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Life Cycle Cost Modeling and Simulation
to Determine the Economic Service Life of Aging Aircraft

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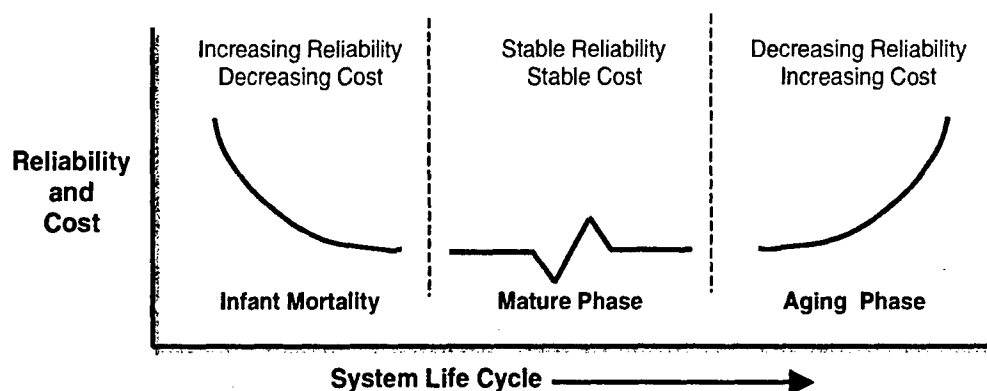**Major K.E. Burns, Ph.D.**
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Abstract   Estimating the point at which the advantages of a modern aircraft alternative exceed the economic burden of maintaining aging aircraft is very complex. This paper presents a cost estimating methodology to forecast costs associated with maintaining an aging aircraft fleet, by combining traditional Operation and Support (O&S) cost elements from a USAF AFI 65-503 CORE model, with expert analysis to quantify maintenance cost growth due to aging. The result is an Economic Service Life (ESL) model that can be used to determine the economic service life of an aircraft. The uncertainties associated with long-range forecasting are considered by combining range estimates within a Monte Carlo simulation for each critical input variable. The model's cost output then becomes a useful fleet management tool to evaluate potential fleet costs while varying annual flying hours and/or aircraft inventory and aids in the evaluation of modernization/ retirement scenarios. Cost output from the model is presented in Constant-Year (CY), Then-Year (TY) and discounted or Net Present Value (NPV) dollars to allow further economic decision analysis.

Background Cost analysts often describe Life Cycle Costs as following a "bathtub" cost curve, which is generally related to the more common reliability bathtub[1] curve. This is defined by a system experiencing early failures during the "burn-in" or "infant mortality" phase due to manufacturing and design defects that are gradually remedied. The next phase is defined by a long period of operation with stable and predictable maintenance costs during the "mature" phase. After the system reaches a certain age, defined by cycles, flying hours, or calendar years, failures and costs begin to rise during the wear-out or aging phase. This later phase is attributed to cumulative component stress, corrosion and general deterioration of the system.

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[1] J.W. Langford, Logistics Principles and Applications, McGraw Hill 1995

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                    |                         |                          |
Increasing Reliability    Stable Reliability      Decreasing Reliability
   Decreasing Cost          Stable Cost              Increasing Cost
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Reliability and Cost

Infant Mortality   **Mature Phase**   **Aging Phase**

System Life Cycle ⟶

Intuitively as an aircraft ages, like health care in people, maintenance costs increase during the aging phase. For aircraft, the onset of "Aging" is defined as when a system reaches its Designed Service Objective[2] (DSO). DSO has been defined by the FAA and various aircraft OEMs as 20,000 cycles, 20,000 flight hours or 20 years, which ever comes first.
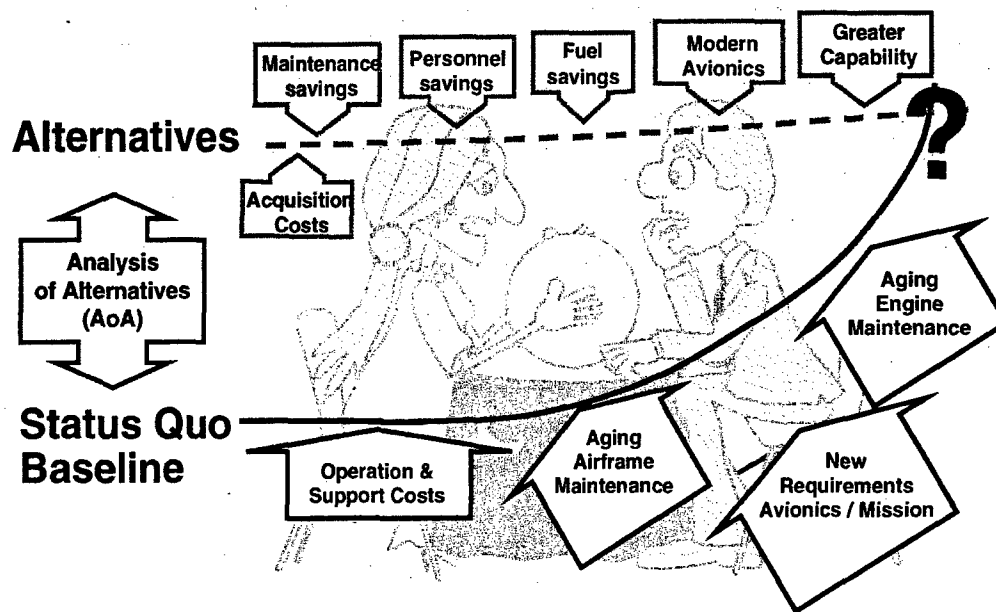
To determine the economic service life of an aging aircraft the most probable "status quo" cost forecast baseline must be compared to the cost baseline of the alternative(s). In order to project costs forty-years into the future, of an aircraft already twenty to forty years old, the analyst must quantify the cost growth of two primary areas: 1) maintenance[3] and 2) modifications. Additionally, the cost baseline of the alternative(s) must also consider cost growth in these same two areas, given their maintenance costs will similarly increase with age.

Traditional Air Force Operating and Support (O&S) cost estimating models have never been tasked to provide a forty-year forecast, especially for an aircraft already forty years old. Tasks of this nature have previously been addressed by merely replicating the current year O&S costs for forty years, and declaring this omission in the Ground Rules and Assumptions. The concept of potentially operating an aircraft for eighty years has previously not been an issue, however many designs from the 1950s are now being studied using modern Durability and Damage Tolerance Analysis (DADTA)[4] techniques. Today with a combination of advanced structural inspection techniques, limited budgets, and aggressive modernization programs, Service Life Extension Programs (SLEP) are being considered for many aircraft. The following overview of recently developed economic service life modeling techniques is offered as an evaluation tool to aid in the decision making process.

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[2] M. Didonato, G. Swears, The Economic Considerations of Operating Post Production Aircraft Beyond Design Service Objectives. Presented at the Aircraft Heavy Maintenance and Upgrade Conference, The Boeing Company, December 4, 1997.

[3] R.C. Rice, Considerations of Fatigue Cracking and Corrosion in the Economic Service Life Assessment of Aging Aircraft, The Battelle Corporation, November 10,

[4] Dr. Hal Burnside, "Flying Longer with Confidence," Technology Today, September 1993, Vol. 14, No.3

Rather than simply answering which alternative(s) has the lowest costs, an Economic Service Life (ESL) model was developed to provide the capability to evaluate multiple and simultaneous "what-if" scenarios. This model would allow changes to both the "status quo" cost baseline as well as each competing alternative. The capability to evaluate operational changes such as the number of aircraft, annual flying hours, personnel to aircraft ratios (crew ratios), as well as changes in estimated maintenance and modification requirements are included. Capability to perform sensitivity analysis by varying both model inputs and the uncertainty associated with each model input was included. The uncertainty of each model input, as well as the model input values themselves, were developed by an Integrated Process Team (IPT) consisting of aircraft industry experts, aircraft operators, and aircraft maintainers who studied and evaluated relevant historical events. Additionally, a thorough review of relevant aging aircraft cost growth studies were evaluated and found to complement the findings and cost output established by this ESL model.
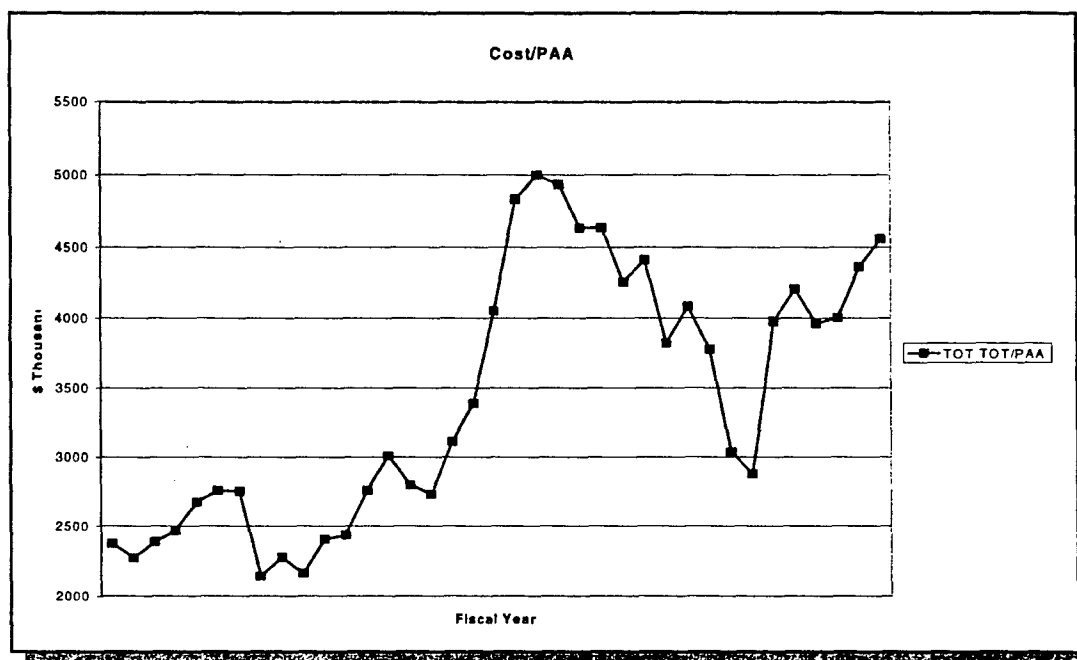
Cost analysts working with aging aircraft recognize the need to account for cost growth as a function of equipment age. Cost growth, even in a Constant Year (CY) dollar analysis is necessary to estimate the real growth in both maintenance and modification requirements.

Data Analysis

Cost forecasting of aging aircraft is a difficult business. Historical data can be hard to come by and "useful/relevant" historical data rarer yet. One must exercise caution however, even when good historical data are obtained. Numerous problems can arise in forecasting aging aircraft costs.

A relatively easy approach is to fit a statistical model, such as a regression model, to the historical data and then project into the future using the fitted model. The analyst makes a number of assumptions when this approach is taken. Perhaps the most basic assumption is that no underlying circumstances surrounding the aircraft system have substantially changed throughout the life of the aircraft and that there will be no significant changes in the future. Conversely, one must be assured that the processes that shaped the historical data will continue into the future.

Often this assumption is not valid. Many changes occur to an aircraft as it ages. A simple example can illustrate this point.
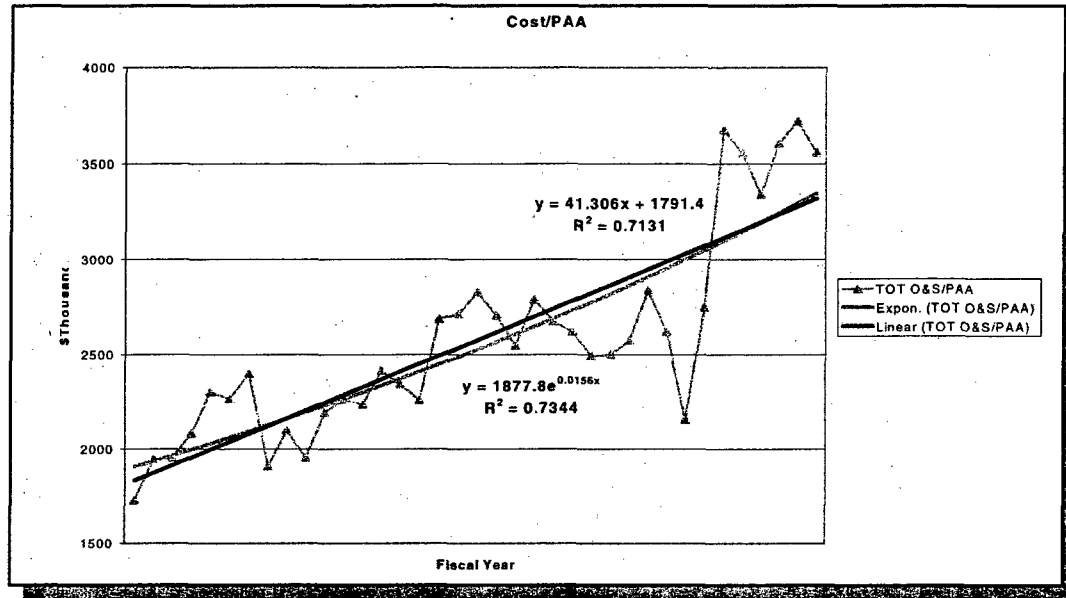
Cost/PAA

In this example, there are at least two problems with the assumption that nothing changed throughout the life of the aircraft. The first is the large "hump" approximately 2/3 into the time span indicated. This "hump" can be attributed to a very substantial modification program. The aircraft may or may not experience a similar modification again. A second problem is with the tremendous single year increase observed directly after the modification program. This increase is attributed, in part, to substantial accounting changes in how costs were attributed to the aircraft system.

If the aforementioned assumption is valid, there are still difficulties to overcome. Even if the analyst limits himself to regression models, there are important choices to make. There are at least two different methods of describing growth rates in historical data: linear and exponential. Often, the fit, as measured by R^2, the coefficient of determination, can be quite close. However, projecting out over long periods of time in the future can result in tremendous differences between a linear growth rate and an exponential growth rate.

As an example, consider the following historical data on an aircraft system.

The R^2 values for the two models are very close. It is not obvious which model fits the historical data better. If the analyst chooses to project one or the other of these models, the choice is an important one; the difference in projecting out these two models is quite

large. For this example, after 20 years the exponential growth projects an annual expenditure 10% higher than the linear growth model. After 40 years, the exponential growth projection is 25% higher.

Finally, finding a metric that is fair to compare over lengthy time intervals also poses difficulties. Analysts often recognize the need for normalizing cost data to compensate for differences in fleet sizes and/or flying hours over time. While this is understandable, it is not always so easy to do. Cost per flying hour is a common metric that is used to track cost trends over time. This metric can be misleading for certain aircraft fleets; this is particularly true for aircraft fleets that have relatively high fixed costs due to low utilization rates.

Again, an example is helpful.

Then Year Dollars	1996	1997	1998	1999	2000
Total Cost $	$1,486,300,237	$1,508,306,188	$1,722,946,676	$2,141,593,513	$2,004,591,495
Total Flying Hours	213,885	209,755	210,118	212,953	175,330
Cost Per Flying Hour $	$6,949.06	$7,190.80	$8,199.90	$10,056.65	$11,433.25

In the above table, note that the total costs increase 35% in four years. However, if the analyst chooses to report cost per flying hour, note that costs increase a staggering 65%!

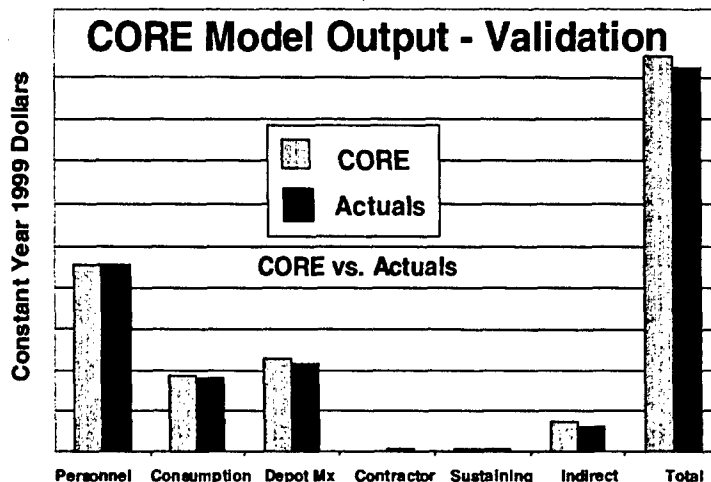These types of issues and other need to be taken into account for any ESL model.

Developing a CORE Model

At the heart of the ESL model is a Cost Oriented Resource Estimating[5] (CORE) model. The CORE model is used by the USAF to develop Operating and Support (O&S) costs estimates. Model output can be used for either budgeting/programming exercises or Life Cycle Cost (LCC) studies. Standard model inputs are obtained from manual look-up tables, which are updated and published annually based on fact-of-life budget realities from the previous year. Additional model inputs in the form of Cost Estimating Relationships (CERs) tailored for the specific Mission Design Series are

CORE Model Output - Validation

CORE vs. Actuals

- CORE
- Actuals

Personnel Consumption Depot Mx Contractor Sustaining Indirect Total

Model output mimicked real world ~3%

required to be developed. CORE model output is provided in Cost Analysis Improvement Group[6] (CAIG) hierarchical cost structure. CAIG structure defines O&S costs as: 1) Mission Personnel, 2) Unit Level Consumption, 3) Intermediate Level Maintenance, 4) Organizational Maintenance, 5) Depot Maintenance, 6) Contractor Support and 7) Indirect support. The USAF CORE model was used primarily for it's capability to provide O&S costs in CAIG format which are directly comparable to cost output from the Air Force Total Ownership Cost (AFTOC) reporting system. Validation of CORE[7] model output against same year AFTOC costs is recommended to insure realistic output and model accuracy. Any significant deviations between model output and the AFTOC / ABIDES "reality check" must be explained.
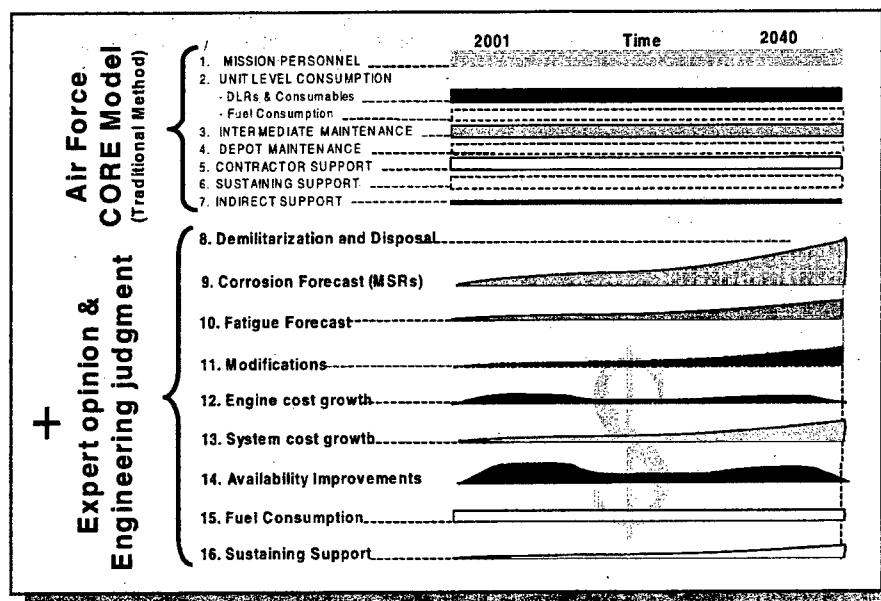
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[5] Air Force Instruction 65-503, Attachment A54-1, 31 October 1994, http://www.saffm.hq.af.mil/

[6] The Air Force Total Ownership Cost (AFTOC) management information system Cost Analysis Improvement Group (CAIG) format identifies all costs (direct and indirect) to both CAIG elements and sub-elements and to the appropriate major system or aircraft Mission Design Series (MDS) by MAJCOM, Numbered Air Force (NAF), Unit (Wing), and Base. https://aftoc.hill.af.mil/aftocmis/default.asp
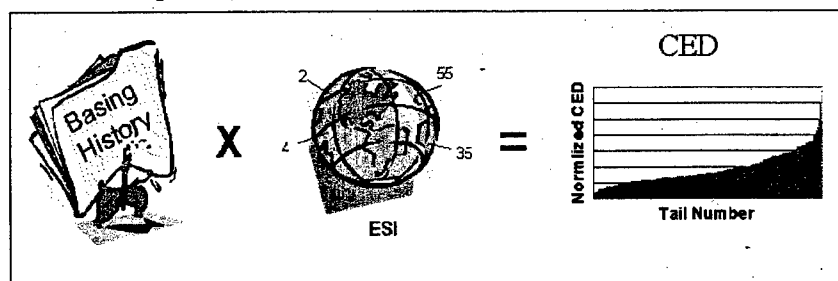
[7] "The Air Force Total Ownership Cost (AFTOC) Management Information System responds to the Secretary of Defense's Year 2000 goal for each Service to develop a system to provide senior leadership '...routine visibility into weapon system life cycle costs.' Additionally, it supports the acquisition community in meeting the Defense Systems Affordability Council direction to the Services' Senior Acquisition Executives to '...establish aggressive, time-phased TOC reduction goals.' By completion of the third phase of AFTOC development, the system will provide detailed cost information on all major weapon systems, inclusive of aircraft, space systems, and missiles. The AFTOC system, when fully implemented, will be the authoritative source across the Air Force for financial, acquisition, and logistics information."
.... SAF/FM

This list of CAIG cost elements is then augmented by the addition of Demilitarization / Disposal costs, plus expert opinion and engineering judgment of "Aging related" costs. Aging maintenance costs were grouped in the major cost elements of: airframe corrosion, airframe fatigue, modifications (both structural and non-structural), engine cost, aircraft systems costs and aircraft availability improvements. An additional cost category identified as "unknown-unknowns" was also added due to the uncertainty of long-range cost forecasting.

Expert Cost Estimates

One example of expert cost estimates used to augment the CORE model is estimating the cost due to Major Structural Repairs (MSRs). MSRs due to corrosion were estimated by first establishing the relationship between an aircraft's Cumulative Environmental Damage (CED) and
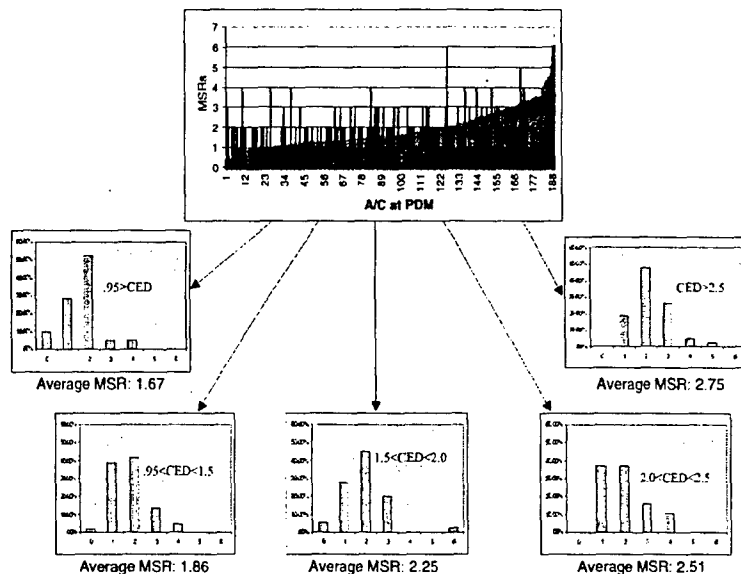

documented MSRs. Each aircraft's basing duration (in days) was multiplied by the Environmental Severity Index[8] (ESI) for the location of the aircraft. The product is an ordinal index, ranking aircraft by their exposure to corrosive environments. To validate the accuracy of this index, a cumulative MSR count based on Programmed Depot Maintenance (PDM) records were matched to specific tail numbers to calibrate the index. This matching was hampered by the relatively small population of reliable maintenance

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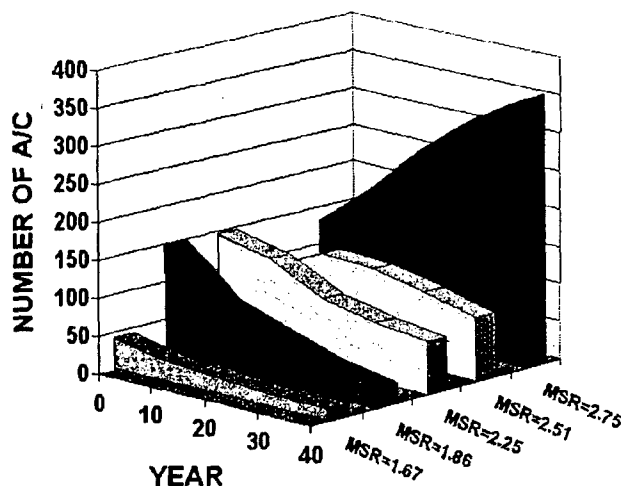[8] Environmental Severity Index produced by NCI

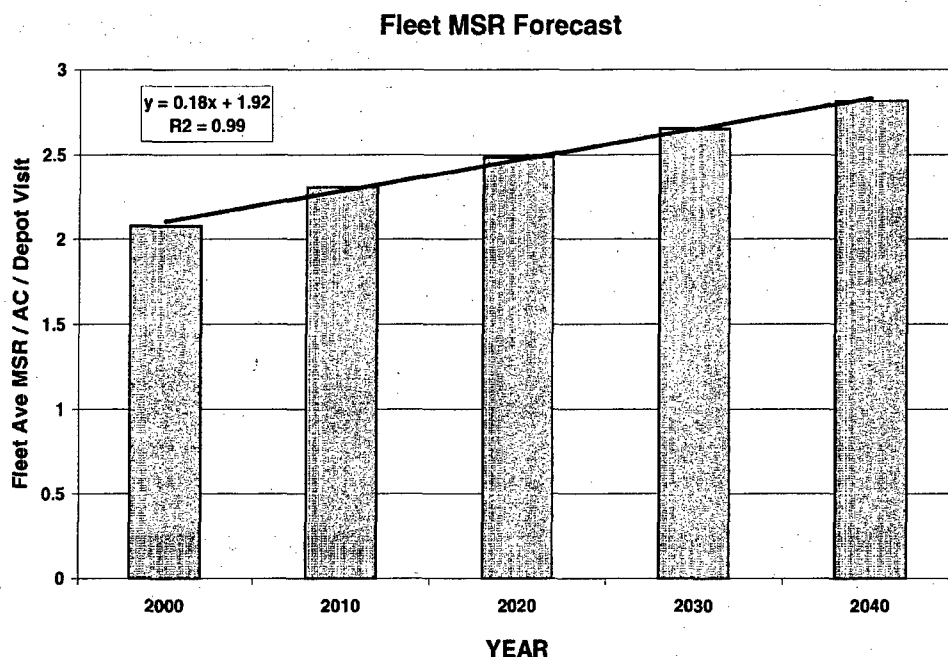(PDM) records. The PDM data available represented only 15 years from only one of three PDM facilities.

With a relationship established between calculated CED and MSRs the cumulative fleet environmental damage was then calculated by advancing the fleet's age forward in time according to the current aircraft basing assignments and forecast aircraft rotation plans. The fleet age was advanced in 10-year increments to account for the CED. Damage due to fatigue for this application is insignificant due to the very low annual utilization.

Average MSR: 1.67

Average MSR: 2.75

Average MSR: 1.86   Average MSR: 2.25   Average MSR: 2.51

Note how the fleet population shifts from a high percentage of the fleet population in a low MSR category (average of 1.67) to a high MSR category (average of 2.75) with the passage of time.

Major Structural Repairs are estimated to increase from approximately 2.0 MSRs per aircraft per depot visit (5 year interval) to approximately 2.75 MSRs per aircraft per depot visit. This maintenance growth rate considers the fact that the MSRs that are now being experienced based on the first forty years of service, will likely not be necessary for another forty years. The repairs performed today use newer technology materials and modern installation practices with corrosion resistive properties.
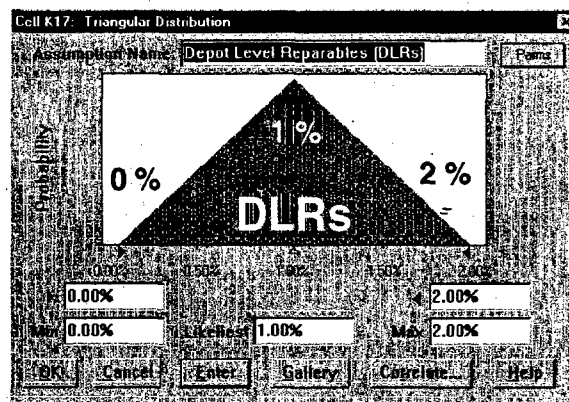
Fleet MSR Forecast

Uncertainty in cost forecasting

From the aforementioned discussions, it is apparent that an analyst has to deal with uncertainty. This is true in dealing with historical data as well as future projections. Anytime an analyst makes a projection, it is important to provide some idea of the variance of that projection. This can often be accomplished by providing a range of estimated costs. A very common way of dealing with this is to use probability distributions to model the uncertainty inherent in forecasting long-term cost estimates.

When estimating the economic service life of an aircraft fleet, the analyst typically must estimate many different costs. Because each of these estimates involves uncertainty, providing an overall ra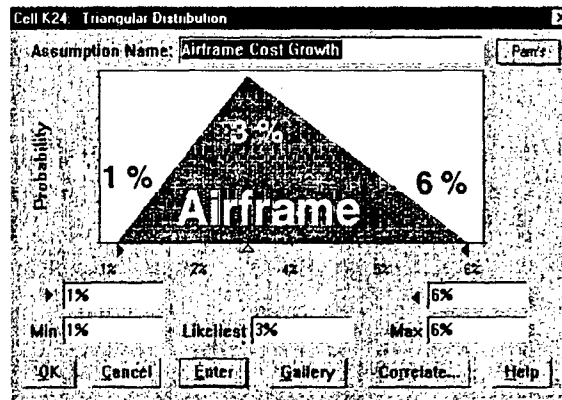nge estimate of the total cost can be difficult. This task is made easier by spreadsheet tools that allow the analyst to take advantage of Monte Carlo techniques. Monte Carlo can be described as a method for estimating the answer to a problem by means of an experiment with random numbers[9]. The idea is to simultaneously vary several different inputs in a model to obtain the final output; this process is repeated many times to produce a distribution of final outputs. The average and variance of this distribution can be used to make a range estimate of the total cost.
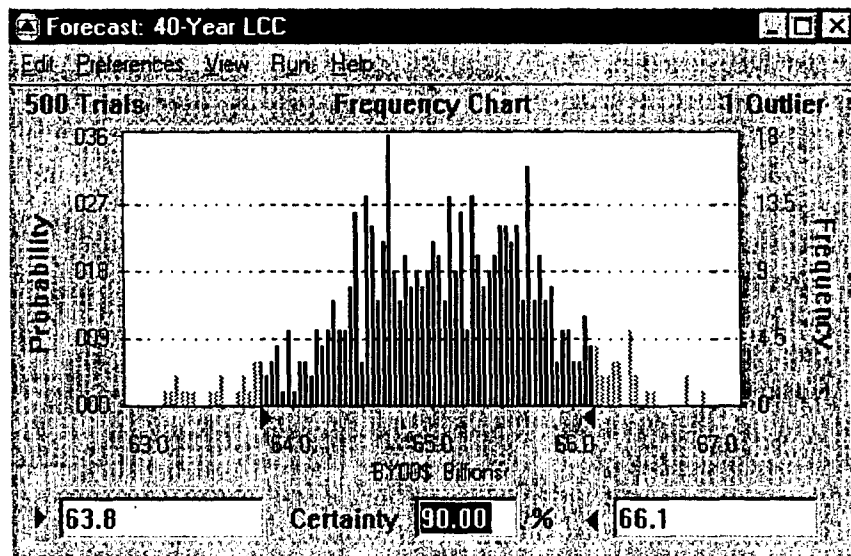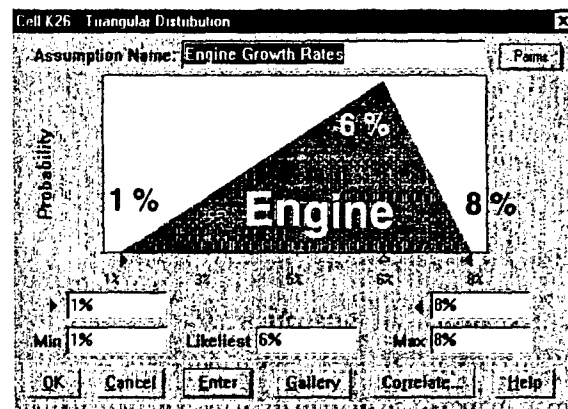

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[9] E. S. Quade ed., An Appreciation of Analysis for Military Decisions, 1966

Sample input variables for Depot Level Repairables (DLRs), airframe maintenance, and engine maintenance are presented in terms of annual cost growth. Each input variable identifies the minimum, maximum and most likely values.

When all of the inputs are varied simultaneously, an overall cost estimate of the entire system is produced. Performing this operation numerous times produces a distribution of final life cycle cost estimates. This distribution allows the analyst to produce range estimates of the overall life cycle cost, allowing for the inherent uncertainty in the system.
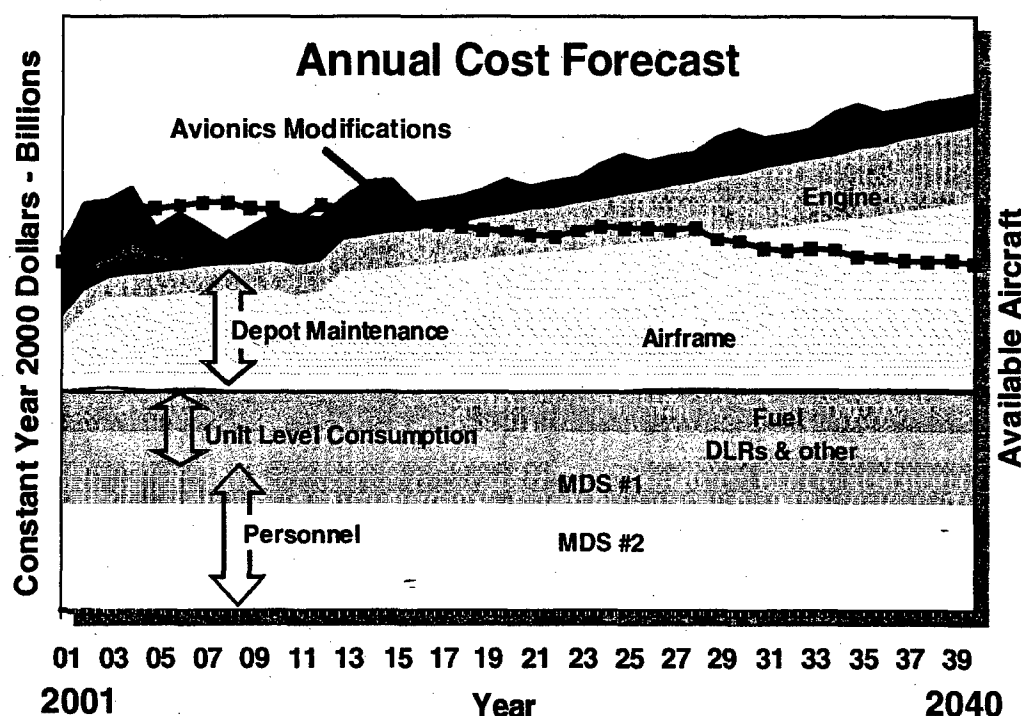
A sample output from the ESL model is included below.
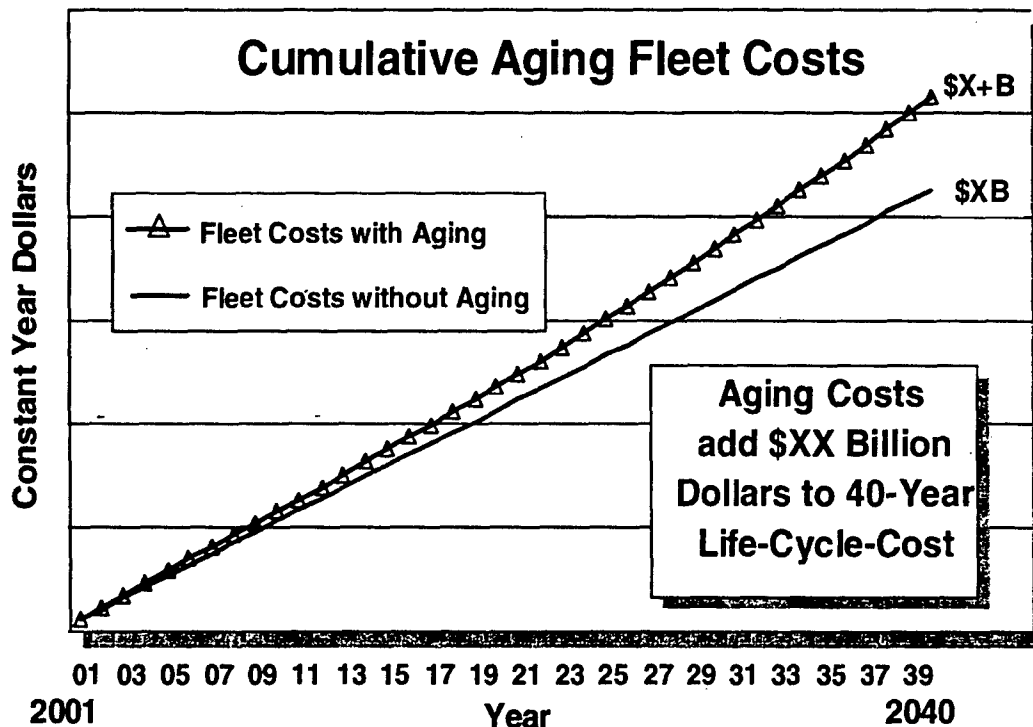
Economic Analysis

By definition an analysis of alternatives (AoA) is an analytical comparison of the operational effectiveness and cost of proposed materiel solutions to shortfalls in operational capability[10]. In the case of deciding whether or not to procure a new fleet of aircraft, an AoA requires comparing the costs of the new fleet to that of operating the current fleet. In the case of replacing a large fleet of expensive aircraft, this process will likely take place over many years. The result of this is that it would be helpful to have a tool that allows the analyst to perform several "what if" scenarios. These scenarios would naturally involve changing the number of aircraft and flying hours in the old and new fleets over time.

An AoA requires a cost model that includes the ability to model research and development costs, procurement costs, operations and support costs, and disposal costs. Traditional Air Force cost modeling (USAF AFI 65-503 CORE) can help in this respect. However, because of the need to compare costs over time, it is necessary to have a model that takes into account aging aircraft effects.
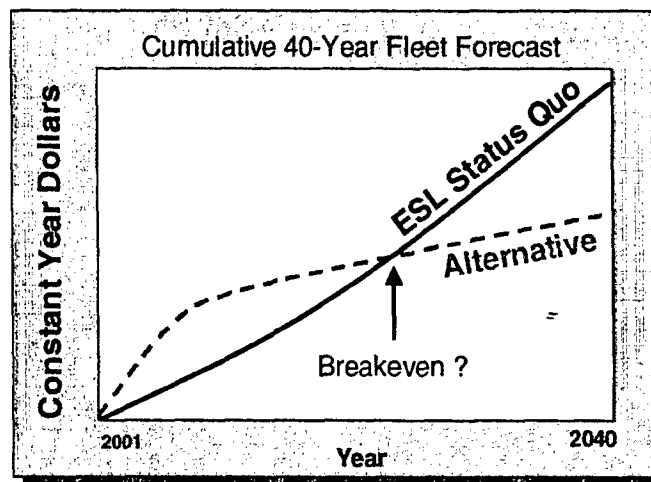

Taking all of the above observations into account, one of the goals of an AoA is to determine the economic service life of the current aircraft fleet. To determine the economic service life of an aging aircraft fleet, the model must be able to project the increasing costs of the current fleet and then compare that to the costs of a potential new fleet. The following two graphs depict what type of output the ESL model is capable of producing.

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[10] Office of Aerospace Studies, AoA Handbook, June 2000

Cumulative Aging Fleet Costs

The ESL model combines the many elements that a cost analyst needs to help answer the complicated question of when an aircraft has reached its economic service life. This model will be extremely useful to Air Force analysts who are conducting AoAs on aging aircraft fleets.

One of the strengths of this ESL model outlined herein is the built-in flexibility. As new information becomes available over time, the analyst can update the cost estimates with the very latest information. One of the most important things to realize in estimating costs over a long period of time is that the estimates will certainly change with time. This model gives the analyst that flexibility to refine estimates as new information becomes available.

The bottom line is that this tool allows the analyst to provide the best information available to the decision maker in a useable format.