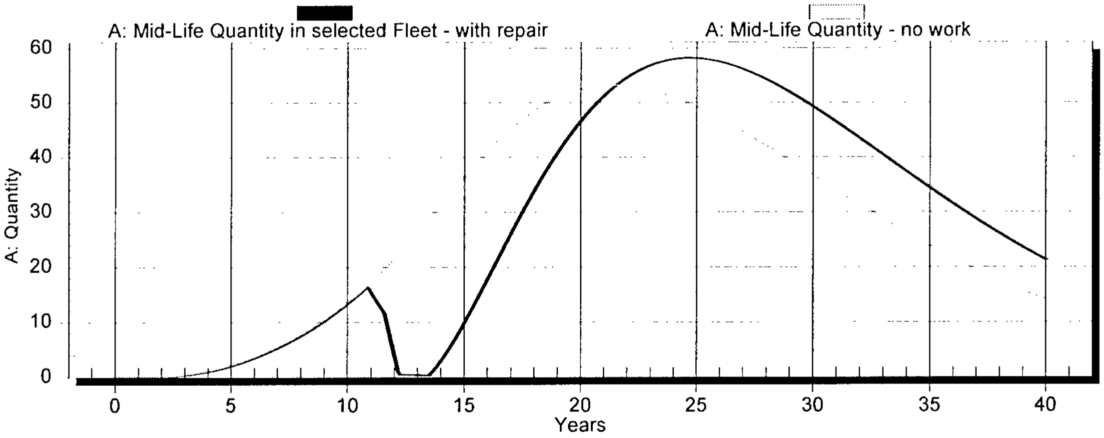


Figure 16. Effect of Upgrade on 'Mid-Life' Category

The graphs also show the fleet availability (figure 17). As the Availability section notes, there is no decrease in the availability of the fleet. This shows that if a component goes down for repair, or upgrade, that the aircraft does not have to go down also. In this case, this behavior is indicative of the actual plan for Aircraft Upgrades. Again, the C-17 fleet uses a sub-fleet of aircraft, known as the Backup Aircraft Inventory (BAI), when it performs upgrades. That is, an active plane transfers from active status to BAI status. Upgrades occur only to BAI aircraft. Because of this plan, scheduled maintenance does not affect Fleet Availability. Therefore, when performing upgrades in this model, only components are "brought down," not the full aircraft.

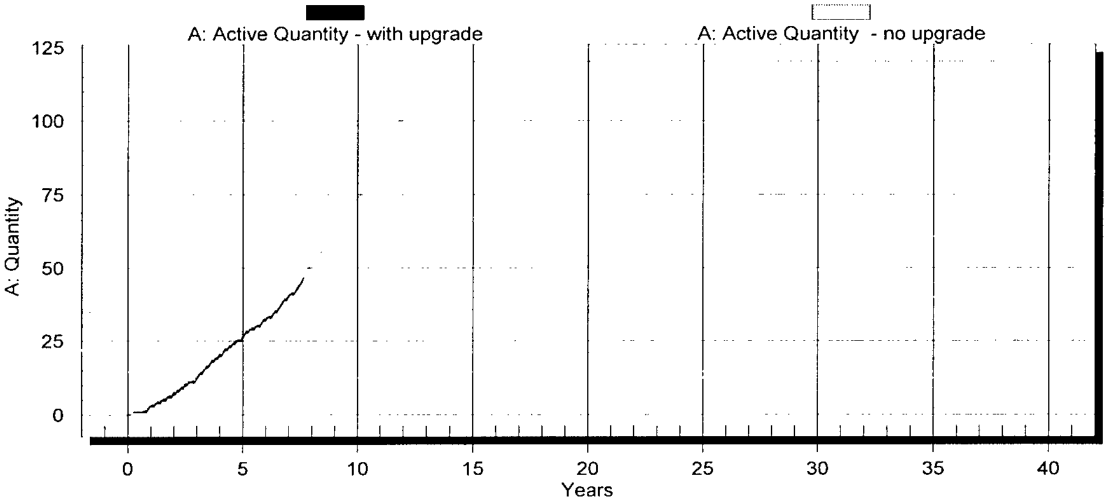


Figure 17. Effect of Upgrade on Availability

Finally, the cost variables are graphed (figure 18). The important thing to verify is that the costs produced by the model match the expected cost profile. In this case, the model predicts the same behavior, and the total costs do match the labor and materials costs, as estimated by Boeing.

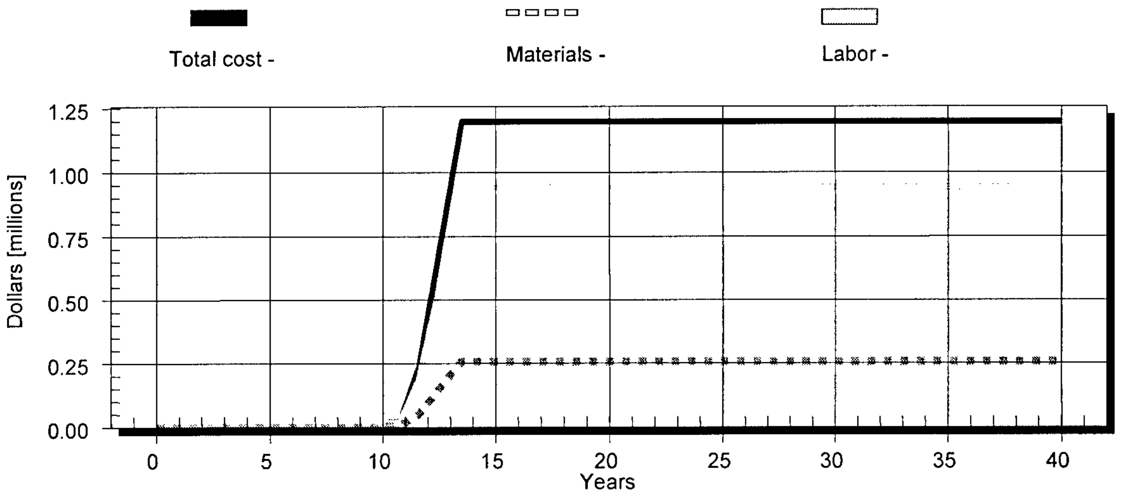


Figure 18. Tracking Costs of the Upgrade

This scenario considered many important factors. First was the ability to upgrade a component. Not all components have the same expected life span. The ability to track these components separately, and the ability to model their influence on the aircraft, is important, to simulate real life. This scenario also shows that we can track the dependent and independent influences of the various WBS elements on the complete system. Also, the costs involved for these items can be tracked separately, facilitating categorization to match the OSD/CAIG O&S requirements. Finally, this scenario shows the predictive nature of the model. The expected life span of a component is compared to the actual life span; as data is collected, any difference in the expected value identifies a possible influence. These divergences provide early indicators to decision-makers. It is important to reiterate that to achieve the 30,000 expected flight hour life from the C-17, all maintenance must be accomplished as expected. The impact of the aging FLEFs should only negatively affect the A/C if not performed as required. The last scenario will demonstrate this effect.

5.0 Paint SLEP 2.

This scenario is designed to follow the first SLEP, and show the impact of a second, or subsequent, SLEP. However, this SLEP (Strip and Paint the Fleet) occurs on a different assembly from the FLEF, therefore requiring the creation of a "Paint" assembly.

A strip and paint is required every 10 years for the aircraft, again, it is a scheduled maintenance item, so it does not "take down" the aircraft from the fleet. In reality, painting and ACIs occur in conjunction. The induction schedule shows aircraft 1 being inducted at its 10, 20, and 30 year points. At the same time, AC 50 will be inducted at the same time, but its 10-year anniversary is the same as AC 1's 20-year anniversary, so for that month, two planes will be stripped and painted. The paint has an expected life span of 12 years, compared to the A/C's expected life span of 30 years.

The current thinking is that the repair facilities have the capacity to handle these multiple strip and paints. One interesting thing to determine, is what would be the impact of insufficient paint capacity (increased costs – due to subcontracting the work out, and or, increased failures due to delaying the activity and experiencing more corrosion). This scenario does not explore these concerns, but the final scenario will explore the effect of not updating the paint on the fleet.

Strip-and-Paints occurs at the BASC, and the associated labor, kits, and costs are attributed to this facility. The WBS element "paint" allows identification of the condition of the paint, which in future analyses can indicate increased costs due to delay or aging characteristics of this assembly.

The graphs depict the expected behavior of this activity. In the new category, we reach a point of equilibrium, figure 19, because we are painting on a constant basis, as the paint gets old, it is upgraded to new. Therefore, we should see a flattening of the aging category lines, for paint, below the quantity of the unpainted fleet, and we should note a flat line in the new category, when compared to the unpainted fleet. These behaviors are shown in the graphs, figures 19, 20, and 21.

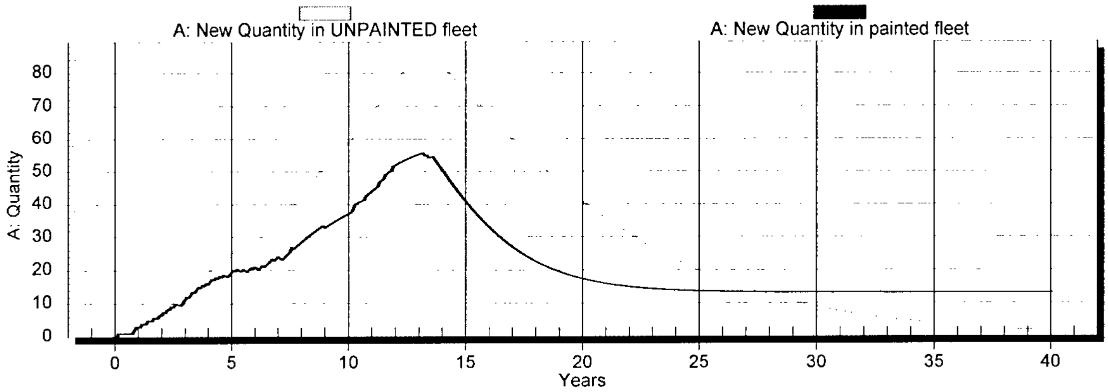


Figure 19. Compare Constant Upgrade to the Fleet - 'New' category

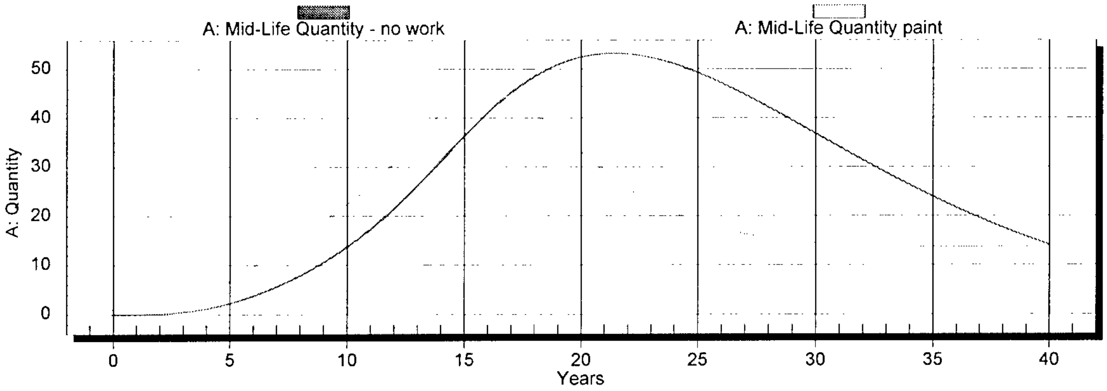


Figure 20. Compare Constant Upgrade to the Fleet - 'Mid-life' Category

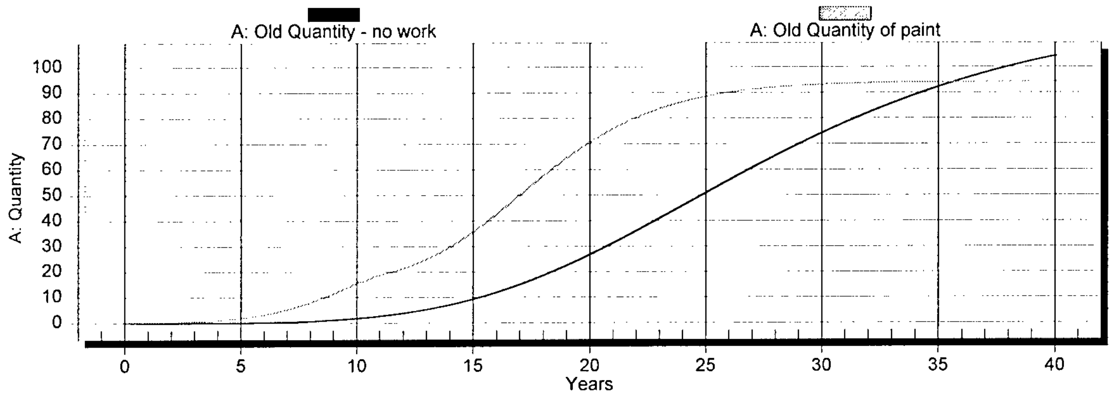


Figure 21. Compare Constant Upgrade to the Fleet - 'Old' Category

Another comparison to make, is the condition of the paint compared to the aircraft (figure 22). This could identify when the decision-maker might want to reconsider painting the aircraft, as there might be little need to repaint a plane that is about to be retired. Tests verified the induction schedule, and costs associated with the upgrade.

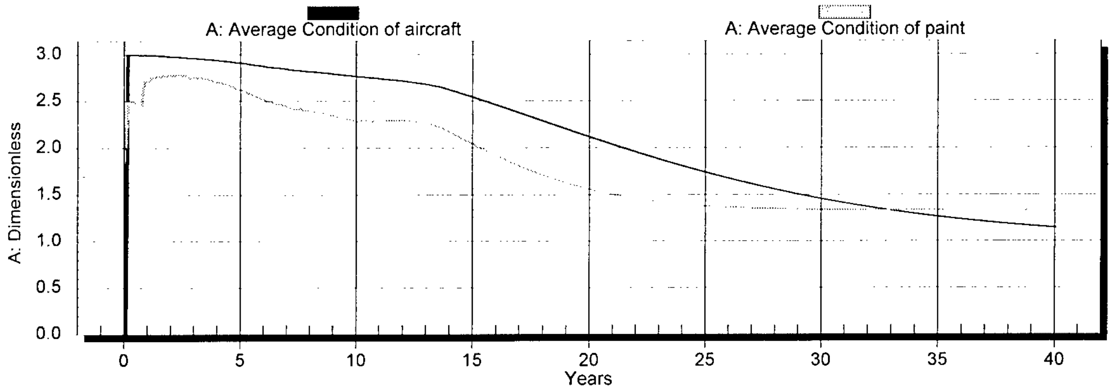


Figure 22. Comparison of Paint vs. A/C Condition

6.0 Retirements and Acquisitions

This scenario examines the impact of retiring one product (a C-17 A model) and acquiring a new hypothetical aircraft (C-17 B). In this case, 50 A models were retired, and 50 B models were acquired. This hypothetical aircraft has an expected life of 45 years. So, the differences in costs should reflect both a younger aircraft, and one that does not age as quickly as the 'A' model aircraft. The maintenance costs should be higher for the fleet that had no retirements or acquisitions (figure 23), which is logical, because the planes in this fleet were older, and would therefore experience an increase in maintenance activity. More dramatic differences are caused if more aircraft are changed.

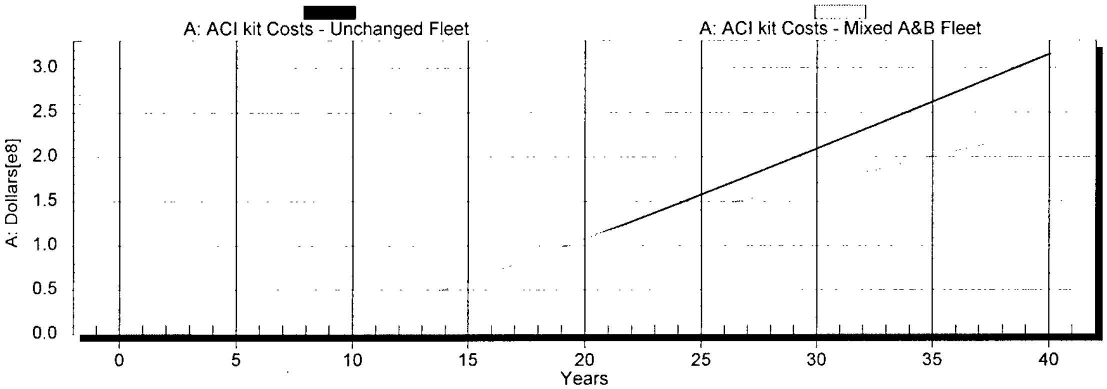


Figure 23. Compare Fleets - "A" fleet to "A/B" Fleet

The other graphs for this scenario help validate that the expected behaviors do in fact occur. Again, the fleet total; new, mid and old life; and costs are graphed. They show the expected behavior, namely, the fleet will decrease as planes are retired, and increase, as planes are acquired (figure 24). If the planes have a longer than expected life span, we would expect them to enter the age categories at a slower pace (figures 25-27).

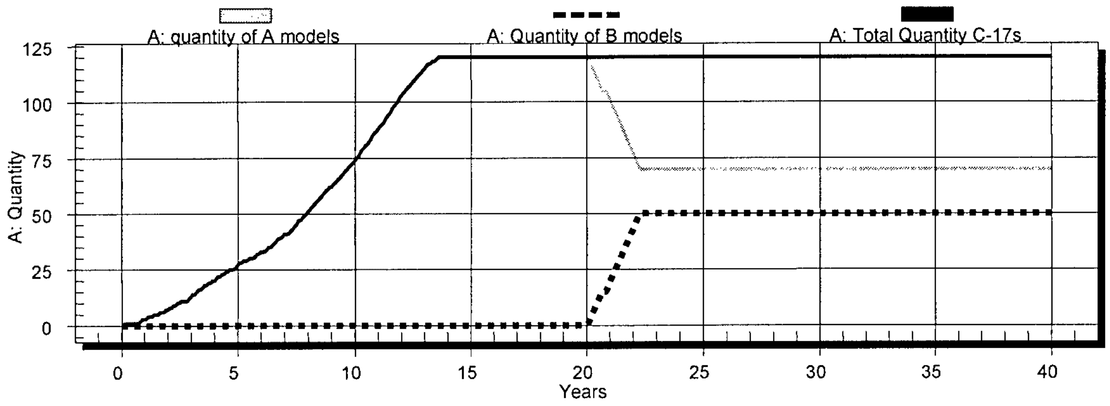


Figure 24. Verifying Acquisitions and Retirements

Figure 24 shows the expected behaviors. This graph shows that there is an equal number of acquisitions and retirements, therefore the fleet maintained the same quantity of aircraft. This matches the profile entered into the planned production schedule.

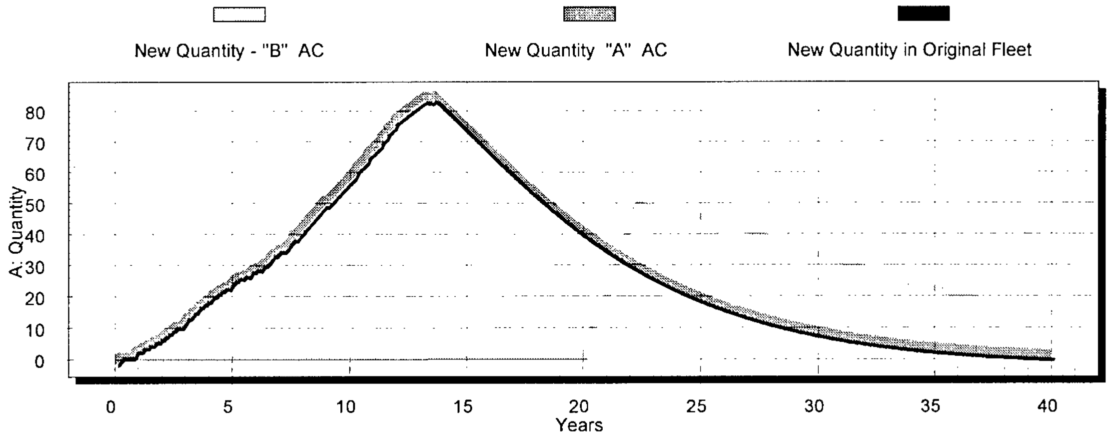


Figure 25. Comparison of 'New' Categories

The steeper slope of the "original" fleet shows the impact of a shorter expected life span (30 years compared to the "new" 45-year plane). Deviations from this expected line would indicate accelerated or decelerated aging influences, and would serve as advance indicators to the decision-makers.

Unlike the graphs that follow, the 'New' Category shows little difference due to the retirement of the 'A' model A/C. This is because there are enough 'Old' and 'Mid-life' A/C to retire, before needing to retire 'New' A/C. This logic prevails, as the older A/C that are retired first, when upgrading a fleet.

Figure 26 shows the expected behaviors in the mid-life fleet. Comparing against the baseline, when the "A" model planes are retired, the old planes go first. Any remaining retirement requirements come from the mid-life aircraft. Therefore, we expect to see a drop in the number of aircraft in this category; and as it is the oldest of these aircraft that are retired, more midlife aircraft accumulate before they enter the old category. This accounts for the minor peak at around year 24, before the start shifting to the old category.

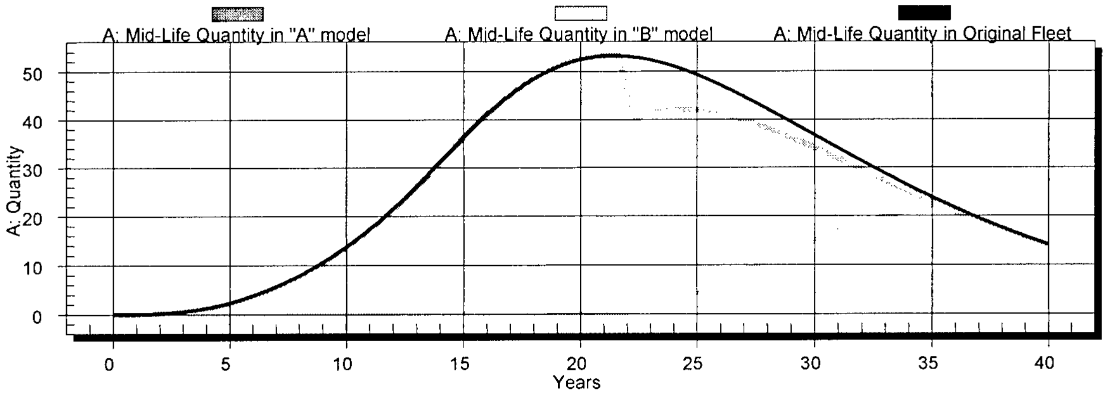


Figure 26. Comparison of 'Mid-Life' Categories

Figure 27 shows these effects on the old category. The retirements completely deplete the "A" fleet's old aircraft, and the "B" model's aircraft take a while to reach the old status. This delay in B's aging line is caused by both the longer expected lifespan of a B model aircraft, and the fact that they are acquired in a new status.

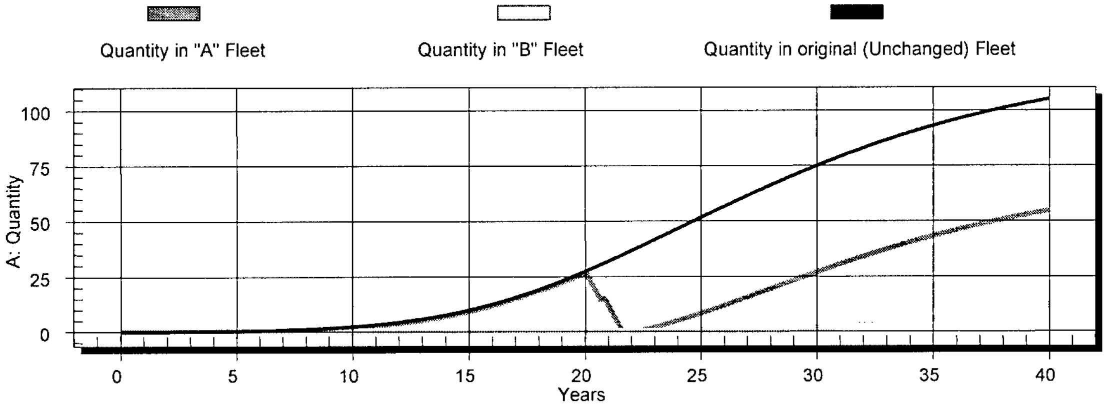


Figure 27. Comparison of 'Old' Categories

7.0 WBS

Scenario 7 offers a chance to evaluate this upgraded fleet, and explores the impact of a maintenance task on the engines of this fleet. For this scenario, .12 failures per thousand flight hours is the initial failure rate of the engines. This rate is expected to climb to .24 as the engine gets old, therefore, "high" impact influence was warranted. This same influence was set for both graphed fleets (hypothesized and baseline fleets). Therefore, the F-4 Table influence (Failure rate due to aging) was set to double as the "Remaining Life" dropped to zero. However, no impact was implemented for increasing the man-hours per repair, or decreasing the maintenance interval (F-3, and F-2 tables). An important discovery was made while doing this scenario, the fleet would need some spare engines. As the end of the expected life approached, the number of failures dropped to zero (as did the number of flight hours flown), indicating the fleet was no longer flying. When engine spares were added, the expected behavior of failures, consistent with the previous trend, continued. This behavior further strengthens the confidence in the ability to accurately model the system with this SD tool. Bizarre behavior usually indicates a failure of the modeler to provide required inputs (spares for instance).

The graphs show, first, that each fleet requires the same number of kits, figure 28. This verifies that the fleets have the same number of Aircraft, but that the aging factors are turned "off" (the older fleet will not experience more repairs than a younger fleet). However, when comparing the two fleet's engine condition, the differences due to aging are obvious. The graphs also show that the number of engines required stays consistent across fleets. Also, the failure rates are consistent between the fleets, figure 29 (the Original and Model A fleets are the same until the Model A fleet experiences its retirements).

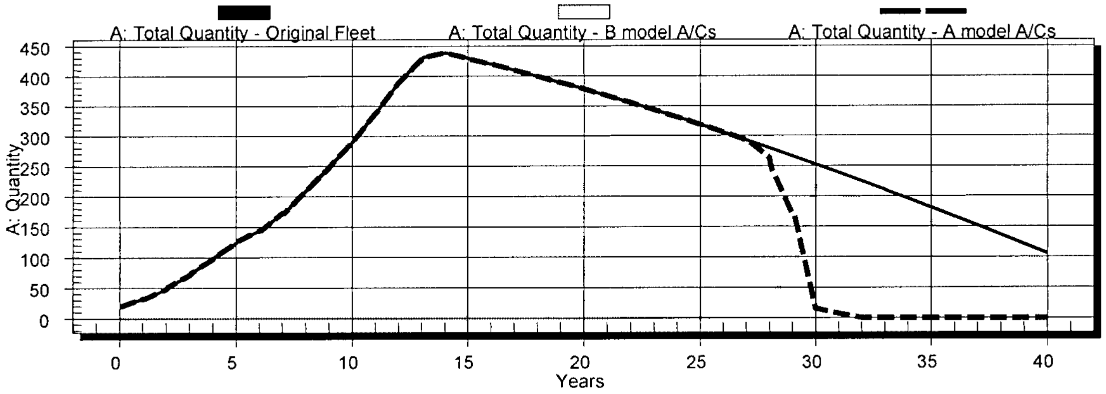


Figure 28. Kit Quantities Required per Fleet

The interesting behaviors on figure 29 are caused by the fact, that when we eliminate the 'Old' engines, the remaining engines have a relatively better condition, thus we see a spike in their condition. However, those engines are quickly "used-up," and their condition falls. The newer engines, from the new acquisitions, continue to perform at their higher condition level.

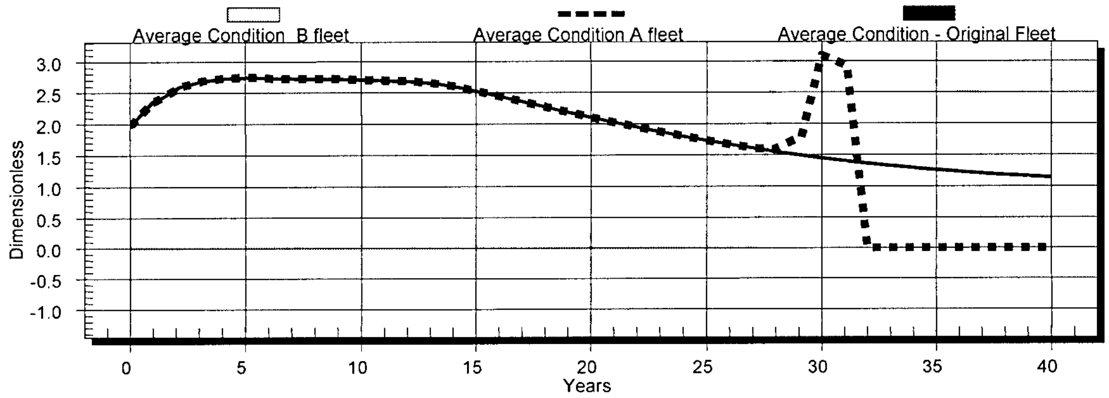


Figure 29. Average Engine Condition per Fleet

The value of this scenario is shown by the ability to model two (or more) activities and compare the results on the same chart. By performing comparative analysis, various results stemming from possible decisions can be graphed, and their influences tracked.

8.0 Multiple Fleets.

This scenario explores some of the differences between fleets that have different missions, and the impact of the stresses on the aircraft assigned to those fleets. The C-17 will operate out of four bases, three have similar (operational) missions; and one (Altus) is a training base. Training planes suffer more abuse than operational planes. Currently, the planes rotate through Altus for one year, then transfer back to the operational fleet. This scenario explores the differences between the fleets assuming the Altus planes are isolated at Altus. Actual fleet quantities are used. As of FY 99, Altus had 8, Charleston had 36, McChord had 1, and Jackson ANG had not received their aircraft yet. The Charleston and McChord planes are operational, and the Altus planes are "Training." Only the C-17 A aircraft is used, no hypothetical "B" model is used in this scenario. All acquisitions are of this same aircraft, with similar aging characteristics.

To evaluate different influences of stress on the aging characteristics, two different sub scenarios were used. The strength of the stress influence can be of any user-defined magnitude. To provide a baseline for comparison, scenario 8.0 was used to provide a representation of a "no stress" influence. Scenario 8.1 has aging turned "on." Other than these two characteristics, these scenarios are identical. Figure 30 is a representative graph.

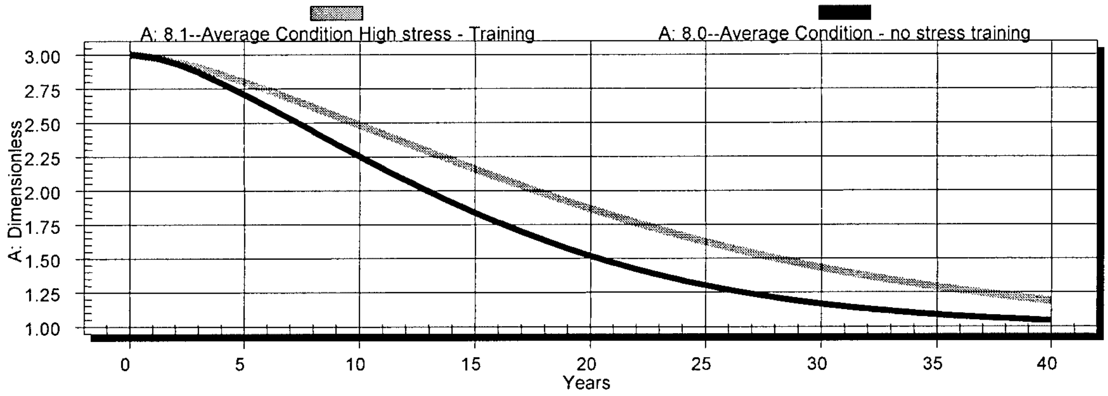


Figure 30. Compare High to No stress on Average Fleet Condition

This graph apparently shows a paradox. The fleet with the "Stress Impacts" turned to high, seems to last longer than the "No Stress Impact" fleet. Trying to rectify this aberration took considerable effort. While discussing the issue with the software developer, we came to the realization, that stress worked both ways when it has a strong influence. When a fleet is under stress, as measured by actual flight hours flown, divided by design flight hours, aging characteristics are accelerated if the quotient is greater than one. Conversely, the aging characteristics are decelerated if the quotient is less than one. In this case, the average C-17 is actually flying considerably less than its design flight hours, so as expected, if stress is a factor of aging, the C-17 should last longer than originally planned. This graph identifies this behavior, and further build confidence for the model. Aberrant behavior is not necessarily an indicator of a problem. In this case, if failures do not seem to increase at the expected rate, it might indicate that stress influences used in the model need to be adjusted.

The example above incorporated the stress function for a fleet of 45 aircraft. Using the projected fleet of 120 aircraft, and examining a hypothetical doubling of the flight hours, the added stress and effects on maintenance are explored. Figure 31 shows these influences. This graph points out that the costs for a "high stressed" fleet can be expected to grow at an increasing rate. When comparing this estimate to the current C-17 pricing model, the differences are even greater because the current model has labor costs as fixed and does not increase them with an increasing ops tempo. This graph shows that as the aircraft reach the end of their useful life, an additional $3 million is needed each month to cover maintenance costs due to labor. Additional costs would be expected for materials and spares.

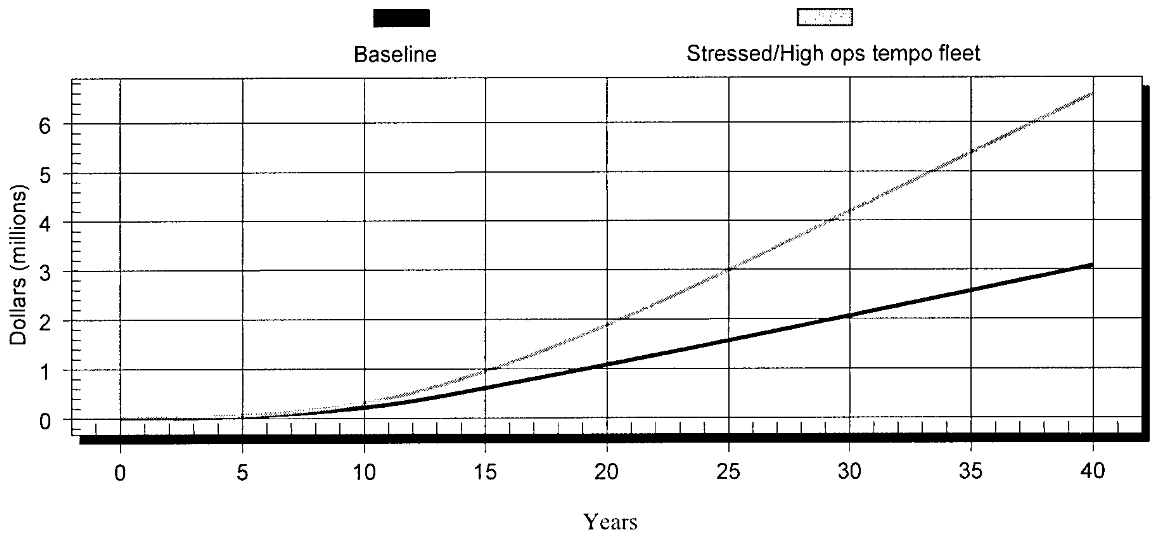


Figure 31. Monthly Maintenance Costs

Scenario 8.0 also incorporates two other "what-if" simulations. They were an attempt to determine the optimal time to replace (upgrade) the fleet. Is it better to replace a high stress fleet early or later, how about the operations fleet? Conventional wisdom is that the training fleet will burn out faster than the ops fleet. Therefore, the decision-makers will need to know the best timing to replace this fleet.

Figure 32 shows that if the fleet is to be replaced, the later it is accomplished, the better. By waiting for a significant number of A/C to reach the "old" status, before replacement, the fleet experiences a greater lengthening of is expected life span. However, cost benefit tradeoffs should be accomplished to compare the cost of upgrading an old fleet, compared to upgrading a younger fleet, also considering the differences in the maintenance costs created by waiting for the fleet to become old. The SD model allows the decision-maker to make these comparisons.

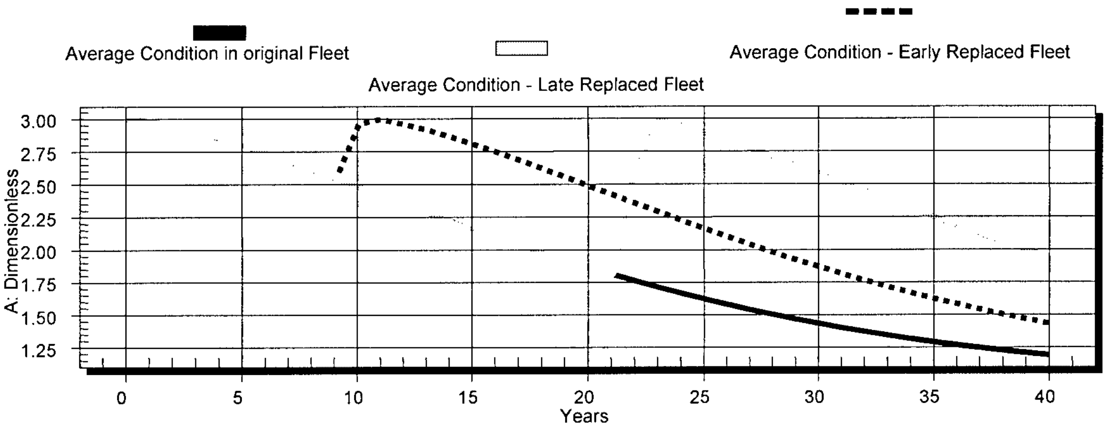


Figure 32. Comparison of Replacement Timing

9.0 Operations

This scenario explores how to accumulate O&S costs. Additionally, it experiments with fixed and variable cost accumulators. The labor component of a mission is a fixed cost because the airplane crew receives their salary whether they fly or not. Fuel costs on the other hand are completely variable. Other costs include the costs for Engine Cycles and spares, which are factors of flight hours. This scenario implements two operations tasks, training flights and operations flights.

Major Rick Rupp, AMC/XPRA provided the mission length data (Training 5.5 hours, ops 11 hours) and Maj Steve Baerst, C-17 MS IPT suggested using 6.6 hours of training and 13.4 hours of "operations" per week per plane. Because future flight hour profiles are expected to increase, the assumption is made that 1/3 of the flight hours are for training, and the other 2/3 are for operations missions. The simulations included crew size of three members, with costs for a Major, Capt, and Tech Sergeant identified from the Air Force Manning Costs (AFI 65-503). Fuel prices were estimated to be $.82 per gallon. Usage rates for fuel were 3000 gallons per hour for training and 2500 gallons per hour for ops missions (average to 2700 gallons per hour (for FY 99)). These factors came from AFI 65-503. The results are shown in figure 33.

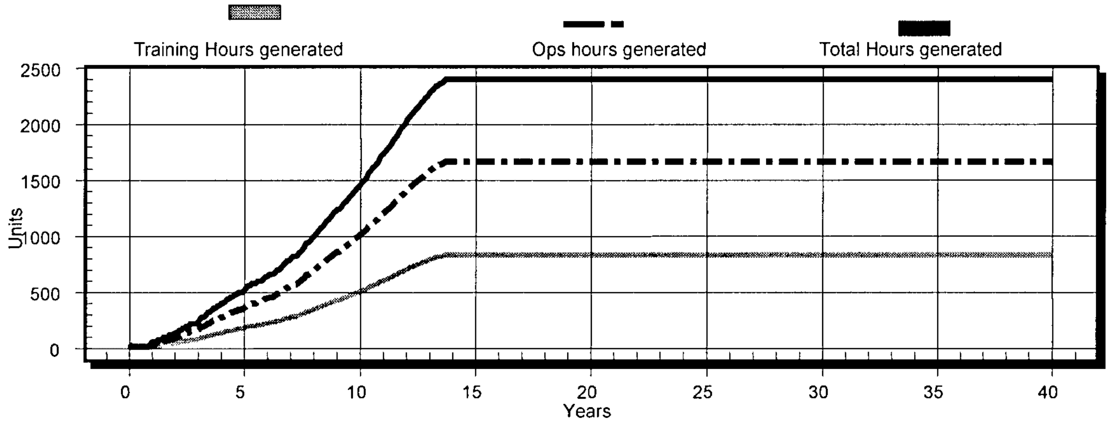


Figure 33. Flight Hours Generated Using the Interval Method

For training missions, a moderate deferral impact was used to show that as the needs of the ops fleet increased, training missions would decrease. There could be two influences, first, bad habits would not be corrected, so decreased efficiency may occur, conversely, training missions are hard on the aircraft, so aging characteristics are lower for ops missions. Because the C-17 is a homogeneous fleet, the specific influences of these two missions are not noticeable. However, if the two fleets were separated (ops vs. training) the influence of the teo stresses could be implemented by using different stress factors. These factors are represented in the F-6 (Stress Change Due to Operating Hours) and P-2 (Change in Aging Due to Mission Stress) tables for the training fleet. These influences would increase the aging of the airplane to correspond to the increased stress on the aircraft, due to the type of flights it performed.

Scenario 9.1

This scenario further explores the dynamics of flight hours and fuel costs. Instead of relying on a percentage interval to generate the hours flown, the accumulator was changed to one flight hour per operation hour, in effect using the operations (regular flight profile) flights to control the amount of operations tasks. Figure 34 shows the flight hours generated using the "direct to operations" method. The results indicate that the two methods to generate the variable data are equal. In both cases (scenario 9 and 9.1), the resultant data shows the logical outcomes.

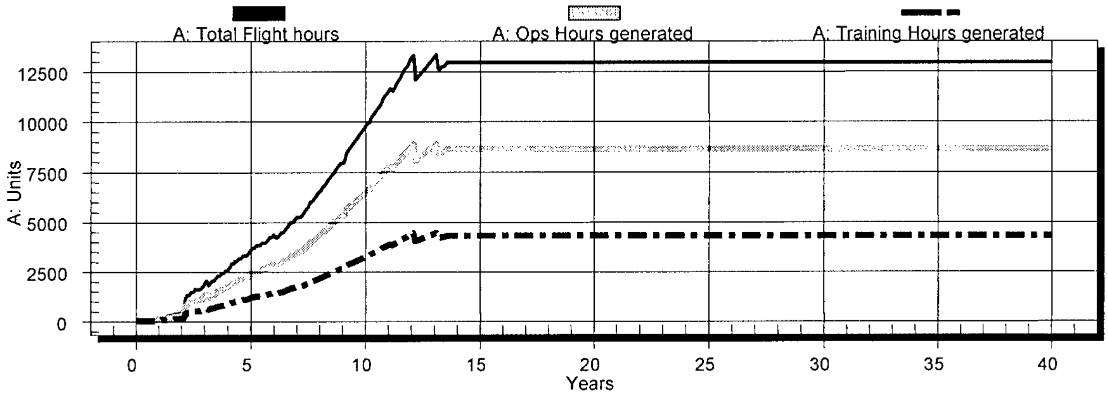


Figure 34. Flight Hours Generated from Operations Schedule

When comparing the two methods, the interval method makes for a smoother line, however it may miss real bumps in the planned schedule. To show that this software can be used for cost estimating, Table 1 depicts the estimate for fuel usage and its corresponding costs for the next 16 years. After year 15, no change in the flying profile is anticipated, therefore usage and costs are flat-lined (dollars in constant FY 99 dollars).

Table 1. Estimates For Fuel Usage and Cost

Year	Annual Fuel Costs	Fuel Usage, in (000s) of Gallons
Year 1	$ 2,169,720	1,060
Year 2	$ 7,934,976	3,838
Year 3	$ 35,029,908	17,286
Year 4	$ 59,573,610	26,620
Year 5	$ 89,414,280	37,800
Year 6	$ 102,482,820	47,652
Year 7	$ 122,717,592	56,320
Year 8	$ 152,464,896	70,144
Year 9	$ 192,139,776	88,192
Year 10	$ 235,613,880	108,252
Year 11	$ 280,502,730	128,455
Year 12	$ 323,108,946	147,595
Year 13	$ 337,460,094	152,462
Year 14	$ 343,119,078	154,712
Year 15	$ 344,321,280	155,520
Year 16	$ 344,321,280	155,520

This scenario has shown that SD can be used to accumulate fixed and variable costs. Variable costs can be generated both by a per flight hour calculation, or by time unit. This flexibility allows the modeler to accumulate costs, accurately, into their required categories.

Scenario 10

This final scenario is designed to compare the SD model to the current pricing model used by the C-17 SPO. As discussed in chapter II, the current pricing tool is a model developed cooperatively with Boeing, to price their Flexible Sustainment contract. An evaluation of this Joint Cost Model shows that labor costs are fixed, regardless of activity level, and materials costs are directly variable to flight hours. For this scenario, to show the benefits of SD in modeling, a hypothetical situation occurs, and its influences are modeled. This "situation" is a decision to reduce costs by not re-painting the aircraft after its initial production paint wears out. The purpose is to show how differences in approach provide vastly different estimates, and how the dynamic influences generated by the SD model simulate expected behaviors more realistically than the current model.

The assumptions for this scenario are that paint has an expected life span of 12 years; paint is the primary corrosion inhibitor; and corrosion decreases the life span of the airframe, which in turn negatively influences the life span of the aircraft. Although many factors contribute to the damaging effects of corrosion (AGARD1976: iii), for ease of comparison, paint will be considered the sole endogenous variable affecting (increasing or decreasing) expected airframe life span. This causal effect is warranted by research on the affects of corrosion (Promisel 1976:1-5 and Simard 1984: 8-2).

Figure 35 shows the comparison of the effects of not painting the aircraft, with the established baseline of the 30,000-flight hour fleet.

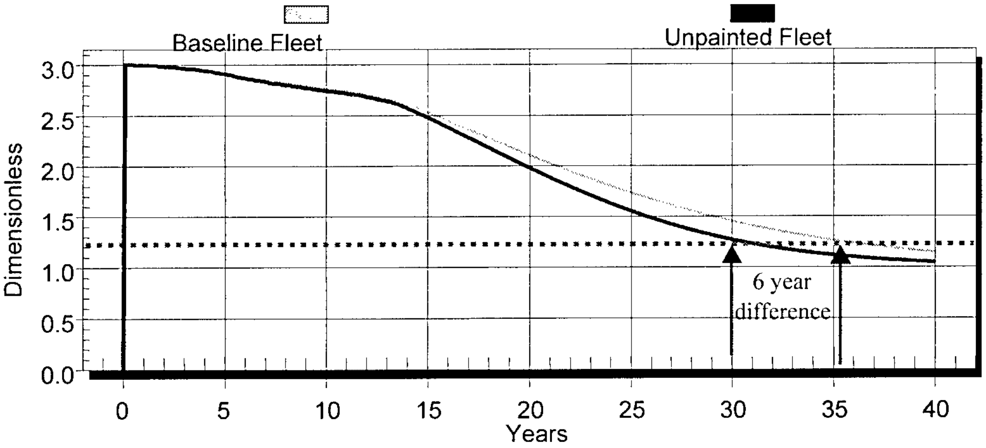


Figure 35. Effect of Not Painting Fleet

The original baseline has the effective life of the fleet depleting at year 36. The life span is depleted by 6 years if the aircraft is not repainted, assuming all other tasks are completed as designed. To compare the two cost models, their costs must be generated. Because causal effects are not included in the pricing model, the C-17 cost analysts determined there would be savings of $23.4 million. This is due to eliminating the requirement to paint an aircraft eight times over its expected life span, for each of the 120 planes in the fleet. Labor costs are fixed, so no savings accrue due to fewer maintenance tasks, and the only savings occurs due to materials savings. The SD model on the other hand shows that the fleet's life span is reduced by 6 years. Over the 120 aircraft fleet, this amounts to 720 aircraft years. In C-17 equivalents, this amounts to 24 additional aircraft necessary to complete the required missions. If the "Must Cost" value of a C-17 is used ($150 million per plane), the partial cost of not painting is equal to $3.6 billion. This amount does not include the extra materials for ACIs, corrosion repair, or other non-quantifiable costs such as reliability, safety, mission capable rates, or legal costs (Promisel 1976, 2).

Conclusion

This chapter demonstrated how to model specific influences, and the results of those influences. Where applicable, comparisons between the SD model and the C-17 Joint Cost Model are made. This analysis showed the applicability of SD and some of the benefits of this methodology when performing cost estimates. The next chapter will present the detailed conclusions that these scenarios suggest, present limitations of the model, and make recommendations for further study.

Chapter V. Conclusions

Introduction

This chapter presents conclusions, reviews the findings, and discusses the satisfaction of the stated objectives; recommends areas for further analysis and research; presents limitations, disadvantages, and work-a-rounds used to build the model with the FleetSight (F/S) software; and concludes with the advantages of using the F/S modeling tool for O&S cost estimating.

Satisfaction of the Stated Objectives

The thesis question was:

> Can system dynamics modeling be applied to cost estimating? If so, can a model be built that is sufficiently robust, to predict accurate cost and system performance behaviors? Can it therefore provide decision-makers with a tool through which significant cost drivers can be identified, estimated and analyzed? Does this technique indicate clearer representations of cost drivers and their effects, when compared to the current pricing model?

Applicability

Two tasks helped demonstrate applicability. First the Stella flow diagram, using the System Dynamics Methodology, was developed. Appendix B detailed this task. This task showed how significant cost drivers could be modeled, and how the hypothesized influences generate the behaviors expected by maintenance and cost experts. The second task was to use the SD software, to demonstrate its capabilities. C-17 SPO cost personnel were curious about the ability to use the various causal effects experienced by an aging system, while generating standard O&S cost estimates. Scenarios 1.0 through 10.0

demonstrated these capabilities. Additionally, these scenarios provided examples of the three important criteria needed to prove applicability. First, the model should accurately predict system behaviors. Secondly, it should accurately predict cost behaviors. Finally, it should be able to produce the results in the required OSD/CAIG format.

Predicting System Behaviors

As identified in chapter II, many factors drive costs. In addition, causal influences affect those drivers. One of those causal influences is aging. It is therefore understandable that the affects of aging should be incorporated in any model that would attempt to predict costs over the long-term. SD uses this influence as one of the key drivers of behavior. The scenarios showed how aging is incorporated, and how it can be used to emulate the expected behaviors that historically occur in aging aircraft, especially in the realm of increased maintenance requirements, and increased failures, as alluded to in the theory of the bathtub curve.

Additionally, interdependencies between system elements also drive cost levels, their influence should be incorporated into the model. Many of the scenarios presented showed examples of the logic of these dependencies. Specifically, the last scenario, dealing with paint showed how one component can affect another, and how that secondary element can affect other systems. These cascade failures occur, and because the SD model incorporates these influences in its WBS structure, confidence is built that the predicted behaviors do in fact represent what would be expected in the actual system.

Finally, the model was shown to work mechanically, by matching the production schedules and flight hour requirements to the planned levels of these activity drivers. Taken together, these examples point to the obvious conclusion that the SD model is able to predict system behaviors.

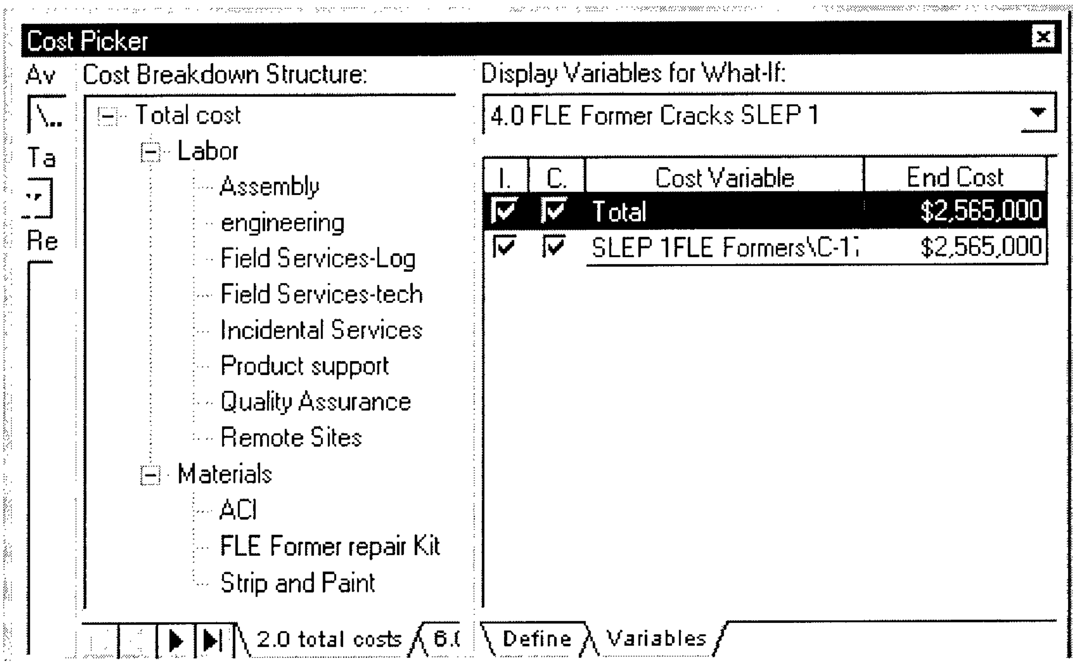
Predicting Cost Behaviors

The obvious point of a cost estimate is providing the expected cost of the item under investigation. Therefore, our model, to be applicable to cost estimating, must do the same. It is not enough, for this exercise, to predict system behaviors. The scenarios anticipated this requirement. As a specific example, the FLE Former upgrade was modeled. The output costs of the model were then compared to the cost proposal made by the contractor. These two values matched. For these values to match, both labor and materials costs needed to be accumulated properly. This shows, on a mechanical level, the model does in fact accumulate costs, in the expected categories, in the anticipated amounts.

On another level, the paint scenario provides insight into a different type of cost, "ripple costs." These are the costs that occur due to some previously made decision, whose impact will not be felt for many years. In this case, the impact of not painting the fleet caused a six-year decrement in the fleet's life span. The ripple costs are those costs that are required to place the fleet back to the status it would have been. In this case, one solution was purchasing 24 more C-17s to make up for the anticipated loss of 720 cargo years. Other costs that could be used instead, include costs of additional maintenance, costs of additional facilities required to perform maintenance, increased labor costs, and other material constraints. What-if drills can be performed to explore the level that these additional costs would need to be increased in order to achieve the baseline fleet life.

OSD Format

Finally, in order to be acceptable, our cost estimate must match the OSD/CAIG seven-category format. In order to achieve this goal, costs are accumulated within their logical parameters. Certain costs are fixed, while others are variable. Variability can be based on activity, such as flight hours, or on time, such as a monthly charge for flight crew labor. The cost breakdown module can be manipulated to capture these different costs, in their required format. Figure 36 provides an example.



Cost Breakdown Structure:

- Total cost
  - Labor
    - Assembly
    - engineering
    - Field Services-Log
    - Field Services-tech
    - Incidental Services
    - Product support
    - Quality Assurance
    - Remote Sites
  - Materials
    - ACI
    - FLE Former repair Kit
    - Strip and Paint

Display Variables for What-If:

4.0 FLE Former Cracks SLEP 1

I.	C.	Cost Variable	End Cost
☑	☑	Total	$2,565,000
☑	☑	SLEP 1FLE Formers\C-1	$2,565,000

Figure 36. Cost Breakdown Structure Example

Therefore, because these scenarios were able to demonstrate the ability to accumulate costs in the required formats (fixed, variable by time, and variable by activity); demonstrate expected aging characteristics and predicted effects; and demonstrate causal interactions; I conclude that SD can be used to make accurate predictions of O&S costs. Therefore, the applicability of SD to O&S cost estimating is established, and the second question becomes relevant, is a SD cost estimating model a valuable tool for decision-makers?

Value to Decision-Maker

Two key areas established the model's value to decision makers. First, the SD model makes clearer cost representations of expected cost behaviors, when compared to currently used models, and secondly, key cost drivers are identifiable, therefore trade-offs can be evaluated through manipulation of the scenarios.

Clearer Cost Representations

The various scenarios were all designed to show how the intuitive logic of the causal influences generated expected cost behaviors. The intuitive nature is easier to understand, and therefore defend. When expected behaviors, such as increasing maintenance requirements due to aging aircraft influences, are presented and accepted, the corresponding costs should be accepted. When compared to regression equations whose inputs may not be logical, but whose statistics show correlation, the better deafened position will be the one flowing from a logical foundation. SD provides that foundation, when the methodology is followed to achieve model validity. This clarity is exemplified by the comparison of the SD model to the pricing model currently used by the C-17 SPO, in scenario ten.

Identification of Key Cost Drivers

Finally, to establish the value of this SD model to decision-makers, it must be demonstrated that the model can give insight into the effects of various decisions. By performing this service the decision-maker is given a tool that can be used to maximize resource utilization, or minimize the costs of negative causal factors. Specifically, the timing of upgrades to maximize mission capable rates or adjustments in flight hours to minimize the effects of aging on the fleet, can all be explored before making a decision that has the potential to obligate the Air Force for a significant must-pay-bill.

Additionally, insight into potential trade-offs in reliability, durability, schedule, and cost could be made, even for a weapon system that has not yet been developed. The ability to use an analogy cost estimating approach in a parametric simulation tool will allow the decision-maker to optimize the acquisition planning process. Cost As an Independent Variable (CAIV) could finally be effectively used and acquisition reform would achieve another milestone. Therefore, the conclusion can be made that the ability to model and explore the impact of these key cost drivers does provide a valuable tool to the decision-maker.

The research questions have thus been answered in the affirmative, SD is applicable to cost estimating, and it does provide a valuable tool for decision-makers.

Recommendations for Further Study

The use of SD for cost estimating is an intriguing opportunity. Because the C-17 is a relatively new aircraft, insufficient data exists to build substantial confidence, at this time, of the predictive capabilities of this model. I would recommend, now that F/S has been shown to be capable as a SD model building tool, to tackle the building of a full model for aircraft such as the C-5 and C-141. This would further build confidence in the ability of these models to accurately predict behaviors and costs over a long-term profile. For instance, would a C-5 model, using data from 30 years ago, predict the severe spares shortages that the C-5 fleet is experiencing? The behaviors presented for the C-17 would indicate this would be the case, but actually building and testing such a complex model would be the next logical step in proving validity of this methodology for cost estimating.

The SD methodology has no one-time test for validity. The process is to slowly build confidence that the model accurately predicts future behaviors. Therefore, I also recommend that the C-17 SPO continue to build upon the effort completed to date, and continue to collect data to verify the strengths of influences, which for this model were hypothesized from expert opinion.

Another area for future work, would be an attempt to generate a generic model., whose details could be filled in by any SPO. It would facilitate a standardized SD model for cost estimating, similar to the CORE model, which relies on data from AFI 65-503. My final recommendation/dream would be to see the entire Air Force, or DoD modeled. While doing research for this thesis, questions arose from various interested parties about modeling the influence from one fleet to another. For instance, what is the impact on the C-17 fleet from the aging C-141s, or the chronically broken C-5s? What will be the impact on the KC-10s and KC-135s when the C-17 incorporates extended flight range capability, and no longer needs aerial refueling? Even cost trade-offs could be explored between decisions to fund modernization efforts vs. lifetime extensions. Once the ability to model causal effects is accepted, its uses will be limitless.

Limitations/Work Arounds

This section will identify some of the details of the modeling effort. In many cases, the approaches used to model specific influences were not initially intuitive. Because the F/S software has no "model builder's guide" at this time, certain scenarios were difficult to develop. Through this modeling process, I identified certain limitations of the F/S software. Many of these limitations will be fixed in subsequent software upgrades. This section can be skipped without missing the point of this thesis effort. It is included more to help fellow model builders who may use this software, before the changes are made.

Individual Aircraft.

An attempt was made to model the current C-17 policy of rotating planes into the training fleet, and then moving them into the ops fleet. Although it is possible, the technique is not recommended at this time. To accomplish this feat, each aircraft would need to be modeled independently; therefore each Maintenance task, Upgrade, and Failure would need to be calculated for each aircraft (all 120 of them). Then the modeler would need to track that airplane's flight hours, by location and mission. Although this would yield a more accurate cost estimate, this excruciating detail would prove too cumbersome for the software and modeler at this time. This problem could be overcome by changing the software's acquisition algorithm. Currently only a new aircraft can be acquired, if acquisitions of old aircraft were possible, these various fleet profiles could be simulated.

Task Intervals.

To dynamically generate the frequency of tasks (operations and maintenance), task intervals have to be calculated. These intervals are not initially intuitive. One must understand, that the interval used is the time allotted to perform the task on the entire fleet. For instance, to generate flight hours, the mission profile was established as a per-flight-hour mission. Assume an aircraft flies approximately 30 hours per month per plane. If 2/3 of the hours are operations tasks, 20 hours each month are operations flights. Therefore, we must determine an interval to account for these 20 hours per plane each month. Instead of setting an interval of one flight (that lasts 20 hours) per month, I initially set an interval at 20 one-hour missions each month. This was the wrong interval however. To calculate the true dynamic interval, the interval for the entire fleet must be generated. Therefore, the proper interval is 1/20 times per month. This is done, because an interval of 20 would mean, over the course of 20 months, do the entire fleet once. Therefore, an interval of 1/20 translates, do the fleet 20 times per month. Using the intervals this way allows the costs for fuel, engine cycles and replenishment spares to be tied directly to flight hours.

Non-Dynamic Inputs

Induction schedules, flight hour profiles, acquisitions, and retirements have to be input by hand. This was a tedious task to accomplish, because of the requirements of inputting the actual schedules into the FleetSight model in the various D(t) selected. If one were to model in months, then the schedules by month need to be input, the same goes for days, years and hours. The most obvious detriment in this effort, is exploring multiple what-if scenarios. For each one, the values needed to be input by hand.

Optimization.

At this time, the model is not able to determine an "optimal" solution. To determine an optimum, many scenarios would need to be calculated and their costs, spares requirements, and failure profiles compared against each other. The software developers are working on a genetic optimization algorithm to perform this analysis.

Quantity Limitations.

At this time, the various quantity accumulators (spares and kits) are limited. In one case, when I tried to model fuel by gallons, I could not accumulate enough fuel (limited to one million units per month). I had to change the fuel from gallons, to fuel "packets," equal to the amount of fuel used per flight hour (average 2700 gallons per hour). The cost is then had to be calculated, requiring another step.

Fixed Costs.

I had a more difficult time trying to account for fixed costs. When I tried to account for the data by using one kit per month, the influence of the number of aircraft still impacted my costs. For instance, it generated a kit for each aircraft, for each time period. To counteract this influence, I tried a different approach. I set up another product in the fleet, set an initial quantity of one, and had it "fly" one hour per month. I then tested a "Crew" kit (which was a fixed cost for one labor unit consisting of a pilot, co-pilot and loadmaster). The model then showed using one kit per month. This reflects reality better than current models that tie salaries to flight hours, because in actuality we will pay for the crew, whether they fly a thousand hours or none. Figure 37 shows the differences between the "interval" method vs. the "fixed cost Generator" method.

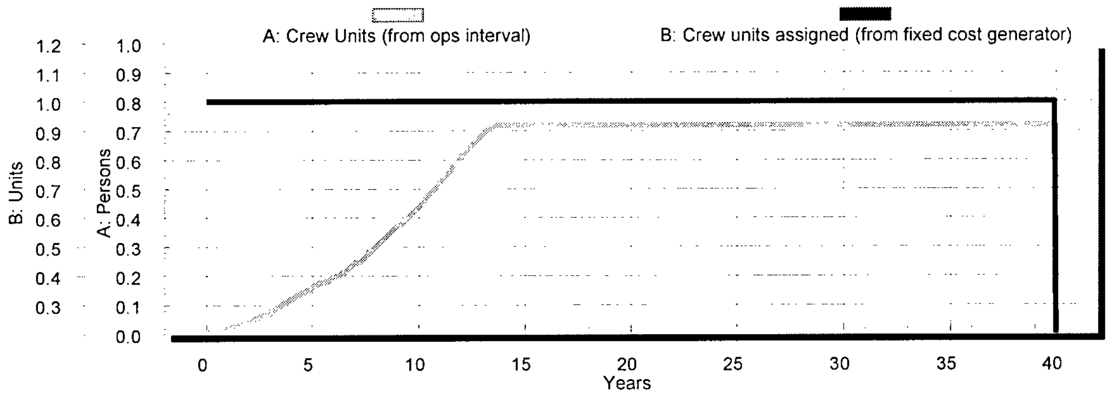


Figure 37. Comparison of Fixed Cost Generators

These results show that when using the interval method, we only apply 75% of a labor kit each month. When talking about people, it is obvious that we would need a full unit. The fixed cost generator on the other hand does generate one full unit. Therefore, I conclude, that the variable costs are better calculated by the interval method, but fixed costs should be estimated separately, through the fixed cost generator.

Benchmarking.

Because I am the first Air Force person to attempt this software, independently of the software developers, I did not have an independent source with which to compare behaviors. As this software becomes more common place, benchmarking and cross-talk will help future model builders to quickly incorporate changes and verify behaviors.

Advantages of F/S

The final area I want to address, is why the C-17 cost analysts wanted to evaluate F/S specifically, and not SD in general. SD has been around for decades, but it has not been used for cost estimating. There are certain complexities and limitations in SD that make it challenging to use. Some people have even suggested that cost estimating is an inappropriate use of SD. F/S offers many advantages that overcome some of the disadvantages that a model builder faces when staring at a reference mode, and is attempting to build a flow diagram. In building any model, the boundaries of the model must be established and firmly adhered to. F/S limits the amount and type of structures that the model builder can create. The modeler is bounded by the product chosen (aircraft, ship, helicopter, etc), and the WBS elements used for the model. This is an advantage, because it opens the possibility that generic models can be created for use with different products. The tendency to build overly complex models, and improper structure is eliminated, by reducing the choices down to established structures that are duplicated as necessary to model a particular product, component, or task. With other modeling tools, the model builder has no template with which to incorporate various hypothesized influences and model structures. F/S provides this boundary and validated structures, so at least the model builder can trust the mechanics of the model created. Care must be taken to ensure that time, units, and magnitudes are consistent across tasks, but this is no different from other SD tools.

Finally, one does not have to be an accomplished System Dynamic Modeler to successfully use and implement a F/S model. Stocks, Flows, and Rates, are hidden behind a graphic user interface that asks for WBS elements, tasks, and intervals. It carries the intuitive nature of SD model building into the language of the cost estimator, which further enhances its ease of use, and eliminates the influence to build exceptionally complex structures.

It is hoped that this will not have been simply an academic exercise limited only to satisfying the requirements for graduation. I hope it will be a stepping stone to a new methodology of O&S cost estimating, one that will enhance the military's ability to efficiently allocate resources, by forecasting events and proactively addressing deficiencies.

APPENDIX A

Explanation of System Dynamics Terms

This section defines systems thinking and some of the terms of SD.

> Systems thinking provide us with tools for better understanding of difficult management problems…however, these approaches require a shift in the way we think about the performance of an organization. In particular, they require that we move away from looking at isolated events and their causes (usually assumed to be some other events), and start to look at the organization as a system made up of interacting parts (Kirkwood 1998:1).

> R.G. Coyle (1977:2) defines SD as: A method of analyzing problems in which time is an important factor, and which involves the study of how a system can be defended against, or made to benefit from, the shocks which fall upon it from the outside world. It is that branch of control theory which deals with socio-economic systems, and that branch of Management Science which deals with problems of controllability.

Some of the terms used extensively in SD are Reference Mode, Influence Diagram, Flow Diagram, Converters, stocks, flows, valves, causal loops, and feedback loops (Kirkwood 1998).

Reference Mode: A conceptualized pattern of behaviors of a set of variables in their expected pattern. It is a graph that describes the key variable in question, along with some of the variables that have an influence on the key variable's behavior (Coyle, 1996: 49). This picture guides the model builder to a mechanistic approach to modeling. By knowing or hypothesizing what the behaviors of key variables will be, the modeler is guided to certain structures in the conceptualizing of the Influence Diagram.

Causal loops are the diagrams of the interactions (the feedback loops) between stocks. Feedback loops are the closed paths connecting in sequence a decision that controls action, a stock, and information about the level of the stock, which returns to the decision point (Forrester, 1968: 7). These diagrams help build the Influence Diagram, which is a collection and combination of causal loop diagrams, that define the system.

Influence Diagram: This is a further conceptualizing of the system. This diagram shows the major logic influences of the system (the influence that one "activity" or "event has on another). Circles representing variables or actions, arrows indicating causal influences, and +/- signs indicating either positive or negative influence between those variables characterize the influence diagram (Coyle, 1996: 10). Appendix B shows an example.

Flow Diagram: This is the actual software coding of the model. It is created from the logic identified in the influence diagram. The model that is built should maintain the same logic structure indicated in both the influence diagram and the reference mode. The flow diagram is made up of three elements – stocks, flows, and converters.

Stocks: These are the "accumulators," as a bank account does for money, they hold items that are deposited (flow into the stock), until they are expended (flow out of the stock). In a flow diagram, rectangles represent these structures. These variables are not use to accumulate physical substances only, but they can represent conceptual ideas also, such as burnout, happiness, and productivity.

Flows: These are the "pipes" that "fill-up" or "deplete" the stocks. These are represented by a pipe-like structure with a valve (circle) attached to it. They control how fast, or strong as stock is influenced.

Converters: Circles represent these variables. Converters represent many things, including information, events, or rates, that influence flows or each other, and can be influenced by flows, stocks, and other converters.

A simple example of the items identified above, showing their appearance (from the Stella SD modeling software program) is as shown in figure 38.

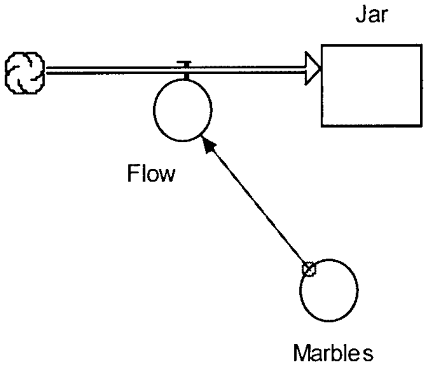


Figure 38. Simple Flow Diagram – marbles accumulating in a jar

The single line indicates that the converter is influencing the flow (marbles) into the stock (jar). The marbles converter would have some value attached to it, for instance five marbles. The flow in this case, would say, each time-period, add five marbles to the jar. The time-period could be any period, minute, day, year, decade etc. The cloud indicates that there is an unlimited amount of marbles available to flow into our jar. The jar has no flow out of it, so it will only accumulate, if it had an outflow, the marbles could flow into another "cloud" or another stock. There are hundreds of ways these different elements can be connected; this basic structure as shown represents a linear growth of marbles into a jar.

APPENDIX B

This section is devoted to the initial investigation of the cost model. It follows the SD mechanistic approach to model building, beginning with the reference mode. The point of this exercise was to determine the key cost drivers, and seek out areas for further investigation.

Conceptualization of the O&S model – Reference Mode

The modeling process begins with the Conceptualization phase. To begin, expert opinion was used to hypothesize what the behaviors of the key variables were (Total Cost, Failures per Aircraft, Support Personnel, Mission Capable Rates, and Number of Available Aircraft). The Cost, Maintenance and Logistics experts from the C-17 System Program Office were consulted, and that the behaviors they predicted are indicated by the following pattern (figure 39).

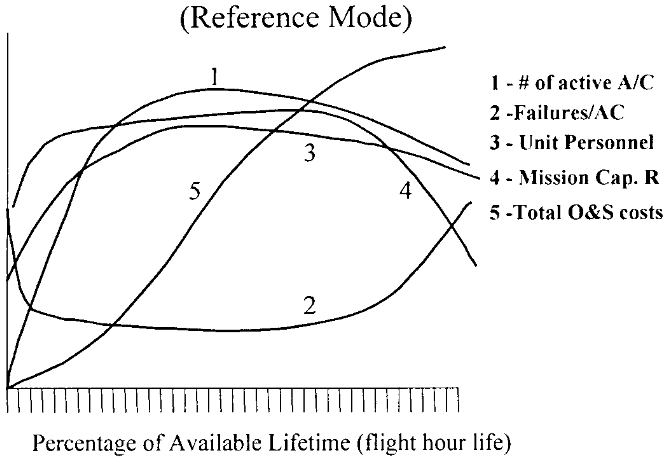


Figure 39. Initial Reference Mode

This is the original interpretation of what the key variables would do over time. Specifically, the number of Active Aircraft (1) would increase with production, then as they are used, they would break, be destroyed in battle, and the inventory of planes would deplete to the point that the Air Force would dispose of the system. The disposal period is not modeled, nor displayed in the above reference mode. Failures (2) were hypothesized to follow the standard "bathtub" curve, specifically a period of early failures, followed by chance failures, followed by a final period of wear-out failures.

Unit personnel (3) would increase as the number of aircraft increased, and as aircraft leave the inventory, the personnel needed to fly and support them, would also decrease. Mission capable rates (4) are the indicator of an aircraft's availability. The theory is, that as the number of failures increased, and the number of planes in the inventory decreased, that Mission capable rates would also decrease, at an increasing rate. Finally Total Costs (5) were hypothesized to show an "S" shaped curve behavior. The experts thought there would be a period of slow growth as the inventory of planes was increased. Then, as the aircraft were operated, there would be steady growth in the costs. But, at some point Congress would start depleting the money supply (as the planes began to spend more time in the shop getting repaired than they were flying missions). This depletion would cause cost growth to stop, and eventually as the program would come to a stop, and costs would stop also. After further discussions with professors on reliability and failure rates, changes were made to the reference mode. These changes include a delay in the number of active aircraft, to account for the delay in production "ramp-up," a steeper decline in mission capable rates, a steeper decline in active aircraft as failures increase (to indicate that those planes that are broken are not available to fly missions), an elimination of the "early" failure rates, and an elimination of the reduction in costs. A rethinking of logic brought about this final change. There is no set trigger that would cause Congress to cut funds. So for the reference mode, the cost profile was changed, knowing however, that there is something out there that could influence costs to decrease. This factor will be shown in the influence diagram. The reduction of the early failure rates comes from a new understanding that the airplane is not a single entity, it is a collection of systems, which are a collection of components. These components are subject to early failures, but these failures will be eliminated by the time the aircraft reaches operational capability. The new reference mode is shown in figure 40.

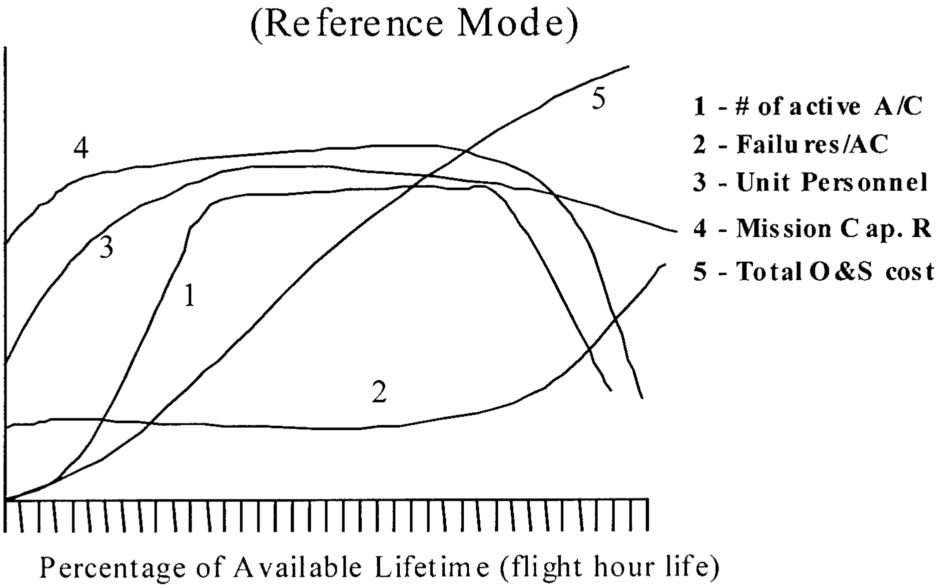


Figure 40. Updated Reference Mode

The whole point of the reference mode is to guide us in thinking about what structures of influences are indicated by the reference mode. There are five classical structures; each has its own behavior. If our reference mode shows that behavior, it points to a possible structure. Using these structures as a guide to model development gives us a starting point for building the influence and flow diagrams. The corresponding flow diagrams for the structures will follow the influence diagram.

Structures evidenced in the Reference Mode:

Co-Flow – evidenced when one behavior closely follows another, and is logically tied to that variable. These variables are Personnel and Available Aircraft, which co-flow with Aircraft Production; and Costs, which co-flow with all cost drivers (personnel, maintenance, failures, and flight hour costs

Goal seeking – Although not graphed in the reference mode, Aircraft Production uses this structure. Its influence is noted in the Available Aircraft line. The logic of this component was added, with the understanding that something needed to "ignite" this system. The goal seeking that occurs is in regards to the number of aircraft we plan on purchasing. There is an added component to this behavior, and this is the delay that occurs in the production of aircraft. It takes a while to setup and produce aircraft, this logic is shown on the influence diagram by a double line and a "D" on the line between production and Total AC Purchases.

Production: a linear growth or linear decline evidences this behavior. It shows that the stock is either draining faster than it is being supplied, or not draining as quickly as it is being supplied, but at a constant rate. Personnel exhibits this behavior in a negative sense after the goal seeking behavior is no longer influencing additional personnel acquisitions.

Compounding (Reinforcing): the final behavior that is indicated near the end of the useful life of the aircraft, is collapse. This behavior is marked by an increase in one stock at an increasing rate, possibly depleting another stock at a rate faster than the first stock can recover. In this case the Maintenance and Failures stocks both deplete and replenish the Available Aircraft Stock. However, as the aircraft ages, failures increase at an increasing rate, while repair continues to take the same amount of time. No additional logic was introduced at this point for increasing the delay of repair of aircraft, as more planes await repair. The C-17 maintainers adamantly state that they have plenty of capacity to repair aircraft, and therefore there would be no extra delay in repair times as more aircraft needed repair. The point is that the draining, caused by increasing failures, accelerates until the Aircraft Availability stock is fully depleted. Because there are no more planes to fly, failures fall off. The new failure rate is reduced down to the maximum Available Aircraft, which is held constant by the repair time. The system never recovers, once this "bottom" occurs.

Draining: is a compensating behavior, evidenced by exponential decay.

With these structures in mind, the influence diagram was built using a modular approach, i.e. the actual building process was done in components. For instance, when analyzing the goal seeking structure for Aircraft Production, only that area's influences were modeled. Each area was built individually, and then they were assembled into the final product, analyzed for logic, and adjusted. This process continued until the logic presented in the diagram matched the reference mode.

Conceptualization of the O&S model – Influence Diagram

Figure 41 shows the final influence diagram.

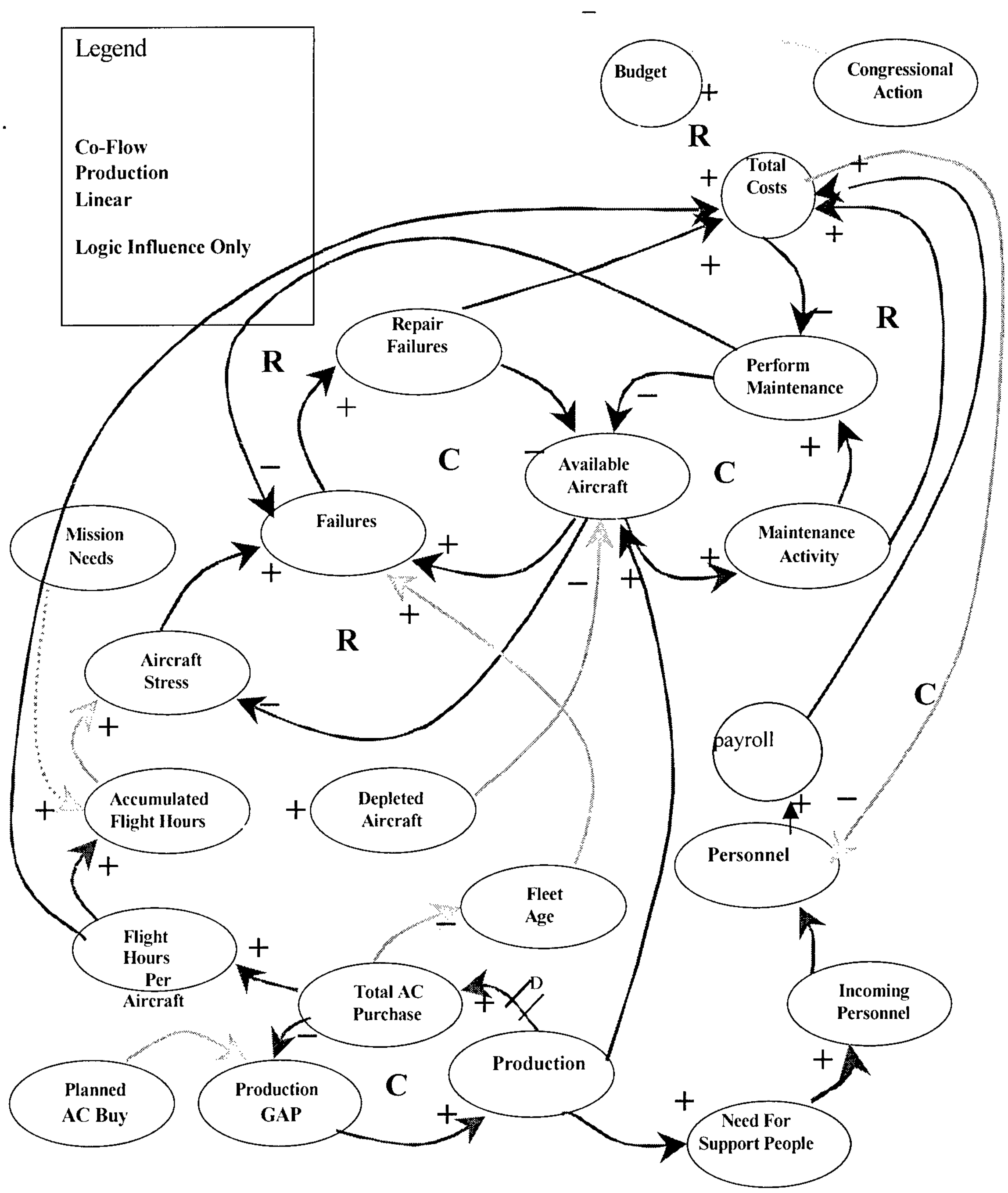


Figure 41. Hypothesized Influence Diagram

The next step is to build the flow diagram, based on the logic of the influence diagram. Because of the relative ease of throwing structures together, often the complexity of the flow diagram becomes excessive. In order to keep the logic simple; a modular approach is used - break down the structures identified above into their individual flow components, before assembling the complete picture.

Aircraft in Inventory - has the following structure figure 42 shows the influence diagram.

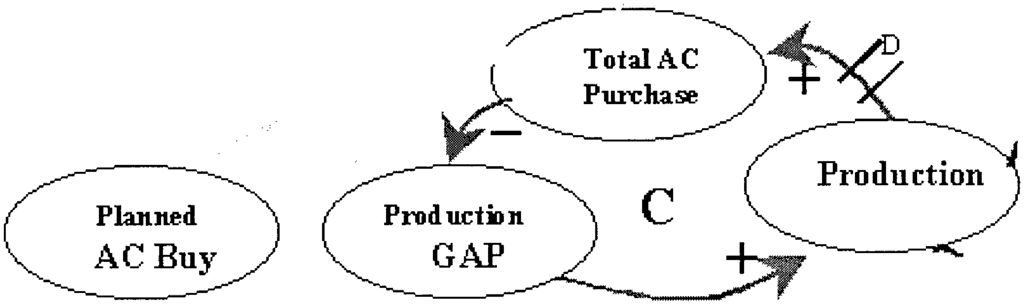


Figure 42. Aircraft Inventory portion of Influence Diagram

This structure is narrated as, there is some planned aircraft buy, this buy goal is compared to the total we have purchased. If there is a difference, a signal is sent to production to make more aircraft. There is an initial delay in this production, however this process continues through time, until the goal is met, at which time, production of new aircraft stops. This is "Goal Seeking" behavior. The Production rate is limited to a maximum of 15 aircraft a year, based on the maximum production capability of the Boeing production facility. The Production Delay is a "time" delay, based on actual delay times experienced by the C-17 production facility. The Stella flow diagram to match this logic is shown in figure 43.

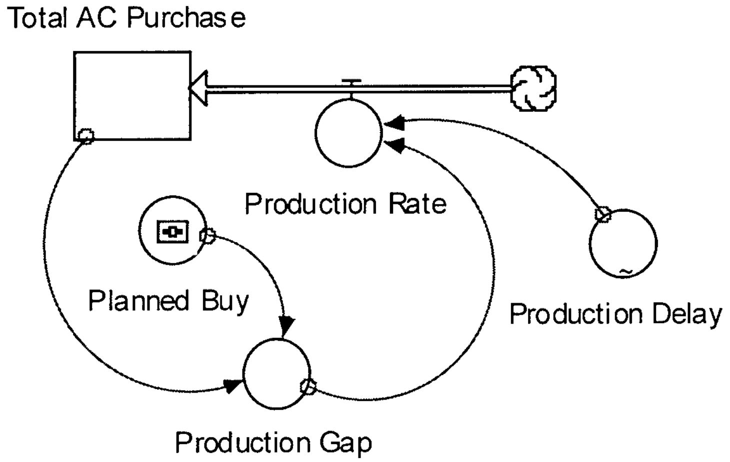


Figure 43. Flow diagram of aircraft production

Incoming personnel and Available Aircraft exhibit Co-flow behaviors. They have the following generic structure figure 44. These items can be found on the influence diagram.

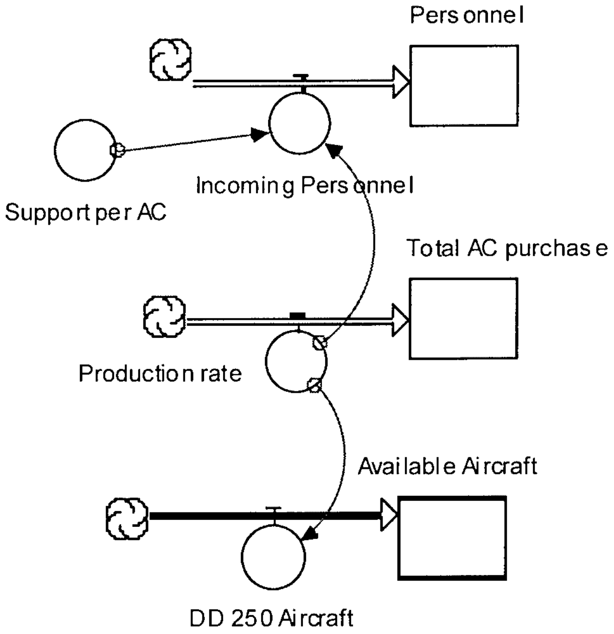


Figure 44. Flow diagram of Co-Flow behavior

However the mechanistic driver for personnel although evident on the influence diagram for the sake of logic, has no separate node on the influence diagram. This logic is implicit in the requirement for "Support per AC", and as the production rate cranks out aircraft, the co-flow nature of the link multiplies the number of aircraft produced in the current period by the converter, which contains the rate of people to aircraft. This amount then flows into the stock of personnel, which becomes the accumulation of all people needed to support, fly and maintain the aircraft. Production also increases the aircraft that are available to fly missions. These are the DD 250'd aircraft, which Boeing has released from production to the Air Force inventory.

Cost is another area that exhibits co-flow behavior. Although the diagram looks more confusing, the basic structure is evident. One flow is affected by another (in this case 3 others). On the influence diagram there are four cost drivers, however only three of these drivers are co-flows in the strict sense of the structure. Personnel, although a cost driver, impacts costs through the stock of hired personnel, not the increase (rate) of those personnel being hired. Had there been a cost to hire, or train, that influence would have been a co-flow. One notable difference is that into the Cost stock there are three co-flows entering it. These are the flows that are influenced by their respective flows from other areas of the model, which will be shown at the end of this section. Figure 45 gives the Stella flow diagram picture of this structure. Another important issue to note is that the structures presented are in their most basic formats. They have been sanitized from the full model that will be presented later. This is done to ease the reader into the model, instead of causing sensory overload, which will be evident later. Some of these sanitized factors are attrition, in both Available Aircraft and in Personnel. This is due in part to standard rates for peacetime aircraft depletion, which accounts for accidents or catastrophic failures that destroy an aircraft.

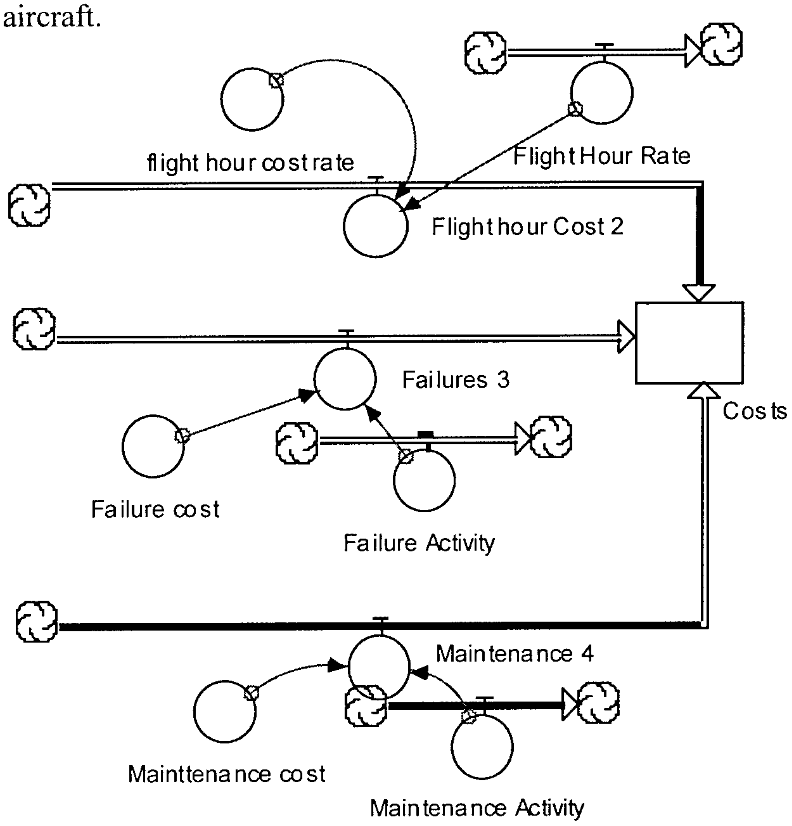


Figure 45. Flow Diagram of Costs

The final area to be presented is the intuitive logic that is contained within the Failure/Maintenance/Available Aircraft section in the influence diagram. It is characterized by one stock influencing the outflow of another stock. Some activity causes an increase in the initial stock (requirements for maintenance). This increase speeds the decrease in the resource stock. In the model the structure is as follows. outflows from the Available Aircraft stock are the inflows to the Repair Failures stock. This structure will have the effect, that at some point, the failure rate on the fleet will be so great, that at one point all the planes will be grounded, and repairs will need to be made. The stress on these few repaired airplanes will be so great, that they will experience a high rate of failures. This means that after this crash, half the remaining fleet will be in repair, and as soon as they become available, they will fail, and need repair. Figure 46 shows the Influence Diagram.

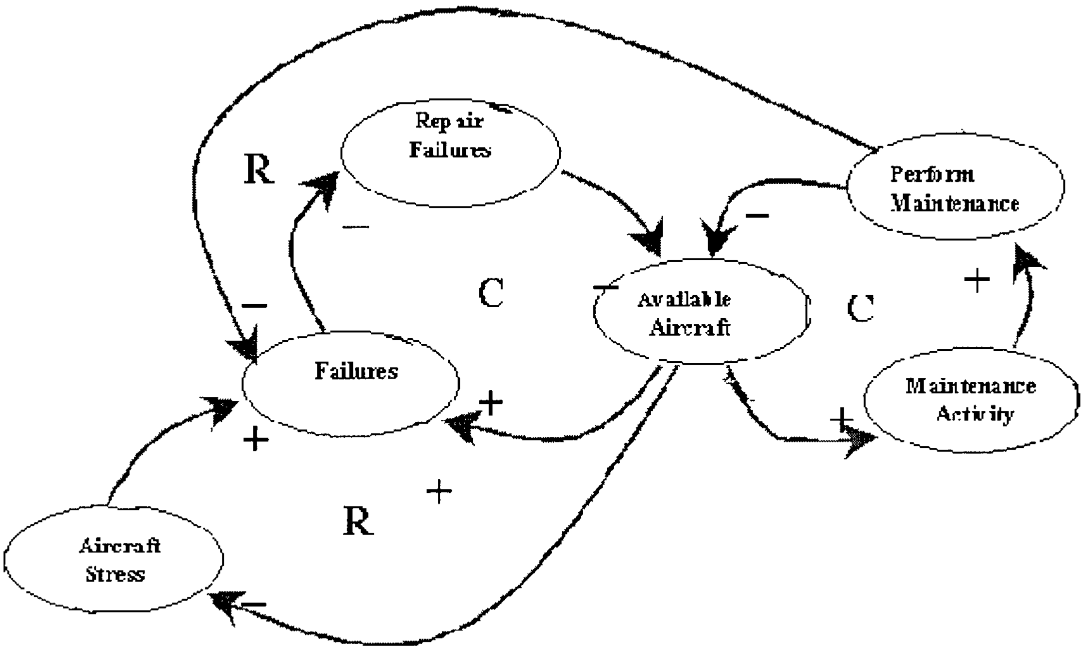


Figure 46. Influence Diagram of Failure and Maintenance

There are some miscellaneous influences that do not have a classical structure. Their influence is derived from a logical review and iteration between the flow diagram and the influence diagram. These variables are defined below.

Fleet stress – this is caused by the aircraft being required to fly more than the standard of 1,500 flight hours per year. Current planning has the aircraft scheduled to fly less than 1,000 flight hours, but the design capacity was 1,500. As planes fail, the requirement to fly the necessary missions is not eliminated, therefore the remaining aircraft in the fleet must pick up the extra demand. These extra hours "stress" the aircraft, and make it more likely to fail.

Aircraft Age – Currently the C-17 is expected to have an average "life" of 30,000 flight hours. As each new aircraft is produced, another batch of average life is added to the flight pool. As aircraft fly missions, the accumulated flight hours approach equality with the flight pool. At 30,000 hours per aircraft, failures are normally distributed about this mean. Therefore, as the planes near this useful life, failures will begin to increase at an increasing rate, until there is complete failure of all aircraft.

Other converters will be noticed in the flow model. These devices are added to allow the modeler to "play" with decisions and explore behavior. These items are:

Budget Reductions – Air Staff reductions to appropriated funds (taxes, SBIR, etc.).

Congressional Action – Congressionally mandated reductions in costs.

Expected Inflation – areas where costs are expected to increase.

Mission needs – at particular times the fleet may be called upon to increase its flights.

Aircraft War Losses – planes shot down or bombed during a war.

Planned Aircraft Buy – how many aircraft will be purchased (currently 120 for the C-17).

Finally, some converters are used to track important rates. For instance, Failures per AC is a converter that divides Failure Activity by Available Aircraft. Mission Capable rate divides Available Aircraft by Total AC Purchase. What follows below (figures 47, 48) is the complete model as developed using the Stella System Dynamics modeling software

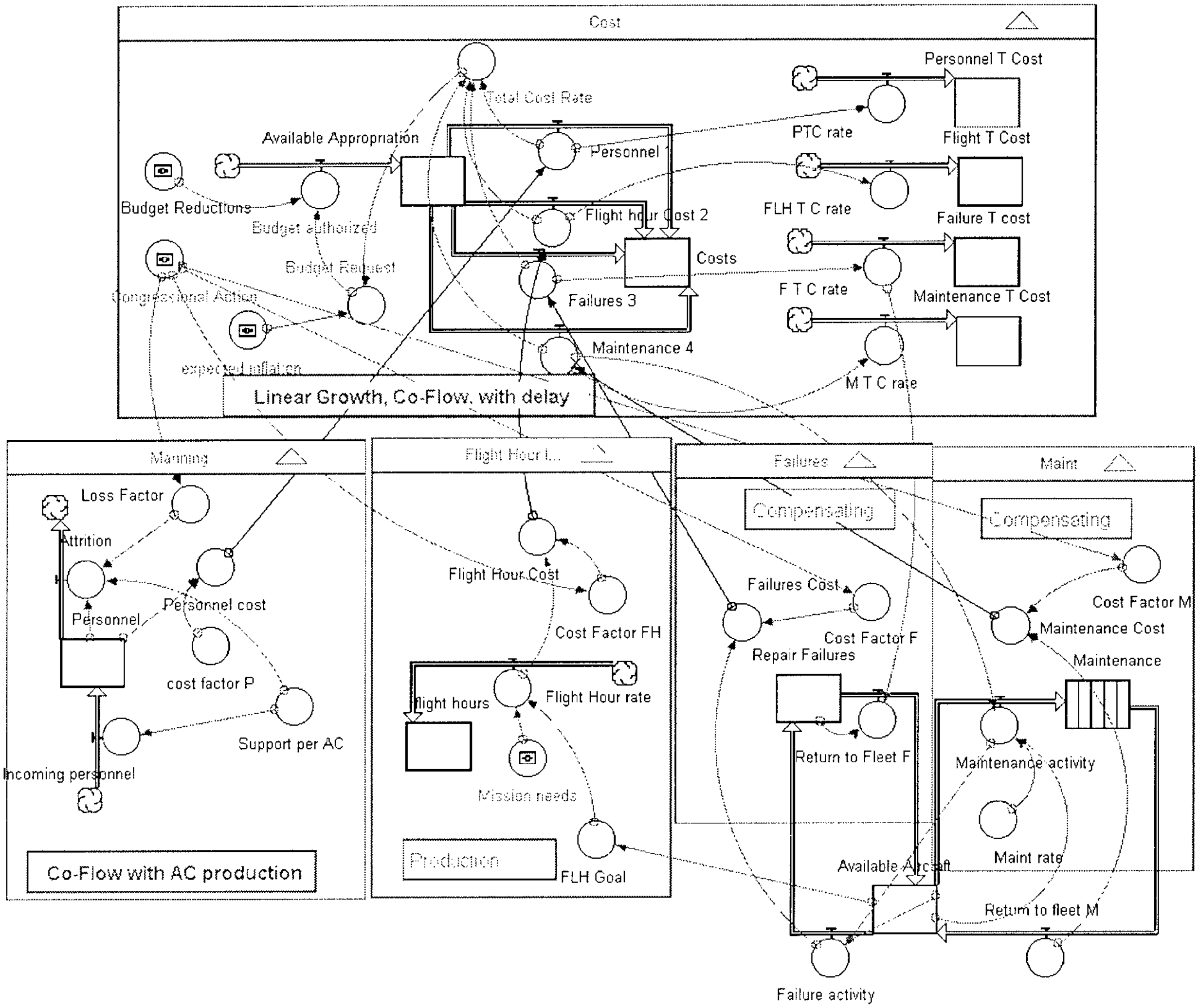


Figure 47. Top part Flow Diagram - complete model

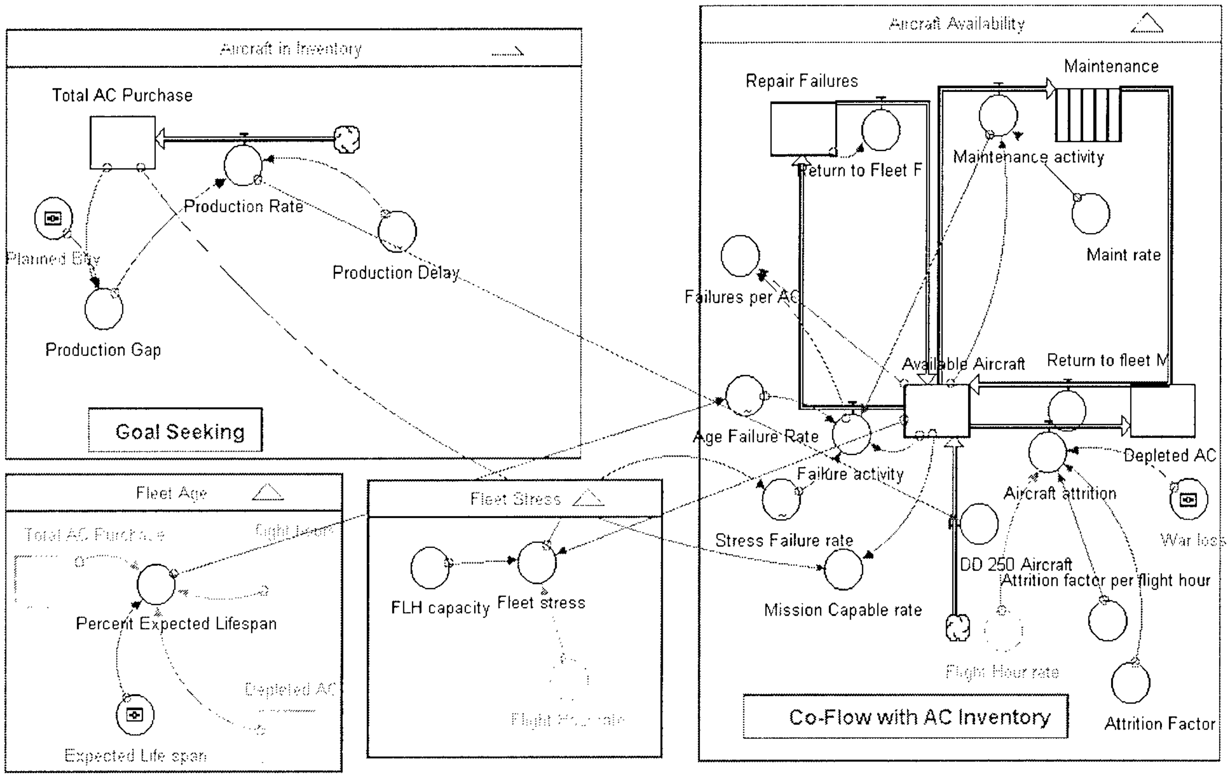


Figure 48. Bottom part Flow Diagram - complete model

Verification of the O&S model

The next phase of model building is to verify that the model is working as intended. There are three areas of testing that can be done, and these processes are explained below.

Testing of the O&S model – Mechanical Mistake Test

After the influences were modeled, the next step is to test that the hypothesized model works the way it was intended, while matching the logic of the influence diagram. The first set of testing is the Mechanical Mistake Test. During this testing, the modeler runs the simulation and checks values of stocks and flows to determine if they respond in a logical manner. This test is performed in a variety of ways. First, the model was built one node at a time, and validated to show that the node worked as intended. Then, nodes were added together, tested, and assembly continued until the entire structure was complete. Secondly, converters were added to make test calculations, like Mission Capable Rates, and to identify their responses. This helped to watch what the rates were doing during the simulation. This technique ferreted out a number of mistakes and miss-applications of logic. For instance in the Flight Hour Rate, the number of Aircraft in the inventory was originally used to determined the rate flown per aircraft. However, the behavior that the model exhibited was unrealistic, as planes started to decrease in availability, the stress level did not increase. This influenced a change in the driver for Flight Hours, it should not be how many planes were purchased, but how many are available to fly. Verification, that stocks such as Available Aircraft never went negative were performed. Although the structure appears to allow it, having negative planes is illogical. The testing for mechanical mistakes drives the elimination of these illogical events.

Testing of the O&S model – Robustness Test

Testing for robustness means testing for how fragile the model is. If an event happens, does the model breakdown in an expected manner, does it recover as expected, or does the behavior that is exhibited have no basis in reality. The key element to this testing is to estimate the behaviors that are expected from any given shock, perform the shock, and determine if your estimate was correct. Any deviations should be thoroughly investigated.

Some of the tests performed in this area were War Losses, Congressional Budget Cuts, Program Cancellation, and Tripling of Mission Needs. In all cases except Congressional Budget Cuts, the model exhibited the expected behaviors.

War Losses – shortened the fleet's life, reduced failures, increased stress

Program Cancellation – Flight Hours, Maintenance, Failures, Stress, Fleet Aging stopped

Tripling of Mission Needs – Fleet Aging increased, expected life decreased

Congressional Budget Cuts – Killed the program.

Because budget cuts of amounts greater than .01 percent had such a dramatic impact on the model, I determined that this area is a place for further investigation. However, because the model is specifically designed for the decision-maker to use, Congressional Budget action is beyond his control. It will have an effect on his program, but because he can't control it, it is not necessary at this point to model this area in more detail. The purpose of this exercise was to determine which elements of O&S costs were significant cost drivers. Therefore, although curious, the Congressional Budget Cuts are not a cost driver the decision-maker can affect.

Testing of the O&S model – Reference Behavior Pattern Test

The final area of testing was to match the Reference Mode Behavior to the pattern generated by the model. The results are shown in figures 49 and 50.

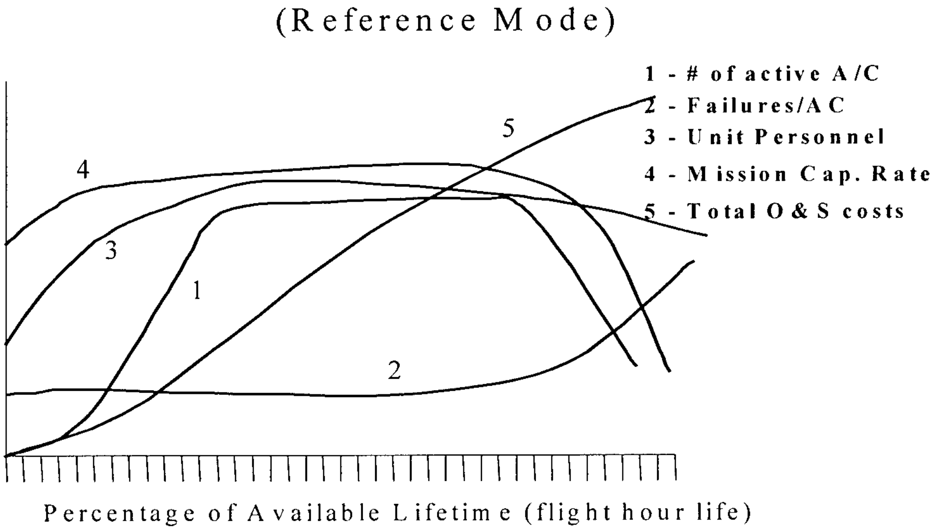


Figure 49. Reference Mode Behaviors

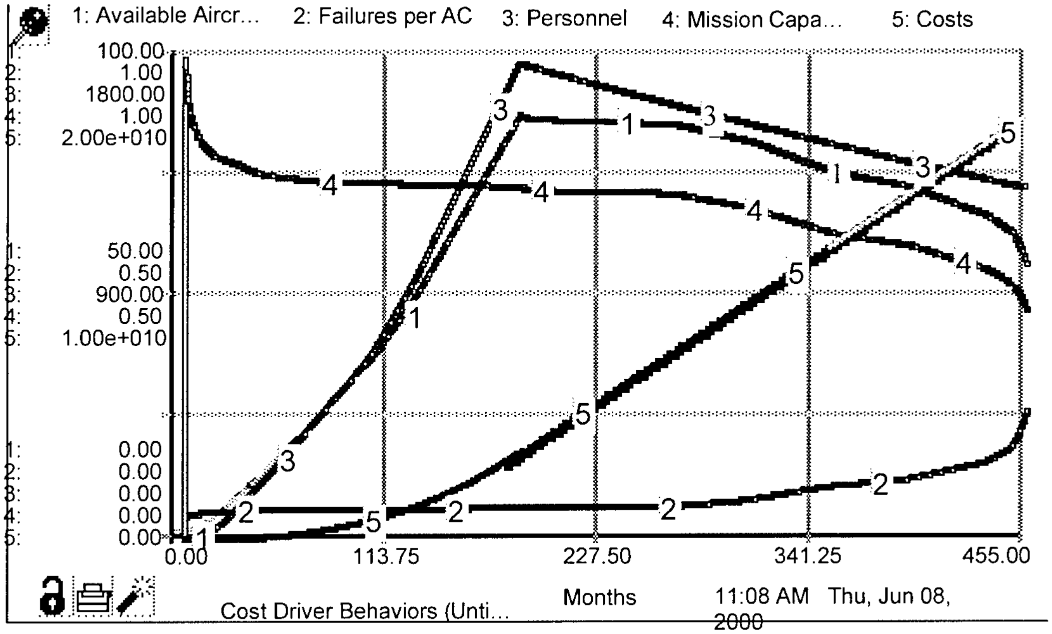


Figure 50. Stella Output of Model Behaviors

As is evidenced by the comparison of these two graphs, the behaviors are remarkably similar. Some of the differences are due to lack of detail in the flow model.

For instance in personnel, there is a steady increase until we have enough, then over the years attrition begins to deplete the ranks. In the reference mode, personnel shows a compensating action, that intuitively shows that as we increase the number of aircraft, personnel is not a one-to-one ratio, that there is an increase, but it is happening at a decreasing rate. If the purpose of this model were to generate accurate O&S point estimates, this detail would be necessary. However, the purpose here was to identify cost behaviors, and their effects from different policy decisions. Therefore, the added detail for smoothing personnel, and available aircraft was not necessary.

Validation of the O&S cost model

The final stage of building confidence that this is a good model, is the validation phase. In SD modeling there are no statistical tests of validity, it is a process of building confidence in the model, first in the modeler, then in the user. In validation there are a number of tests: model structure, model behavior, and tests of policy implication. Certain core tests help to strengthen validity (Forrester and Senge, 1980: 209-227).

Structure Verification – does the model's logical structure match the real system? For instance in the Available Aircraft/Failure/Maintenance structure, we know that if a plane has a failure, it goes into repair, while there it cannot fly missions. This structure is evident, and matches the real world. Another example is Aircraft Production, we know that as we prepare to build aircraft, there is a delay in production, we must build the facilities, hire the personnel, build supply lines, and experiment with production processes. These delays cause a slow ramp-up in production. This "ramp-up" is modeled through the *delay* feature on production's Goal Seeking structure.

Parameter Verification – do the constants in the model reflect observed constants in the real system? In this case, numbers of support personnel, Cost per flight hour, Repair Costs, and total costs can be verified from databases tracking C-17 costs. These numbers were used to verify that the behaviors exemplified in the model were within the scope of the actual C-17 system. In one case, this test pointed to an error in the personnel node. When calculating the costs, a cost factor was used that included annual salaries. However, the model is calculated monthly and at first it appeared that Personnel was the most important cost driver to the system. Verification, comparing the parameters of the model with the real system (VAMOSC data), identified the error.

Extreme Conditions – does the model exhibit expected results if one or more variables goes to an extreme (either huge or 0)? Yes. As alluded to in the error mentioned above, one feature of the model is to eliminate maintenance, as the budget becomes too tight. When personnel costs were too high, shortly after production began, costs skyrocketed, and before production was over, the budget for maintenance had gone to $0. This shows that the logic structures do work, even when extreme numbers are included. Another area identified in the testing above was when a budget of $0.00 was used to initiate the system. As predicted, the system stopped generating costs.

Boundary Adequacy – does the model include all relevant structures? The temptation to add detail to match the details of the real world was strong. However, keeping in mind the purpose of this model, the detail was limited to the questions at hand. For instance in the area of failures, there are five different types of failures, instead of trying to model each one, or trying to model individual component failures, it was kept very top level. Future models will explore these details, but they were not necessary for the policy questions being asked in this model.

Dimensional Consistency – do the rate equations force behavior? In this model, the only rates that drive behavior were those that were determined through a literature search and a class on reliability. These areas were Aircraft Stress failures and Aircraft Aging failures.

Behavior Reproduction – does the model-generated behavior match the observed real world system? For the C-17 it is too early to tell on most of the behaviors. The airplane is still in production, so the out-year cost behaviors cannot be determined. However, Aircraft Availability, Personnel, and mission capable rates are in line with the model's predicted behaviors.

Behavior Anomaly – does the model exhibit some behavior that is anomalous, that might point to a flaw in the model. The failure area is a candidate. Because a plane never gets to the point where it spends all its time in repair, the fact that this model exhibits this behavior, might indicate a problem. In the real world, as a plane reaches its useful life, a Service Lifetime Extension Program (SLEP) is usually initiated which performs a complete upgrade and rework of the system. This model does not implicitly show this happening, it allows the plane to fall apart. However a decision variable that can be played with, is when is the best time to do a SLEP, and would it be cost effective.

Behavior Sensitivity – is there a parameter value that is particularly sensitive, such that small changes in the parameter cause the model to fail tests that it previously passed? There is one area, Budget Reductions, which fits this problem. However, due to the purpose of this model, this feature is not particularly damaging, this area will not be of importance to the Flexible Sustainment model.

Policy Sensitivity – would the same policy recommendation be made if there were different, yet plausible parameter values in the model? Yes, because of the relative non-interaction between different cost drivers, a change in one does not dramatically cause a change in another.

Implementation of the O&S Cost Model

The goal of this appendix was to build confidence that SD can be a valid predictor of future behavior. That it can it be used to answer the key question that started this exercise. It can also be used to determine those areas that need more analysis, or further expounding of their structure.

Identifying areas for further investigation

Mission Needs - a ten percent increase in the mission needs, has little effect for most of the operational life of the aircraft. However, in the out years, it has the effect of reducing availability by more than three years, which is about 10 percent of its expected life. If the requirement increases to 20 percent greater mission needs, ten years or one third of the fleets life is eliminated, if the assumed life of 30,000 flight hours is accurate. This indicates a further analysis of Fleet stress, Maintenance, and aging characteristics is necessary.

Aircraft buy - an increase in the aircraft buy can affect a number of things. If the additional buy is to relieve stress on the fleet, then this can be modeled by decreasing mission needs. If the idea is that the role of the plane will take on a greater importance, then the flight hours flown per plane would be expected to stay constant. In this case, the results are as follows. When the aircraft buy is doubled, with no decrease in mission needs, costs more than double, however, this is caused by a increase in the life span of the fleet. An additional thirteen years is added to the useful life. Therefore, if there is no limit to the capacity of the repair facilities, more aircraft are warranted. It is critical to understand however, that before jumping to this conclusion, more detail is needed for the evaluation of the impacts on maintenance facilities, capacity constraints and aging implications.

Aircraft Aging - if the actual lifetime of the aircraft is only 20,000, when the planned lifetime is 30,000, then the plane will experience an increase in failure rates at about 12 years of age. This contrasts to the expected increase (from the baseline) at 19 years. Although this increase is minor at first, the difference is that if the lifespan is actually only 20,000, the service life will end 9 years earlier. This will be an important indicator for the decision-maker, as it will give him a 9 year window of opportunity to plan for the future. Therefore understanding the implications of aging, and having the ability to forecast signs of premature fleet aging is necessary.

Service Lifetime Extension Program – when is the optimal time for a SLEP in the aircraft's life? For this test, the expected lifespan was divided into equal periods, and a 30,000-flight hour extension program was implemented. There was no difference in life span, as to when the SLEP was performed, the key was to do it before it was too late. Cost and service impacts are minor, as long as the SLEP occurs before AC failure.

Conclusion

The System Dynamic model presented is an important tool to the decision-maker controlling the C-17. Issues of reliability, personnel support, lifetime extension programs and production buys can all be explored. Decision-makers can see how any policy changes they make now will influence costs and expected lifetime of this aircraft. Now, if this model were to be the foundation for a final O&S model, follow on effort would be required to add more detail in the areas that are overly sensitive, or that are significantly important to the system. At this point, the conclusion can be made, that SD does in fact offer capability to the decision-maker that is not available from other cost models. It can also be concluded therefore that exploration of the F/S software program is warranted.

APPENDIX C

The following section is an explanation of the FleetSight model[5]. It was written by Dr. Louis Alfeld, president of Decision Dynamics Incorporated. The purpose of this section is to help the reader understand how the System Dynamics addressed in the previous section, is embedded into the FleetSight program, and how it addresses the issues raised in chapter II (aging, maintenance, and fleet stress).

FleetSight and System Dynamics -Structural and Behavioral Analysis

FleetSight incorporates system dynamics modeling technology as its simulation engine. The FleetSight simulation equations, as well as the interface, are written in Visual C++ but retain a nearly one-to-one correspondence to the system dynamics equations originally written in iThink software. This paper describes the underlying system dynamics structural elements of the FleetSight model. These structural elements are presented in the form of four iThink models. The output of the four models is compared to FleetSight output to verify behavior and to validate structural fidelity.

This exposition describes the first three models as stand-alone for the purpose of testing and verifying input and output variables. The fourth model is a composite of the first three, interconnecting them so as to generate internal dynamic behavior. Equations for all four models are attached as Appendix D.

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[5] As mentioned earlier, the software used to explore these SD characteristics is called FleetSight.™ Through the help of the DoD's Small Business Innovative Research (SBIR) program, DDI has developed this tool to aid in the quantifying of cost, schedule and performance tradeoffs associated with the operations and maintenance of complex weapons systems (Alfeld, 1999:1-3). This software is a model building program. It does not have a prebuilt model that a model builder populates; it has components that the model builder assembles to match the requirements of the specific item and task being modeled. It is for models ranging from general, to very specific. It is like a box of virtual Legos.TM

Model One: Active Aircraft

The active aircraft model in figure 51 tracks the flow of aircraft from active to inactive status and back again. The model contains two levels, Active AC and Inactive AC, which are connected by two rates, AC Down and AC Returned, to create a closed loop system. Aircraft can be added to the system through the AC Acquired rate and subtracted by the AC Retired rate. Several auxiliary variables calculate Total AC and the Fraction Active.

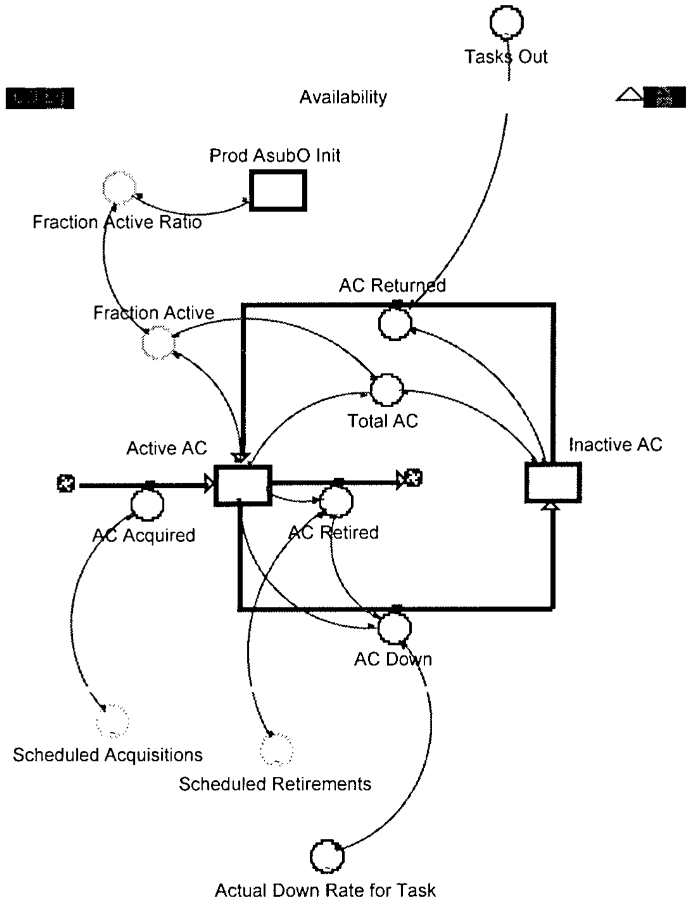

Figure 51. Active Aircraft Model

The model is driven by four exogenous test variables. Actual Down Rate for Task mimics the way in which the FleetSight model generates tasks that bring down aircraft for maintenance. The single task variable can be used to represent scheduled, unscheduled or upgrade tasks. The Tasks Out variable substitutes for all of the resources needed to complete the maintenance tasks. When the Actual Down Rate for Task and Tasks Out variables take the same value, then aircraft flow continuously around the loop. If the Tasks Out variable is less, then aircraft build up in the Inactive AC level until only a minimum remain in the Active AC level.

Figure 52 graphs the flow of aircraft around the loop. Initially 30 Active AC and 10 Inactive AC make up the fleet of 40 aircraft with 75 percent fraction active. At the start of the simulation, the Actual Down Rate for Task equals 10 aircraft per year. Because the Tasks Out rate also equals 10 aircraft per year, the system is in a dynamic equilibrium with all rates equal and the levels unchanging. In Year 5, a decrease in the Tasks Out variable from 10 per year to 8 per year causes the number of Active AC to decline and inactive to rise. If 10 aircraft come down every year and only 8 can be returned to active service, then in 11 years the number of Active AC will decline to 8 aircraft, just the number that can be returned each year. The system reaches this new equilibrium point in Year 16. At that time the fraction active is only 8 / 40 = 20 percent.

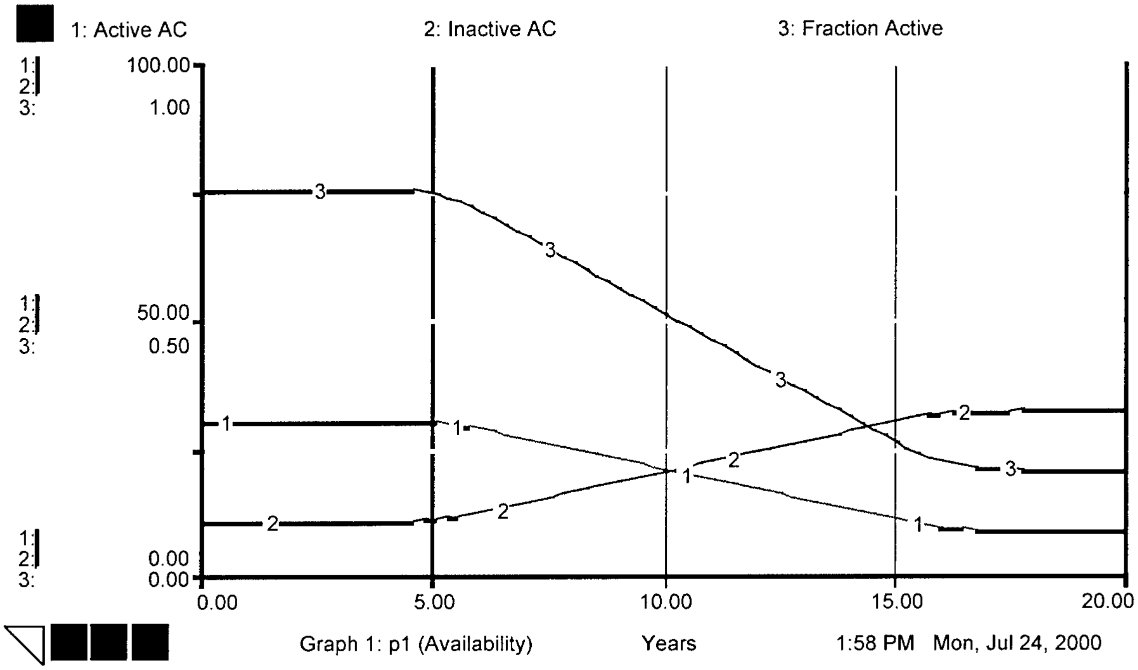

Figure 52. Active Aircraft Decline when Tasks Out Decrease

This behavior mirrors the FleetSight model. Whenever maintenance resources decrease, thus lowering the return rate, the number of active aircraft declines and the number of aircraft awaiting maintenance actions increases. The same structure also applies to the work breakdown structure WBS elements of the FleetSight model.

Model Two: Aging Aircraft

Figure 53 shows the main structure of the aging aircraft model. It is composed of five levels connected in a linear string by six rates. New aircraft enter the model through the Acquisitions rate and old aircraft exit through the Retirements rate. Aircraft age by flowing from the newest level, P1 through the successive five levels until reaching P3, the oldest. FleetSight aggregates the P1 and P12 levels as new, the P2 and P23 as midlife, and the P3 as old.

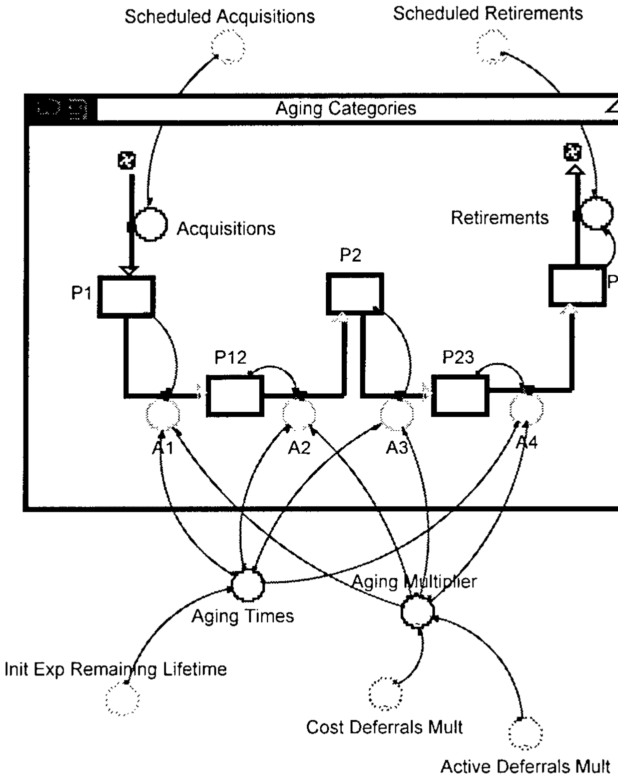

Figure 53. Aging Aircraft Model

The model structure depicted in Figure 53 is called a fifth-order delay, because there are five levels between the inflow and the outflow rate. The model shows an Init Exp Remaining Lifetime variable that defines how long an aircraft is expected to last. This variable determines how long an aircraft remains in any one of the levels. One-fourth of the value given for the lifetime is used to control the outflow of each of the aging rates. For example, a typical equation would be: A1 = P1 / (Init Exp Remaining Lifetime / 4).

This formulation is called an exponential decay. A constant fractional part of the remaining level is lost each time period during the simulation. However, since the level is declining, the actual value of the rate also declines each time period. In the FleetSight model, the user can control the definition of Init Exp Remaining Lifetime so as to override the one-fourth split to more quickly or more slowly move aircraft from new to midlife to old categories.

The Aging Multiplier acts on the normal rate of aging, speeding or slowing the rate at which aircraft pass from P1 to P3 age categories. The model Figure shows two exogenous test functions, a Cost Deferrals Mult and an Active Deferrals Mult. The first multiplier will slow the aging rate and the other will speed it up. These two multipliers act as stand-ins for the many FleetSight multipliers with which the user can model system impacts on the rate of aging.

Figure 54 graphs the normal aging behavior. In the simulation 100 aircraft start as new and decline toward old over a 20-year expected lifetime. Note that at the end of the 20 years, almost all of the new aircraft have disappeared but that about 20 midlife aircraft still exist. This reference behavior mirrors most real-world aging fleets in that, at the end of the expected lifetime, some aircraft are still capable of flying many hours. The model only traces the *average* condition of the fleet, not the condition of any single aircraft within that fleet. Some will age very quickly while others will retain their usefulness for many years.

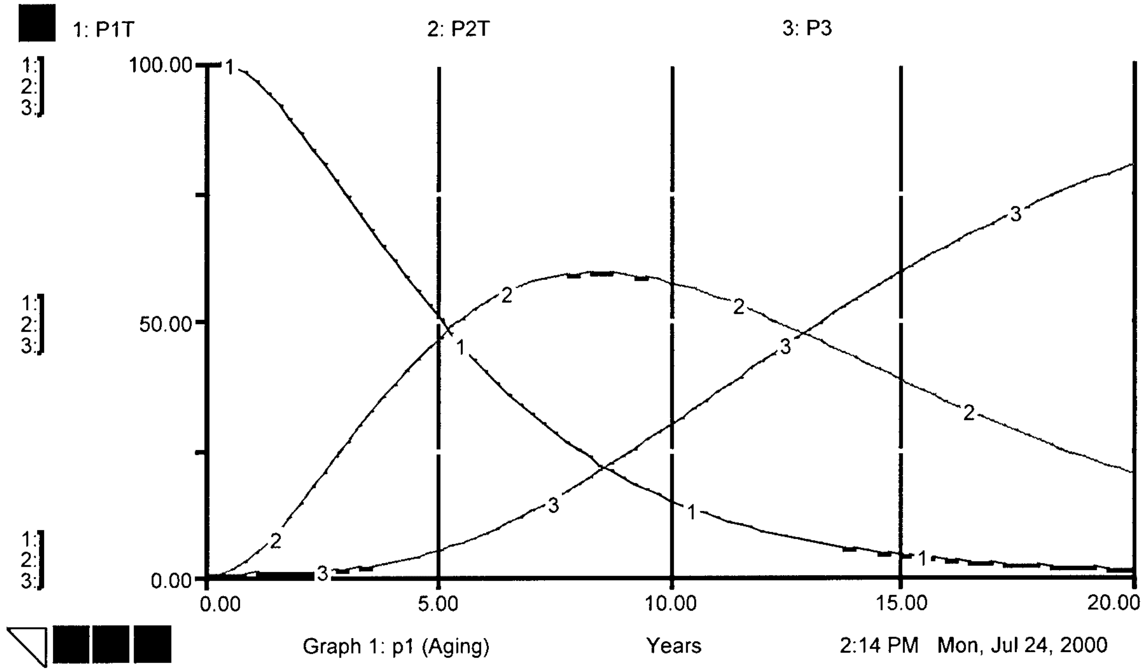

Figure 54. Normal Aging distributes AC Across Three Age Categories

Figure 55 shows the auxiliary equations that accompany the aging model. At the bottom the five levels are added together to get the three age categories, here called P1T for new, P2T for midlife and P3 for old. At the top a weight is assigned to each age category, 3 for new, 2 for midlife and 1 for old, to compute the Avg Condition Calc. The Avg Condition variable equals the Avg Condition Calc unless the Aging Switch is turned off, in which case the average age computation does not change.

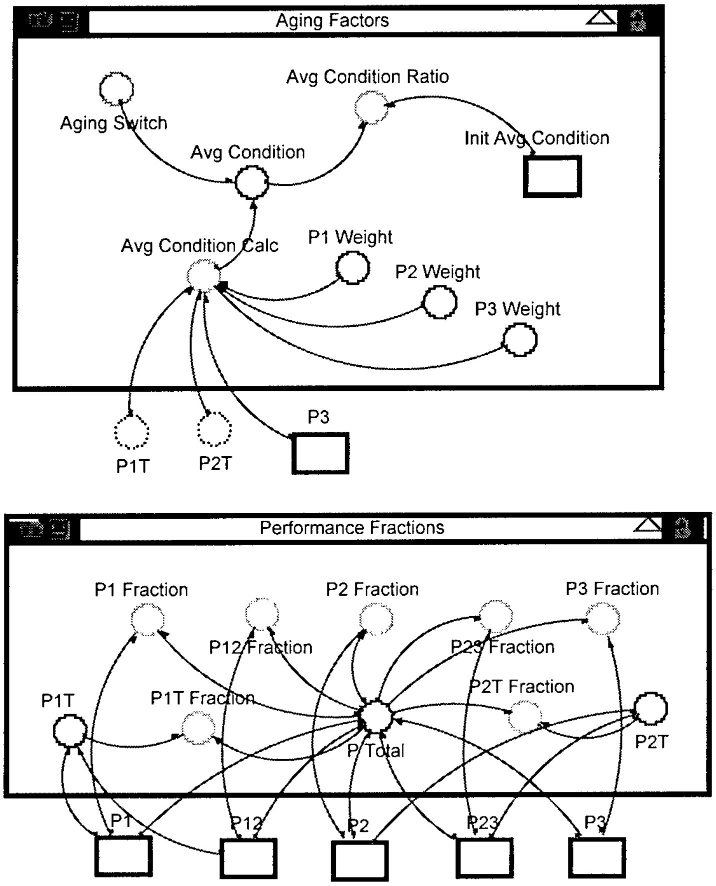

Figure 55. Calculating Average Condition

As the aircraft age through the system, average condition will fall. The highest value that average condition can take is 3.0, when all aircraft are new while the lowest value is 1.0, when all aircraft are old. In practice, however, the lowest value will never quite reach 1.0 because the exponential decay function will never completely empty any of the levels; some tiny fraction of an aircraft will remain behind in each of the levels.

The Avg Condition Ratio is obtained by dividing the current simulated average condition by the initial value at the start of the simulation. The ratio will, by definition, always equal 1.0 at the start of the simulation. As the aircraft age, the ratio will decline;

if upgrades extend the service life, then the ratio will rise. The ratio is used as the input variable for several of the functions in FleetSight.

Figure 56 graphs the average condition curve for the same simulation as shown in Figure 4. It overlays two other simulations, one with an average expected lifetime of 15 years and one with 25 years. The comparison shows that the decline in average condition of an aircraft fleet can vary depending on the rate of aging. Whenever this rate is speeded or slowed by any of the multipliers, the average condition responds by dropping more rapidly or less rapidly as well.

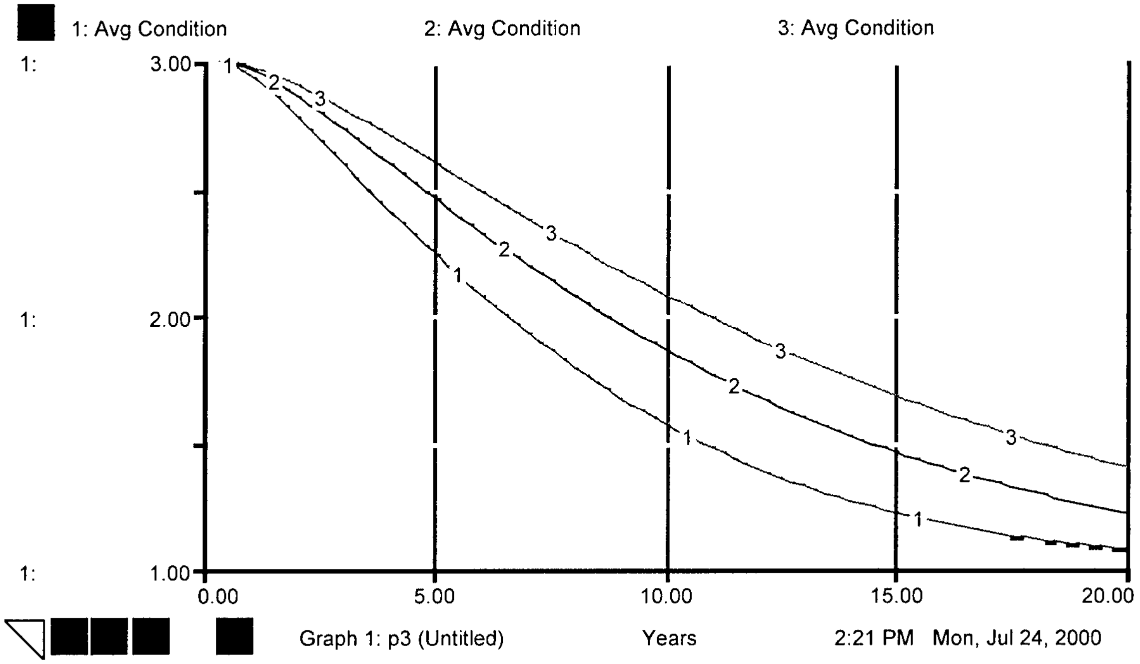

Figure 56. Variable Rates of Aging

The aging behavior is captured in the FleetSight model in exactly the same way as described here. One can model differential aging rates and show the corresponding changes in the average condition of the fleet or of any of the WBS elements.

Model Three: Tasks

The third model verifies the linkage between tasks, labor hours, and aircraft. Figure 57 shows two backlog levels, the Task BL and the WH BL. The Task BL counts the number of aircraft entered into the task backlog while the WH BL counts the amount of work hours required to complete the tasks. A Down Rate for Task, defined below, fills the backlogs and a Tasks Complete rate empties them. WH in defines the number of work hours going into the WH BL as equal to the number of aircraft times the work hours per aircraft. The start value is given by Init Hrs per Task. This initial value can be changed exogenously through the Increased Work Mult which tests the effect of increased work hours per task due to aircraft aging.

The WH Out rate depletes the WH BL. However, since it is too difficult to match the number of work hours for each aircraft going into maintenance and coming out, the out rate is defined as the *average* number of work hours per aircraft in the backlog.

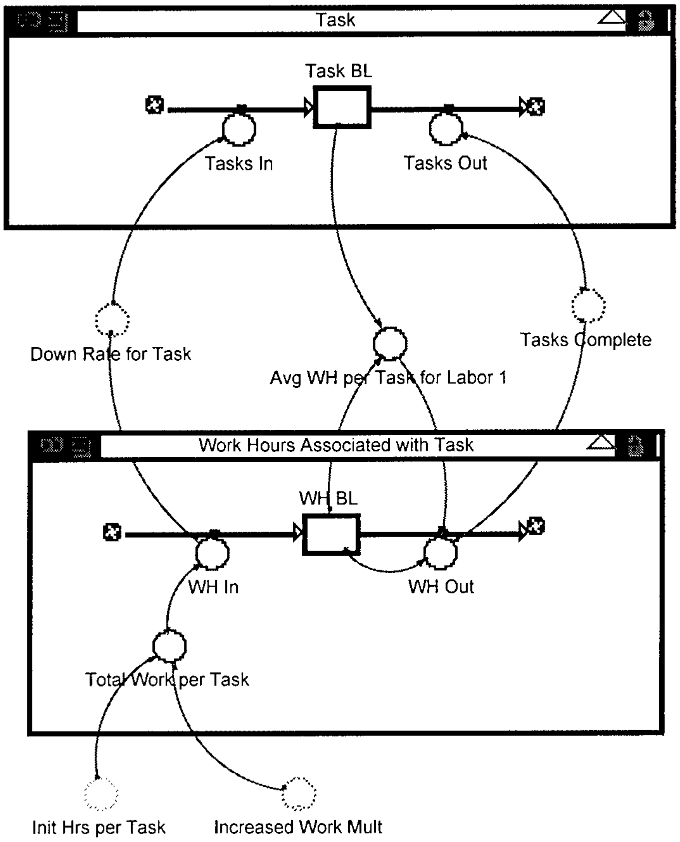

Figure 57. Task Backlogs

This simple task backlog model can be replicated many times to show different tasks. In the FleetSight model the user may define as many tasks as desired for each aircraft or each element of the WBS.

Figure 57 lays out some of the additional equations in the task model. At the top, the Tasks Complete variable is composed of six variables. First, the Task BL is multiplied by the Avg WH per Task (by labor type, if desired) to calculate the number of labor hours in the task. This number is compared to the Available LH to ensure that adequate labor resources are available to complete the task. If material is required for the task, it is compared to available material as well. Lastly, if a work station is needed for the task, it is also checked. Only when all three types of resources -- labor, materials and station -- are available, can the task can be completed and the work backlog emptied.

The Down Rate for Task is seen as a function of four variables, Total AC, the MTBR for Task, the Active Deferrals Mult, and the Frequency Interval Mult. The function cannot bring down more aircraft than are in Total AC. The MBTR function sets the frequency rate for maintenance actions. The active deferrals function tests the impact of decreasing the frequency; the frequency interval function tests the impact of increasing the frequency. As the task frequency changes, the down rate will change accordingly.

A small submodel element at the bottom illustrates how the model tracks material availability. Given an initial amount of material, each task depletes the stock until all is gone and no more tasks can be performed. FleetSight allows the user to add more materials during simulation to track availability as usage rates and order rates vary.

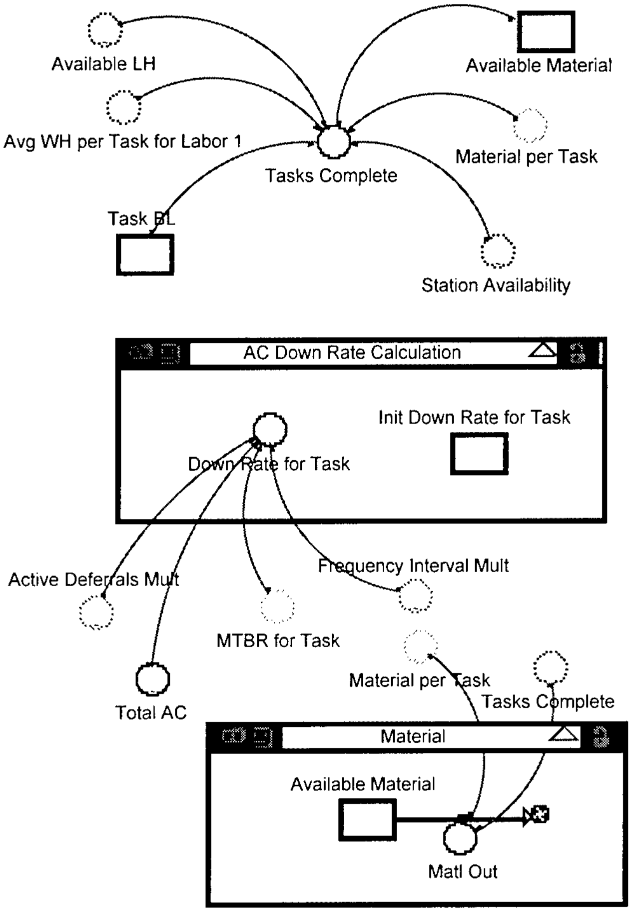

Figure 58. Down Rates and Return Rates

Simulations of the task model show that behavior is exactly as expected. Figure 59 graphs the work backlog, the average work per task and the average condition. Setting the Increased Work Mult to rise as average condition falls results in the graph in figure 60 . After Year 6, average condition falls and both average hours per task and total workload rise.

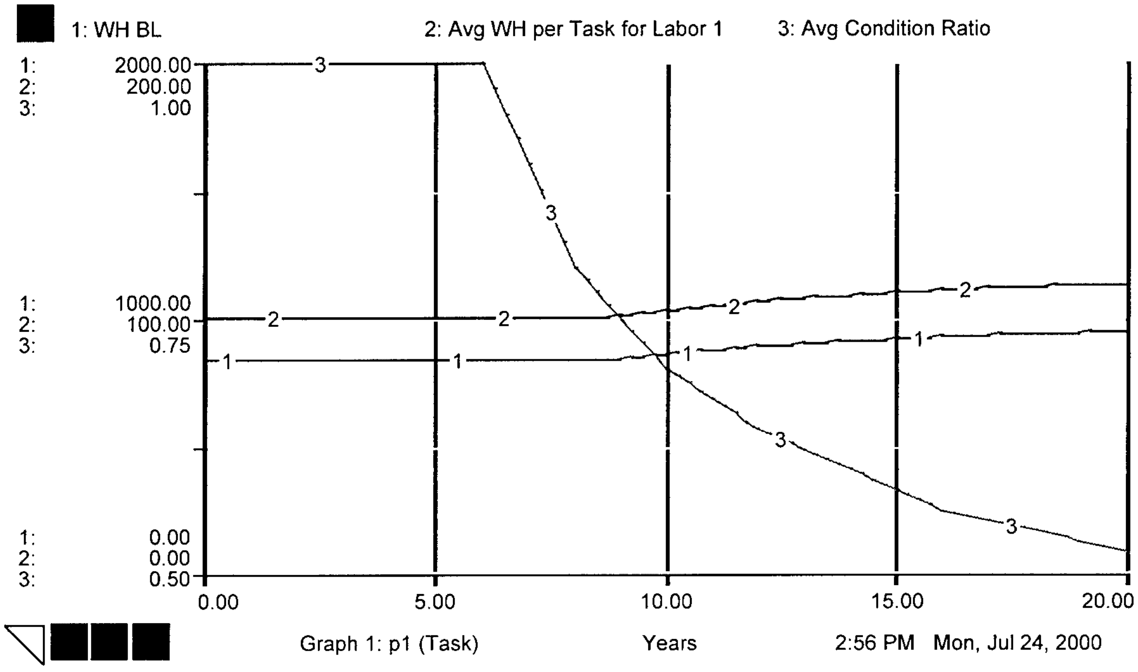

Figure 59. Increased Work as Average Condition Declines

Figure 60 shows the results of changing the Frequency Interval Mult so that, as average condition falls, the frequency interval shortens. Although the average labor hours per task remains constant, the number of work hours in the backlog increase as more aircraft come down for maintenance.

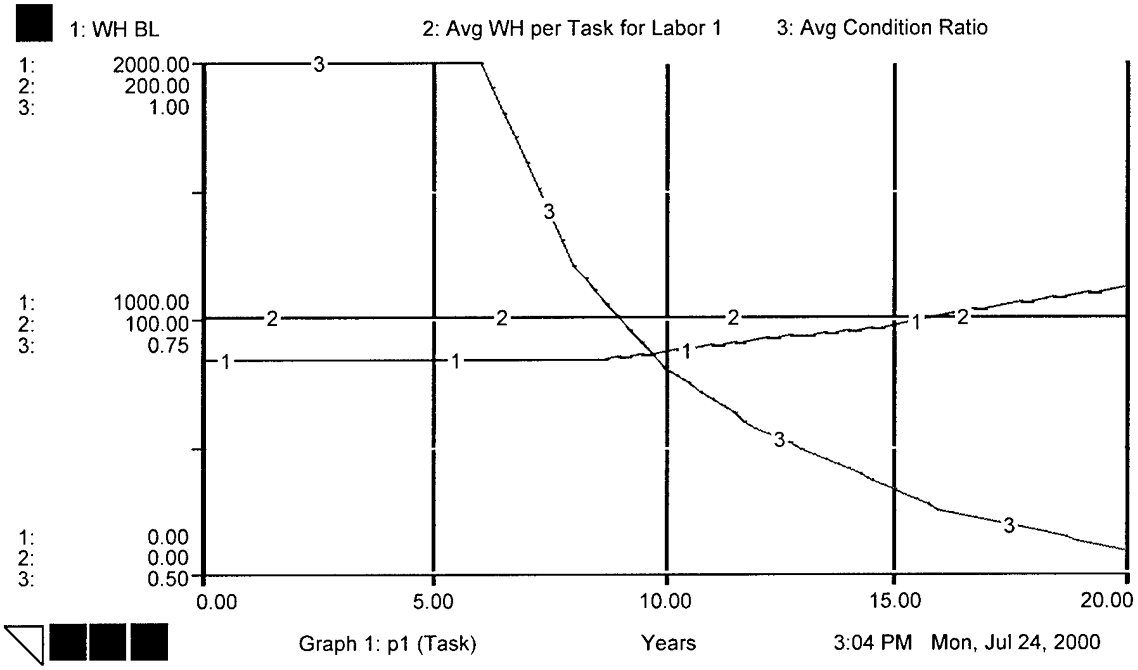

Figure 60. Increased Work as Frequency Increases

Tests of the task model show that its output behavior responds to inputs just as does the real-world. Its behavior also matches FleetSight behavior under similar conditions.

Model Four: Integrated System

The fourth model joins the simple systems described in the first three models to present and test the integrated model. Although the model is simpler than the FleetSight model, it contains all of the important feedback structures, variables and user controls. In addition, it exhibits the same behavior as does the FleetSight model.

The structural elements of the integrated model have all been described in the five model Figures above. The integrated model merely makes all of the inter-model connections, substituting internal model variables for many of the exogenous time-driven functions.

Figure 61 shows aircraft aging. The model begins with 100 aircraft, 40 new, 50 midlife and 10 old. Average condition, therefore, starts at a value of 2.30. After 20 years, average condition has fallen to 1.11 and the average condition ratio has dropped from 1.0 at the start to 0.48 at the end.

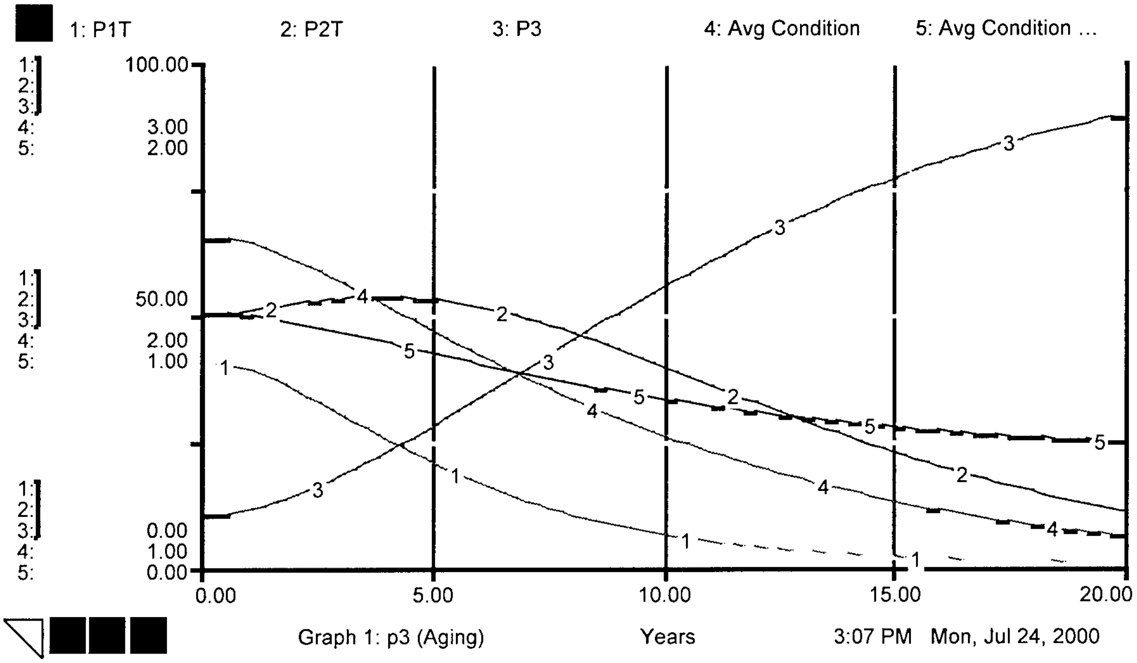

Figure 61. Aircraft Aging

Figure 62 graphs two of the variables that are impacted by the average condition ratio. As average condition falls, the multiplier for work load increases and the multiplier for frequency interval falls. Together, both variables boost the cost of maintenance. The first demands more work hours for each maintenance task and the second increases the number of tasks per year.

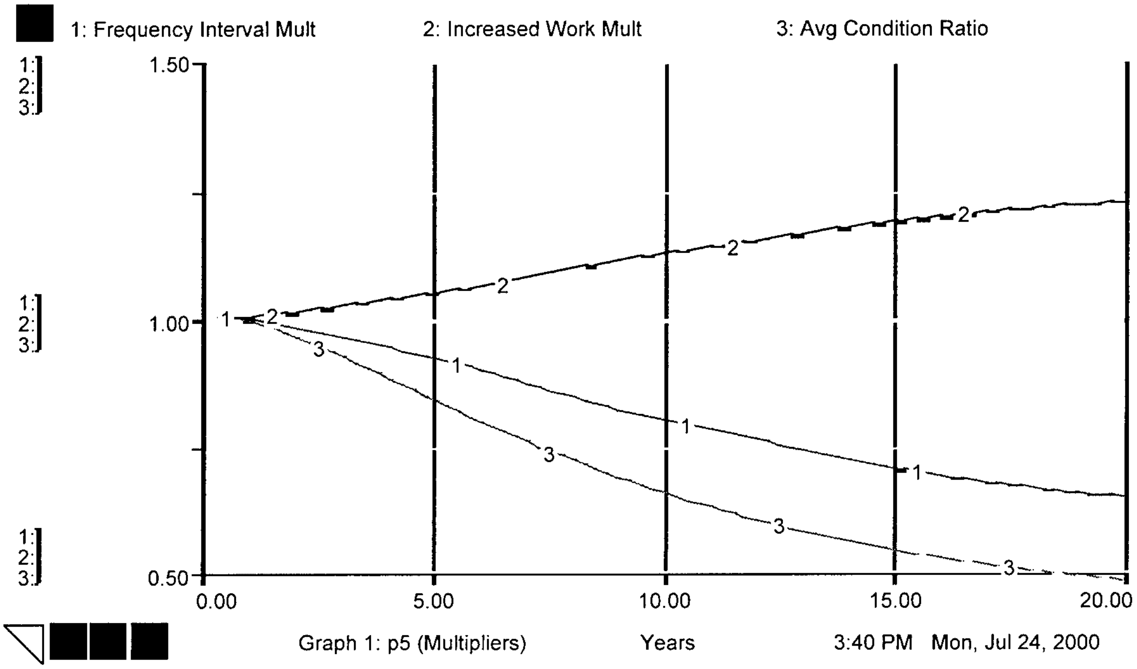

Figure 62. Average condition Impacts Workload

To understand how FleetSight accrues costs, Figure 63 shows that the rate of expenditures per year, Annual Costs, are a function of four cost elements. The number of work hours times the cost per hour gives the labor cost. The number of materials used times the cost per material gives the materials cost. In addition, if desired, the acquisition rate times the cost per acquisition and the retirement rate times the cost per retirement will give the capital costs. FleetSight allows the user to create a cost breakdown structure CBS to capture any type of cost independently and to add them together in any fashion. Figure 64 graphs the labor hour costs associated with the increase in work load simulated in Figure 62. If the workload had remained the same as the fleet aged, the costs would be lower.

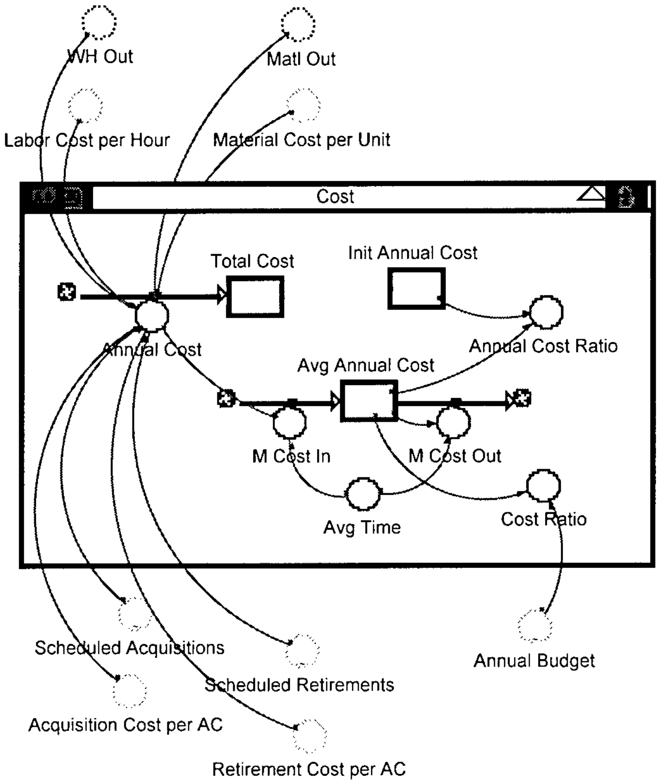

Figure 63. Cost Elements

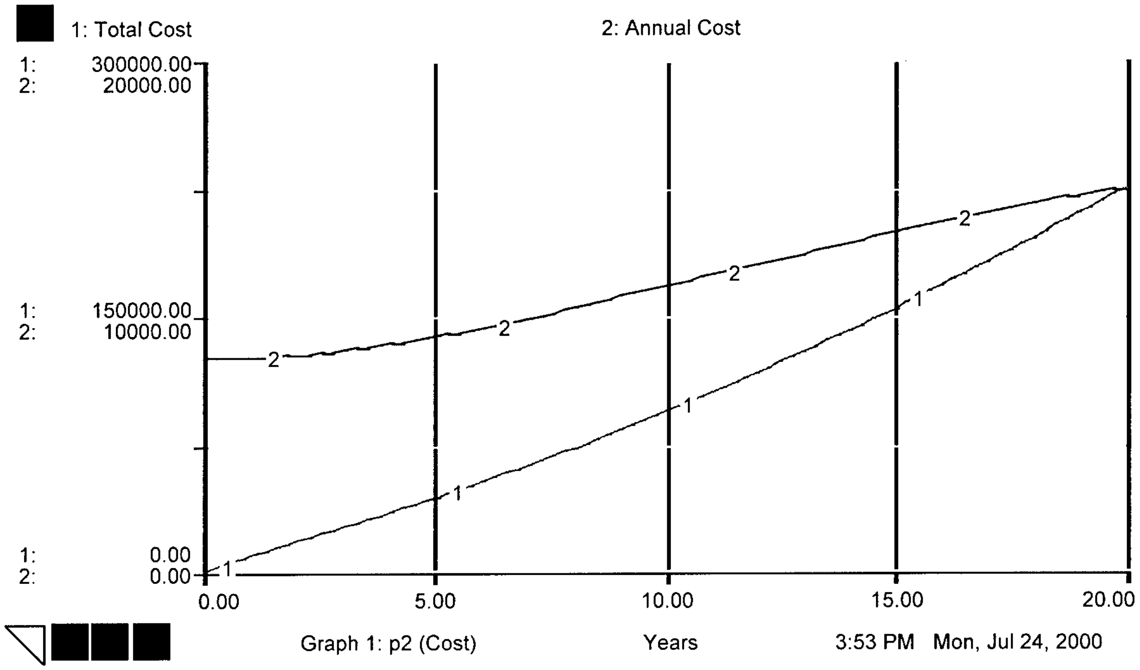

Figure 64. Annual and Total Costs for Maintaining an Aging Fleet

Conclusion

The analysis of the four iThink models demonstrates the ability of a system dynamics model to capture real-world cause-and-effect structure and to simulate realistic behavior. Each of the smaller models has been individually tested to ensure that they behave reasonably under robust conditions. Joined together they offer a simple model of the aircraft aging and maintenance cycle.

FleetSight builds on these same model elements. Through a sophisticated graphical interface, the user can create a model of any specific aircraft fleet, weapons fleet or product inventory. All follow the same general aging and maintenance behavior.

The user can build a model to any WBS depth, repeating the same model structure and linking lower levels to higher ones. As many labor types, material types and work station types as the user desires may also be incorporated into the model by duplicating those portions of the relevant model structure.

FleetSight treats all tasks in the same manner. Maintenance and upgrade tasks bring aircraft down to inactive status while maintenance and repair capacity returns them to active service. Operations tasks are identical except that they do not bring aircraft down. If inadequate operational resources are available, then the operations tasks do not get accomplished.

The integrated model also shows how FleetSight collects costs. Because simulation is basically an activity-based representation of system behavior, FleetSight easily collects activity-based costs. It can also collect costs as resources are used. This simple cost structure allows FleetSight to forecast future operations and maintenance O&M costs under alternative "what-if" scenarios.

APPENDIX D

To improve the quality of these cost estimates, the Secretary of the Air Force (SAF) established the Air Force Cost Analysis Improvement Group (AF CAIG). This group is chaired by the Deputy Assistant Secretary of the Air Force (Cost and Economics) (SAF, 1997, 3). Among their goals, they assist the Office of the Secretary of Defense in reviewing program costs, and determining that Cost drivers are identified and positive action taken to reduce support costs. All Acquisition Category I programs (ACAT I), of which the C-17 is an ACAT-IC (C for Component or Air Force managed) program, must follow the AF CAIG process in preparation for a milestone decision. However, for ACAT IC programs, the CAIG is not required to perform an independent cost estimate, per Title 10, United States Code, Section 2434(b)(1)(A), Independent Cost Estimates for Major Defense Acquisition Programs (SAF, 1997, 4).

CAIG O&S Development Approach.

There are four steps involved in determining the cost estimate approach: identification of key O&S issues; selection of a reference system; development of ground rules and assumptions; and selection of a cost element structure (OSD, CAIG, 1992:3-5). For identification of key O&S issues, the SD model will be aligned with the O&S issues currently identified and approved for the C-17 program. The reference system used will be the C-17 Flexible Sustainment contract structure, which has been jointly agreed to by both SPO and Boeing contracting personnel. Ground rules and assumptions will be spelled out in Chapter IV, they will follow as closely as possible to the current Flexible Sustainment assumptions, altered for inclusion into the SD methodology. Differences will be identified and their impact and sensitivities will be addressed. The Cost Element structure will parallel the CAIG element structure, for the C-17 estimated costs, that are a component of Flexible Sustainment.

CAIG O&S Cost Element Structure.

As part of the mandate to improve O&S cost estimating, the CAIG was tasked to establish standard elements to foster consistency and provide a template of key O&S cost areas to address in the estimate (OSD, CAIG, 1992:4-1). It is important to note, that this structure is a guide only and may be modified. One advantage to using this structure however, is the Air Force has initiated an on-line database with the Air Force Total Ownership Cost (AFTOC) data. This database has every weapon system's costs from 1996 to the present, in the CAIG format, broken down to the third sub level (Smith, 2000:1).[6] The advantage therefore, is an estimate that uses this Cost Breakdown Structure (CBS) will be able to verify its estimates with the individual components being addressed. For instance, in the C-17 Flexible Sustainment Model, some unit level consumption will be estimated, but other portions will not. By being able to verify costs at the various sub levels, only those areas specifically estimated can be checked, as opposed to trying to back-out costs from some total.

There are seven elements in the generic structure, these seven elements are further broken down into sub levels. This structure is as follows (OSD, CAIG, 1992:C-1):

1.0 **Mission Personnel**
  1.1 Operations (officer, enlisted)
  1.2 Maintenance (officer, enlisted, civilian)
  1.3 Other Mission Personnel (captures personnel costs not captured elsewhere)

2.0 **Unit-Level Consumption**
  2.1 Pol/Energy Consumption
  2.2 Consumable Material/Repair Parts
  2.3 Depot-Level Reparables
  2.4 Training Munitions/Expendable Stores
  2.5 Other

3.0 **Intermediate Maintenance (External To Unit)**
  3.1 Maintenance
  3.2 Consumable Material/Repair Parts
  3.3 Other

4.0 **Depot Maintenance**
  4.1 Overhaul/Rework
  4.2 Other

5.0 **Contractor Support**
  5.1 Interim Contractor Support
  5.2 Contractor Logistics Support
  5.3 Other

6.0 **Sustaining Support**
  6.1 Support Equipment Replacement
  6.2 Modification Kit Procurement/Installation
  6.3 Other Recurring Investment
  6.4 Sustaining Engineering Support
  6.5 Software Maintenance Support
  6.6 Simulator Operations
  6.7 Other

7.0 **Indirect Support**
  7.1 Personnel Support
  7.2 Installation Support

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[6] http://aftoc.hil.af.mil

Mission personnel (1.0) includes the cost of pay and allowances of personnel required for operating, maintaining, and supporting the system. These costs are based on manning levels and skill categories (OSD, CAIG, 1992:C-2). This area will not be modeled.

Unit-level consumption (2.0) includes costs for energy resources, operations and maintenance, and support materials consumed at the unit level; stock-fund reimbursements for Depot-level reparables, training munitions, temporary duty pay and other purchased services (OSD, CAIG, 1992:C-3).

Intermediate maintenance (3.0) is maintenance performed external to a unit. It includes labor, material, and other costs expended in activities to support the system or required equipment. These activities include calibration, repair, and replacement of parts; components or assemblies; and technical assistance (OSD, CAIG, 1992:C-5).

Depot Maintenance (4.0) includes the cost of labor, material, and overhead incurred in performing major overhauls, such as an Analytical Condition Inspection (ACI), on aircraft, their components as support equipment. These overhauls may be performed at depots, contractor facilities, or at the base by depot teams (OSD, CAIG, 1992:C-6)

> Contractor support (5.0) includes the cost of contractor labor, materials, and overhead incurred in providing all or part of the logistics support required by an aircraft system, subsystem, or associated support equipment. Contract maintenance is performed by commercial organizations using contractor personnel, material, equipment, and facilities or government-furnished material, equipment, and facilities. Contractor support may be dedicated to one or multiple levels of maintenance and may take the form of interim contractor support (ICS) if the services are provided on a temporary basis or contractor logistics support (CLS) if the support extends over the operational life of a system. Other

> contractor support may be purchased for engineering and technical services (OSD, CAIG, 1992:C-6)

Sustaining Support (6.0) includes costs for replacement of support equipment, modification kits, sustaining engineering, software maintenance support, and simulator operations (OSD, CAIG, 1992:C-7). Indirect support (7.0) includes costs for relevant host installation services, finance, transportation, medical, base operating support, and real property maintenance (OSD, CAIG, 1992:C-10). It is within this framework that the costs should be placed. Because the C-17 is supported by the Flexible Sustainment concept, these costs are rolled up into the total contract cost. Where possible, these costs should be broken out, in a full model, to make comparisons with the current model as accurate as possible

APPENDIX E

C-17 Cost Summary

The total C-17 Support Cost value is the sum of the Flexible Sustainment Contract, and Other Government Costs (OGC). The Flexible Sustainment contract is made up of:

1.0 Program Management
2.0 Sustaining Logistics
3.0 Spares Management
4.0 Sustaining Engineering, and
5.0 Aircraft Maintenance
6.0

For the SD modeling of C-17 O&S costs, the OGC portion of costs, will be left out. The purpose behind the SD model is to look at those key elements that will have a significant effect on future FS costs. The OGC portion makes up only 25 percent of the total cost and a significant portion of these funds are Risk and non-Boeing costs. The following descriptions are provided to show how these different areas will fit into the CAIG format. Because they do not parallel each other, detailed descriptions are required. This information is derived from Jay Asher's Air Force CAIG briefing package (Asher, 1997: 9-115).

Program Management. This cost area is labor driven. The estimated costs were derived from analogies to field support costs based on actuals from January to July 1997 period. In this area, the contractor is responsible for Quality Assurance, Product Support, Engineering, and On-Site Quality Management. In the short term, these costs are fixed.

1.1 Quality Assurance – is the support area that implements and manages the ISO9000 quality system. They manage quality records, customer requirements, quality resources, and take corrective action. They are responsible for pursuing Continuous Improvement, preventive measures, and audits. Finally, they provide Quality Engineering support for ACIs and Corrosion Control.

1.2 Product Support – deals with program integration and data access. Serving as point of contact on class II and III projects, and overseeing integration. They manage all Over and Above (O&A) projects, and provide overall integration and status reports for Flexible Sustainment proposals, and they provide liaison support with internal activities at the Long Beach facility with the field sites. Data Integration is responsible for logging, tracking, inspecting approving, coordinating, and distribution of all data, including airframe and engine data, both written and electronic.

1.3 Engineering – deals with the Configuration Management Plan and Proposal Preparation. In the area of Configuration Management, they serve as the Point of Contact, and they interface with the Air Force and Boeing on control issues, and provide assistance to resolve configuration discrepancies. The Proposal Prep area is responsible for supporting the preparation of proposals, and provides overall proposal coordination between the various Integrated Product Teams under the Engineering department.

1.4 On-Site Quality Management – This team performs many of the same quality responsibilities of the Quality Assurance group. In addition, this team is responsible for performing instruction on techniques for inspections of aircraft, support equipment, tools and test equipment, and subsequent repair of these items. They also facilitate resolution of maintenance, supply and support problems. Finally, they participate in mishap investigations when their expertise is requested

2.0 Sustaining Logistics. These costs are also labor driven and derived from analogy to the January to July 1997 data. However, there is a variable component to these costs. Unlike the Program management area, costs are driven by the hours influenced by the number of Engineering Orders, Time Compliance Technical Orders (TCTOs), Technical Order (TO) changes, and the number of Support Equipment Requirement Documents required.

2.1 Logistics Support – They perform logistics support, provisioning, and transportation analysis. Furthermore, they provide liaison support to the C-17 Training Systems contractors, providing technical, engineering, software and financial data, to support training activities and reviews.

2.2 Technical Orders (TOs) – They Maintain and generate the C-17 TOs for non-class I changes. They provide analysis and changes to the TOs and draft Contractor Furnished Equipment notices.

2.3 TimeCompliance Technical Orders (TCTOs) – This team is responsible for preparing, coordinating and managing the TCTOs, including preparing briefing packages. They also coordinate Retrofit Kit Drawings.

2.4 Support Equipment – For non-class I changes, they analyze support equipment requirements and prepare Support Equipment Recommendation Data (SERDs) and Test Requirements Documents (TRDs). For Class I changes, they implement the change requirements and finalize the SERD release of Support Equipment drawings and TRDs

2.5 Supplementary Provisioning Technical Documentation (SPTD) – The contractor will prepare and submit SPTD in accordance with Contractor Data Requirements Listing number B001, so that if necessary future possible organic/recompetition can be done (Bowman, 1999:40).

3.0 Spares Management. The contractor is responsible for Long Beach, On-Site Logistics, On-Site Technical and On-Site Quality Supply Support of C-17 peculiar items, for which the contractor is designated the Inventory Control Point. This includes labor to manage the parts, and the material dollars required to buy and repair the parts (Asher, 2000). Quantities of parts managed will influence the number of people required, and repair costs will be a function of flight hours and part reliability. The challenge will be in determining how much growth can occur in flight hours, aircraft purchases, or parts managed, before additional people are required. The cost methodology is rather complex for this area, and will follow the task description section for Aircraft Maintenance (5.0).

3.1 Long Beach Supply Support – They are responsible for Asset Management, including determining requirements, performance, and configuration of spares, and supporting fielded aircraft. They will provide for the management of the Repair of Reparable (ROR) program; coordinate engine and Quick Engine Change (QEC) component repairs; and facilitate the necessary activities to receive, induct and document C-17 assets into the depot level repair facility at the Long Beach Mod Center. Finally, they are to manage export control, to include licensing authority, routing and documentation, upon a receipt of a request for shipment.

3.2 On-Site Logistics Supply Support – The contractor will be responsible to meet depot support requirements for spares, allocation and performance monitoring, by providing the necessary interface and coordination with Base Supply. They will stock, store and issue all parts an materials required to support the Operational Fleet. In addition, they will provide the necessary on site activities to receive, induct and document C-17 asset depot level repairs, until the items are transferred to Boeing. They will also act as the liaison to the Defense Logistics Agency, Air Mobility Command, and Warner Robins ALC. Finally, they will administer engine repairs at the repair facilities of the Repair/Overhaul subcontractor.

3.3 On-Site Technical Supply support – For the areas mentioned above, they are also responsible for technical support.

3.4 On-Site Quality Supply Support – Similar to the previous Quality sections, the contractor will implement ISO 9000 and Continuous Improvement initiatives in the supply support arena.

4.0 Sustaining Engineering. Under this category, the contractor is responsible for Air Vehicle Engineering Assistance, Technical Field Support, Airworthiness, and Systems Integration. These costs are also labor driven, fixed in the short term, and derived from the same analogy technique used previously. However, as scope is added, these costs will be adjusted based on technical experience, judgement and inflation.

4.1 Air Vehicle Engineering Assistance – The contractor will manage the Engineering Disposition process, design analysis and support for fielded aircraft and integrate any results from those analyses with the other disciplines. Additionally they will implement Class II and III drawing changes that occur as a result of Material Improvement Program (MIP) projects or field problems.

4.2 Technical Field Support – Interface with users to monitor fleet readiness, consisting of maintenance support, technical assistance to flight crews, support equipment, and training.

4.3 Airworthiness – Be responsible for Force Management, considering maintenance repairs, retrofit activities, flight hours and severity factors. For Analytical Condition Inspections (ACI), they are to generate the task list and plan, review, and make recommendations for the Maintenance Requirements Plan. Finally, they are to review the maintenance and inspection finding s for corrosion issues and make recommendations for Corrosion Control.

4.4 Systems Integration – Provide Systems Engineering Management and analytical capabilities and support for design release engineering. Provide design analysis and support of fielded support equipment, and coordinate engineering changes with requirements. They are to identify, track and investigate Reliability and Maintainability (R&M) issues and drivers. Finally, for Engine Integration, they are to provide the necessary effort to integrate airframe propulsion engineering and original-equipment-engine supplier (Pratt and Whitney) support.

5.0 Air Vehicle Maintenance. Activities include planning, scheduling, managing and performing maintenance and modifications of both scheduled and unscheduled maintenance activities.

5.1 Planning and scheduling – This entails maintaining Integrated Depot Modification/Maintenance Schedules (IDMS) for block Engineering Change Proposals (ECPs), Paint and ACI activities. Costs in this area are again analogy based, adjusted for changes in work scope based on technical experience and judgement.

5.2 Non-Labor Paint and ACI Material – This is a discrete estimate based on the number of tasks performed.

5.3 Paint – This cost is driven purely by age of aircraft. Based on actuals to-date, these costs have been projected into the future. Actuals will need to be adjusted for requirements for additional scuffing and stripping if necessary.

5.4 Scheduled Maintenance – Performing the ACIs and Painting.

5.4.1 ACI is a systematic disassembly and in-depth inspection of the airframe. The purpose is to discover any corrosion or fatigue defects in operational aircraft, that might not otherwise be found by regular maintenance activities.

5.4.2 Painting has two components, a scuff and paint, or a strip and paint

5.5 Unscheduled Maintenance – This area is not pre priced, as the costs are charged to the Over and Above section. But these activities include repair conditions discovered during and ACI, conditions discovered during other tasks, depot levels TCTOs, and sending RAMS Teams when necessary to facilitate aircraft repair. The SD model will include these costs.

Spares Management Cost Methodology

Spares management accounts for 50 percent of the total C-17 support cost. It is expected to cost more than three billion dollars over the next five years. The magnitude of this cost is even greater, considering the life-span of this aircraft is expected to be over 30 years. Understanding these costs, and making decisions to reduce cost growth in the future, is the main reason for trying the SD approach for estimating these costs. Unlike most of the previous labor cost areas, spares management is further broken down into other cost categories. These categories are:

MTA Labor
Investment Spares
Non-Stock Listed
Support Equipment Spares
QEC Kits
Peculiar Consumables
Insurance Spares
Repair of Repairable
Rotable Pools
Engine CLS

MTA Labor (Military Tanker and Airlift Spares Management Labor) costs are derived from Analogy to the same six month period used previously. Its costs are adjusted by changes in work scope as based on technical experience and judgement. These costs account for approximately 4 percent of the total costs.

Investment Spares account for 4 percent of the total cost also. However, these costs are generated by the model. They are based on the quantity of initial spares and encompass the replenishment of condemned spares. The following equations are used for each part:

$$\textbf{Initial spares} = (\text{RTS})\ \text{Qty} + (\text{NRTS})\ \text{Qty} + (\text{SLQ}) \qquad \textbf{(1)}$$

$$\textbf{RTS} = \text{RTS\%} * \text{Base Repair Cycle Time} * \frac{(\text{AFH}/12)}{\text{MTBR}} \qquad \textbf{(2)}$$

$$\textbf{NRTS} = \text{NRTS \%} * \text{DRCT} * \frac{(\text{AFH}/12)}{\text{MTBR}} \qquad \textbf{(3)}$$

$$\textbf{SLQ} = 3.0 * (\text{RTS} + \text{NRTS} + \text{Cond Qty}) + .3 \qquad \textbf{(4)}$$

$$\textbf{Replen Spares} = \text{Condemnation \%} \; \frac{(\text{AFH}/12)}{\text{MTBR}} \qquad \textbf{(5)}$$

Where

RTS Qty = Quantity Repairable This Station (fixable at base level)

NRTS Qty = Quantity Not Repairable This Station (need to be sent away)

SLQ = Safety Level Quantity (calculated at a 96% Confidence Level)

Replen Spares = Replenishment Spares (for items we condemn)

AFH = Annual Flying Hours

MTBR = Mean Time Between Removal (AFH part stays in service)

DRCT = Depot Repair Cycle Time (how long to fix)

Condemnation % = the estimated % of parts broken beyond repair

These calculations are performed for each part that is peculiar to the C-17 and for which Boeing is the designated Inventory Control Point.

Non-Stock Listed Items account for less than .1 percent of the total. Their costs are based on technical experience and judgement. Support Equipment spares, which account for .7 percent of total costs, are a 4 percent factor multiplied by the cumulative cost of fielded support equipment. Engine QEC kits are based on actual costs and quantities directed by the Government. These quantities are based on whole engine spare requirements and lead time to need, based on quantities on hand or on order. At this time, the total projected need is for 21 items, and by FY02, 19 of them will be purchased. The interesting question will be, as the fleet ages will this requirement increase? Moreover, at a cost of $1.5 million a piece, this could be a significant cost driver.

Peculiar Consumable costs are based on a discrete list of parts that are required to provide for the initial consumable spares required for opening a new base or providing additional spares when additional aircraft are assigned to a base. The estimate of the quantities required are currently based on a factor multiplied by expected flight hours. These costs account for over 7 percent of total costs.

Insurance Spares are also based on a discrete list of parts. Their total contribution to costs is less than .5 percent.

The model calculates Repair of Reparables (ROR). The number of repairs is equal to the NRTS quantity, as explained in equation 3. The cost is the actual price per repair for each part. The Rotable Pool costs are also a unit price calculated for each part. These parts are a discrete list of stock items at the supplier depot facility. They are required for meeting specific turn around times. These parts can be considered as a bucket of parts like knobs, dials, wires, screws, etc., a collection is kept on hand so that special orders for each generic knob is not required. The depot will have a bunch on hand, and will re-order in bulk.

Engine Contractor Logistics Support (CLS) accounts for almost 30 percent of the total costs. These costs are repair costs based on a supplier negotiated dollar per cycle rate. It includes costs for transition of the modular replacement center and engine test cell from the Air Force to Boeing.

APPENDIX F

FleetSight Terminology

FleetSight is a graphical interface software package; its elements are organized in folders typical of the “Windows®” environment. The various icons that are routinely used, are identified in figure 65 .

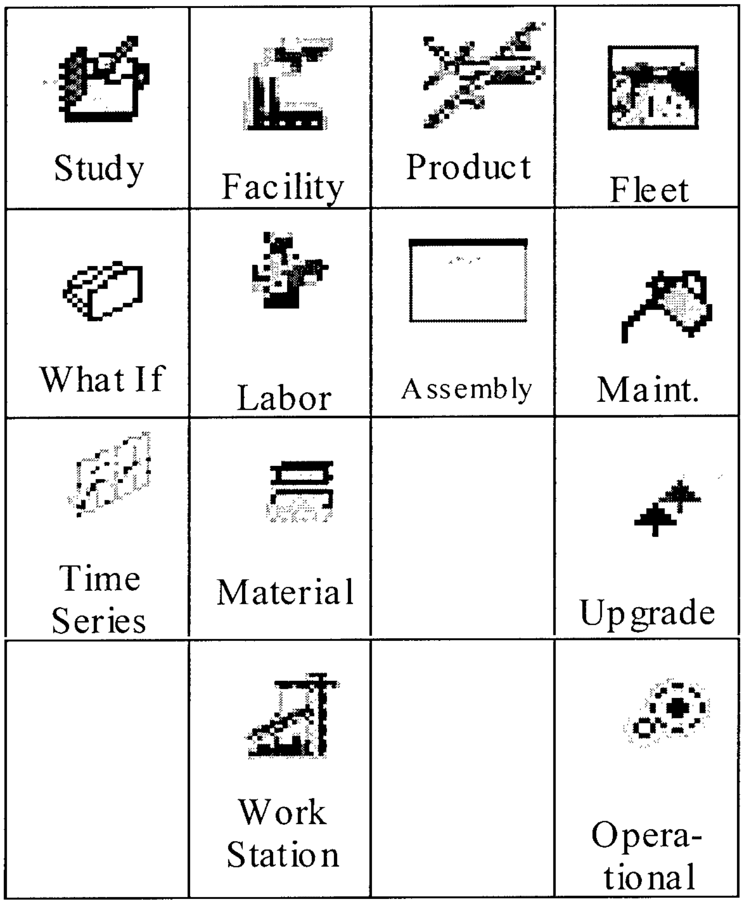
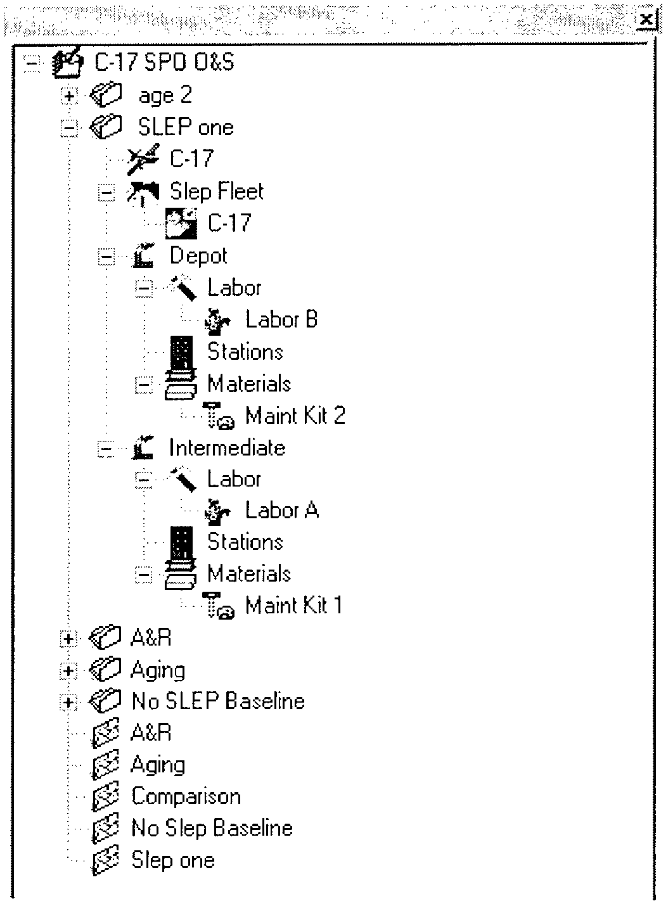


Figure 65. FleetSight Icon Directory

Each of these Icons can be copied and used numerous times. They can be renamed to match whatever structure the modeler is trying to demonstrate. These elements are displayed in the following graphic in the hierarchy, figure 66 , as shown in the FleetSight Project Explorer table.



- C-17 SPO O&S
  - age 2
  - SLEP one
    - C-17
    - Slep Fleet
      - C-17
    - Depot
      - Labor
        - Labor B
      - Stations
      - Materials
        - Maint Kit 2
    - Intermediate
      - Labor
        - Labor A
      - Stations
      - Materials
        - Maint Kit 1
  - A&R
  - Aging
  - No SLEP Baseline
  - A&R
  - Aging
  - Comparison
  - No Slep Baseline
  - Slep one

Figure 66. Example FleetSight Study Map

This table helps the modeler to find the "What-If scenario" they are working with, and explode that folder to examine the detail that is being modeled. In the example shown above in figure 65, under the main folder, named C-17 SPO O&S Costs, are a series of folders. These folders are different "What-IF? Scenarios." It is here that the modeler builds the next level, or incorporates different assumptions to test various aspects of the model. Under each of these What-If folders, is a series of main elements:

Facilities, Products, and Fleets. Under the Facility heading are the resource elements. These resource elements are Labor, Materials, and Work Stations. A Product on the other hand, has only one element, and that is an Assembly. Finally, Fleets, which have Maintenance, Upgrade and Operational tasks.

Facilities – represent a pool of resources. They do not have to be a physical place or location. For instance, in the beginning of the modeling process, one facility will be used; it will represent all resources needed to maintain the C-17. As the behavior is proven, this facility's elements will be broken down into smaller and smaller units, until a level is reached, where added detail does not add new information during a simulation. The various resources that are defined under a Facility are:

Labor – which specifies the number of laborers of each type, their productivity, and the hours worked per day. A global catalog of all labor elements, from the CEO to the gate guard can be input for use in all areas of the model. For each task, these elements are assigned from this global resource pool. This program can track the direct labor by task, or total, to provide the decision-maker with an analysis tool for making labor/productivity/cost tradeoffs.

Stations – specify the number of workstations at this facility, the productivity of this work station, and the size of this station. For instance, if a paint booth was to be defined, the quantity might be one, the productivity might by 90% and the area might be 250,000 square feet. How this comes into play might be, if we find that aircraft need to be painted more often than expected, the decision-maker could experiment with different methods to decrease cycle time. Some of these activities could be: build another facility; increase the productivity (through automation or training); or expand the current facility. The effects of each of these methods and the estimated costs or schedule implications to make the improvements can be modeled quickly.

Materials – specify the supplies needed to perform the various tasks. Not only are initial quantities and costs calculated, but re-supply shipments, cost surcharges, and delivery delays can also be modeled. The cost module can also calculate costs for direct materials.

Products – define a specific weapon system, or subsystem. The product includes the Work Breakdown Structure (WBS), Aging Characteristics, and its Attributes. Products are associated with a fleet. These elements are contained within the Assembly. An Assembly can represent any level of the WBS. For each assembly defined, there is a table that will allow the modeler to assign attributes, quantities, and aging characteristics for that item. For instance, when modeling the front landing gear, one assembly could be the airframe, at a lower level, the whole landing gear assembly, or further broken down into sub assemblies, down to the bolts if needed. If so desired, the entire aircraft could be modeled down to the wire, diode, or bolt level, and each of the aging characteristics modeled. Obviously this is unnecessary for the whole aircraft, but it eventually may be necessary for a component (maybe the MFD, which is an avionics part). The advantage of this modeling technique is that the modeler can start at the general, and slowly build in complexity, as it proves to add additional insight into the dynamics of the system.

Fleets – define where and how the products will be used and maintained. It is at this level that the dynamic behavior becomes apparent. During a simulation, the effect of resource constraints, aging characteristics of products, and maintenance requirements, will demonstrate the predictive dynamic activity, hypothesized to better estimate future costs. When defining a fleet, there are four areas of data to be identified. The first area of data is the quantity of the products, their condition, and their associated components. Secondly, the variables of mission stress, hours of operations and initial failure rate, need to be addressed. Thirdly, the schedule of task events and the resource requirements of those tasks must be identified. Finally, the functions that define Average Condition, Accident Rates, Stress, and Work Backlog, are determined and input. Similar to the Facilities variable listed above, the Fleet section also has items under it that further help to define the dynamic behavior, these include maintenance task requests, upgrade (SLEP) activities, and Operations Schedule. Each of these areas has a separate variable input screen, which allows the modeler to associate tasks, quantities and aging effects based on the other variables already entered.

For instance, if the modeler defined the maintenance task – paint, the labor, materials, and time required to do such a task would be defined. Then, for the fleet, the interval between paint jobs, where the task would be performed, and the effects of aging would be entered (affect of task deferral, increase in frequency due to aging etc.).

Aging. For many of the areas, aging characteristics can be defined. The modeler has four choices for aging impacts. The default is "no impact." If aging has an impact, then, low, moderate, or high can be chosen. Using sensitivity analysis and determining different impacts will help the modeler discover which areas need more detail. For instance, if there is no difference between high and no impact, then the modeler doesn't need to worry about which is correct. However if there are vast differences between high and moderate impact, the modeler will need to do further investigation to determine which is the best indicator of true aging impacts. Aging affects the following areas.

Aging Due to Deferred Work - What will be the impact of delaying maintenance tasks? Will it accelerate or have no impact on aging?

Aging Due To Mission Stress – How will aging be impacted by increases or decreases in the stress?

Aging Impact Due to Work Quality – This is driven by the thought that as quality goes down, aging may increase. There are many factors that influence quality, from lack of training to backlog and rush work.

On the other side of the equation, aging affects other things as well. There may be increased maintenance due to aging. This not only includes having to do tasks more often, but maybe the time to do them also takes longer. For instance, for a paint job, when the plane is new, painting may be just a matter of touch ups, but as it gets older, more of the plane will need to be painted, this will take longer to accomplish. Defining these impacts will help to ensure proper dynamics in the waning life of the plane.

All of these characteristics will come into play at various points in the plane's life. Deciding when to do an upgrade on a component or the product would be one benefit the decision-maker would achieve by having a model that could predict these aging and cost impacts. In addition to knowing when to do the upgrade, knowing how quickly to upgrade the fleet, to have the least detrimental effect on the fleet, would also be important to know. This SD model should provide these answers.

BIBLIOGRAPHY

Advisory Group for Aerospace Research and Development (AGARD), lecture series #84 - "The Theory, Significance, and Prevention of Corrosion in Aircraft," October 1976, Lisbon, Portugal, pg iii (AD-A031642)

Alfeld, Louis, FleetSight^{tm} User Guide, May 1999 Decision Dynamics, inc. SBIR data rights DFARS 252.227-7018, contract No. N66604-98-C-2935

Alfeld, Louis, The System Dynamics Modeling Methodology, Excerpt from unpublished article, Http://www.decisiondynamics.com/systemDynamics/Modelling.htm 1994

Asher, Jay, C-17 Flexible Sustainment, briefing to the Air Force Cost Analysis Improvement Group, December 10, 1997

Asher, Jay, Senior Cost Analysis, ASC/YCFC, Wright-Patterson AFB, OH. Personal interview, Aug 17, 2000

Beals, Everett, "When Should You Trade Your Car?" Industrial Engineering Journal, November 1969

Boeing, C-17 Globemaster III, Technical Description and Planning Guide, Military Transport Aircraft, Long Beach California, August 1996

Bowman, Dan, C-17 Flexible Sustainment Strategic Plan, http://c17mis/ssweb/flex/statplan2.htm, February 1999

Clark, Rolf, System Dynamics and Modeling, Operations Research Society of America, Aug 1990.

Colorado, “Governor’s Task Force on Year 2000 Readiness,” Web Page - Frequently Asked Questions, n.pag. http://www.state.co.us/year2000/faq/faq.htm

Conway, Fred, ***Aircraft Operating and Support (O&S) Cost Model***, facts sheet, Air Force Material Command, n.pag http://www.jast.mil

Cothran, Jerry, Lightning Bolt 99-7, Product Support Partnerships, Acquisition Logistics HQ USAF/ILMY, May 1999

Coyle, R.G. Management System Dynamics, John Wiley & Sons Ltd. May 1978.

Coyle, R.G. System Dynamics Modelling: a Practical Approach, Chapman and Hall, London, UK, 1996

Davis, Col Randy, Phililips, LTC Bill, Vazquez, LTC Bud, “The Phoenix Rises”, Acquisition Review Quarterly, Fall 1997 pgs 411-432

Defense Systems Management College (DSMC), Acquisition Logistics Guide, “Logistics Resources and Tools, Chapter 12.” Third Edition; December 1997.

Department of Defense, Selected Acquisition Report (SAR), (RCS: DD-A&T(Q&A) 823, Program C-17, December 31, 1999

Department of Defense, Defense Acquisition Executive summary (DAES) Report, C-17A program, submission Date 25 July, 2000.

Edwards, Keith, C-17 Flexible Sustainment Overview, road-show slide package of best practices results. September 1999

Forrester, J.W. Industrial Dynamics, MIT Press, Cambridge MA, 1961

Forrester, J.W. Principles of Systems, Write-Allen Press, Cambridge MA, 1968

Forrester, Jay W. Collected Papers of Jay W. Forrester, Wright-Allen Press, Inc, 1975

Forrester, J.W.; Senge, Peter M., "Tests for Building Confidence in System Dynamics Models", TIMS Studies in the Management Sciences, North-Holland Publishing Company, Vol 14, 1980

Foster, N.W.; Hunsaker H.D., The Effect of Aircraft Age and Flying Hours on Maintenance Costs, AFLC Technical Report Nr. 82-099, AFLC/XRS Directorate of Management Science, Deputy Chief of Staff, Plans and Programs, Headquarters, Air Fore Logistics Command, Wright-Patterson AFB OH, June 1983 (AD-A131534)

Gill, Leroy, Class handout, LOGM 569, Life cycle Cost and Reliability, Dept of Systems & Engineering Management, Air Force Institute of Technology, Wright-Patterson AFB OH 1987.

Government Accounting Office (GAO), Military Readiness: Air Transport Capability Falls Short of Requirements, Letter Report, GAO/NSIAD-oo-135, June 22, 2000.

Hale, Robert, “SAF/FM Mission,” excerpt from SAF/FM home page, n. pag. http://saffm.hq.af.mil

Joint Aeronautical Commander’s Group (JACG), Performance-Based Business Environment (PBBE) JACG Flexible Sustainment Guide, 14 August 1997.

Kammerer, Joseph T. “Notes from the Deputy Assistant Secretary, Cost & Economics,” excerpt from unpublished article, n. pag. http://www.saffm.hq.af.mil/fmc/fmc.html

Karnopp, Dean; Rosenberg, Donald, System Dynamcis: A Unified Approach, a Wiley-Interscience Publication, New York NY, 1975

Kirkwood, Craig W. System Dynamics Methods: A Quick Introduction, Apr 1998.

Kissell, M; Schwartz, L, “C-17 Globemaster III Sustainment,” Trainee Research Project ASC/FM Cost & Schedule Data Center, Bldg 14 Rm 143, ACC101.149, July 1999

McClave, James T; Benson, P. George; Sincich, Terry, Statistics for Business and Economics, 7th ed. Prentice Hall, Upper Saddle River NJ 1998.

McLendon, Keith. The Cost Analysis Strategy Assessment Model, facts sheet, US Army Logistics Support Activity, n.pag http://www.logpars.army.mil/casa/fact%sheet.htm Sept 1999

Office of the Secretary of Defense, Cost Analysis Improvement Group (OSD/CAIG), Operating and Support Cost-Estimating Guide, May 1992

Promisel, N.E. presentation to Advisory Group for Aerospace Research and Development (AGARD), "A survey of the Problem" October 1976, Lisbon, Portugal, pgs 1-5 (AD-A031642)

Richmond, Richard, "Systems Thinking: Four Key Questions," High Performance systems, Inc, 1991.

Rolfsen, Bruce, "Report: Two or more wars is too much strain," Air Force Times, a Gannett Newspaper, Military Times Newsweekly Group, Army Times Publishing Co, Springfield VA, Vol. 61 No. 3 pg 20, August 14, 2000

Secretary of the Air Force. Financial Management Cost Analysis Guidance and Procedures, AFI 65-508, Washington, HQ USAF 1 October 1997.

Shelley, Michael, Class Handout, ENVR 642,System Dynamics, Dept of Systems & Engineering Management, Air Force Institute of Technology, Wright-Patterson AFB OH 2000.

Simard, R. "Corrosion Control Maintenance Practices for Canadian Aircraft," lecture notes for presentation to Advisory Group for Aerospace Research and Development (AGARD) Workshop on Requirements for Aircraft Corrosion Control, March 1984, Chapter 8, page 2 (AD-A143 237)

Smith, William D, Welcome to AFTOC Homepage, excerpt from web page. http://aftoc.hill.af.mil/aftocinfo/hlpAboutCAIG.htm. 24 April 2000

Steinlage, Roger, Senior Cost Analysis, AFMC/FMC, Wright-Patterson AFB, OH. Personal interview, May 22, 2000

Walker, David M. "Major Management Challenges and Program Risks" GAO Performance and Accountability Series, GAO/OCG-99-4

White House Report, CYBERNATION: The American Infrastructure in the Information Age. OSTP 1996-1997 Papers, Reports & Publications. Excerpt from web page. http://www.whitehouse.gov/WH/EOP/OSTP/html/cyber2.html

Wolstenholme, Eric F., System Enquiry: a system dynamics approach, John Wiley & Sons Ltd., Baffins Lane, Chichester, West Sussex, England, 1990.

VITA

Capt Christopher D. Purvis obtained a Bachelors of Business Administration degree in Accounting from Gonzaga University in Spokane, Washington, in 1986, and a Masters of Business Administration in Finance from Pepperdine University in Malibu, California in 1997. After pursuing a career in retail for five years, Capt Purvis entered the Air Force in January 1994. After graduation from Officers Training School, he was assigned to the 9th Comptrollers Squadron at Beale AFB, CA. There he served as the Chief - Financial Services Office. In August 1995, he became the Deputy Budget Officer. In July 1996, Capt Purvis was transferred to the C-17 System Program Office, Wright-Patterson AFB, OH, to serve as the Deputy Financial Manager. In August 1999, Capt Purvis entered the Air Force Institute of Technology to pursue a Masters of Science in Systems Acquisition Management. He is a member of American Society of Military Comptrollers, International System Dynamics Society, and Sigma Iota Epsilon (Management Honors Society Fraternity).

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Graduate School of Engineering and Management (AFIT/EN)
2950 P Street, Building 640
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14. ABSTRACT

This research provides a justification for experimenting with system dynamics (SD) for performing Operation and Support Cost estimates. For the C-17 Globemaster III cargo aircraft, these costs could exceed $64 billion dollars. Also, many of our weapon systems are beginning to reach the end of their effective life span, and discussions about the impact of aging, on aircraft, has become a hot topic in the literature.

System Dynamics is a modeling methodology developed in 1958, but never used extensively for cost estimating. SD offers unique capabilities to the cost estimator, including the ability to model causal relationships. This capability offers the cost estimator the ability to estimate O&S costs, spares availability, and mission capable rates, throughout the life span of a weapon system. The primary goal of this thesis endeavor is to prove the applicability of SD for cost estimating by demonstrating the various outputs of a SD model, including fixed and variable costs; secondarily, showing how the results from the SD model can provide a better estimate of future costs, when compared to models in use today.

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