Risk Analysis Approach to Transport Aircraft Technology Assessment

Robert G. Batson*
University of Alabama, Tuscaloosa, Alabama
and
Robert M. Love†
Lockheed-Georgia Company, Marietta, Georgia

The need to quantify uncertainty in the assessment of the costs and benefits of potential applications of advanced aircraft technology is recognized. In this paper, we present a Monte Carlo simulation approach that was successfully implemented in a recent USAF-sponsored technology assessment study. Details are given of the math model used to represent the sensitivity of aircraft performance and fleet cost-effectiveness to technology variations. The uncertainty analysis process is described, and results from the study are presented. Advantages of including risk analysis in all conceptual design studies are discussed.

Nomenclature

AAP = aircraft average productivity, ton · n.mi./day
ACMA = advanced civil/military aircraft
ACP = aircraft cycle productivity, ton · n.mi./day
APOE = aerial port of embarkation
AUWT = airframe unit weight, lb
BUY = airframe acquisition quantity
CD = cruise distance, n.mi.
CFT = cycle flight time, h
CGT = cycle ground time, h
CS = cruise speed, n.mi./h
CT = closure time, days
CTT = cycle taxi time, h
D_i = distance of leg i in deployment network, n.mi.
$\mathrm{ED}_{\mathrm{cost}}$ = total engine development cost, 1982 $
$\mathrm{EP}_{\mathrm{cost}}$ = total engine production cost, 1982 $
ETA = throttle setting (cruise)
FBLK = block fuel weight, lb
FCRU = cruise fuel weight, lb
FF = fleet fuel, lb
FOM = figure of merit
FS = fleet size
LCC = life cycle cost, 1982 $
L/D = cruise lift-to-drag ratio
Mach = cruise Mach number
MF = mission fuel, lb
MM/FHD = maintenance man-hours/flight hour, deployment
MM/FHP = maintenance man-hours/flight hour, peacetime
MOB = maintenance at home base only
MT = maintenance downtime, h
N = number of engines per aircraft
O&S = operations and support cost, 1982 $
PER = percent of maintenance man-hours nondeferrable until the end of the deployment
PERT = program evaluation and review procedure
QTY = engine acquisition quantity
R = range, n.mi.
RF = reserve fuel weight, lb
RFP = request for proposal
RLUT = refueling, loading, and unloading time, h
sfc = cruise specific fuel consumption, lb/h/lb
SIS = spares and initial support (excluding engine spares) cost, 1982 $
TAC = total acquisition cost, 1982 $
TC_x = total airframe cost for x units, 1982 $
TCT = total cycle time, h
TEC = total engine cost, 1982 $
$\mathrm{THR}_{\mathrm{max}}$ = maximum thrust per engine (static sea level), lb
THRUST = thrust per engine required in mission sizing routine, lb
TT = total tonnage, tons
UR = utilization rate, h/day
W_{E} = weight empty, lb
W_{P} = weight of the payload, lb
W_{ramp} = ramp weight, lb
X_1 = avionics system weight, lb $\times 10^3$
X_8 = electrical system weight, lb $\times 10^3$

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*Associate Professor of Industrial Engineering, College of Engineering.

†Senior Operations Research Analyst, Systems Engineering Department.

Introduction

TECHNOLOGY assessment has become an important activity for the U.S. Department of Defense (DOD) as technologies proliferate and recognition is gained that not every development program can be funded. Technology assessment may be defined as an unbiased, systematic approach to estimating technology benefit, development cost, and schedule and to establishing the uncertainty associated with these estimates.

The classical approach to technology assessment for transport aircraft has been to fix a deployment scenario, design a baseline aircraft using current technology, design a set of aircraft utilizing various technology mixes, and then estimate (on a deterministic basis) the figures of merit (e.g., performance, fleet size, life cycle cost) associated with each "paper airplane." Comparing a figure of merit for the baseline with that for the "technology-improved" airplane yields a measure of technology benefit. Estimates of technology development time and cost are usually no more sophisticated than Gantt charts with dollars attached to each activity. Uncertainty in these estimates, if addressed at all, is usually an afterthought, using hard-to-interpret qualitative measures such as low-medium-high risk.

Risk analysis is a subdiscipline of systems engineering (see MIL-STD 499A, USAF), whose objective is the identification, quantification, and reduction of the uncertainty in a system. Risk analysis is distinguishable from other systems analysis approaches by its philosophy and methodology. The philosophy of risk analysis is that uncertainty concerning new technology may best be quantified by 1) eliciting the expert judgment of experienced engineers in the various aerospace disciplines and 2) synthesizing these uncertainty assessments via mathematical models to ascertain their combined, systemwide impact. The methodology of risk analysis consists of techniques for structuring descriptions of potential problems, encoding uncertainty estimates as probabilities, and merging these probabilities via methods such as PERT and Monte Carlo simulation. Quantitative approaches to risk analysis evolved during the 1970's[1,2] and have attained important recognition in the 1980's, as evidenced by recent USAF requests for proposals (RFP) and two DOD publications.[3,4]

Lockheed-Georgia Company, in response to the Technology Assessment Task in the 1981 RFP for the study of "Technology Alternatives for Airlift Deployment (TAFAD),"[5] proposed a method for integrating quantitative risk analysis into the conceptual design process. In particular, Lockheed[6] proposed two risk analysis methods, uncertainty analysis and time-cost trade-off analysis, to quantify the uncertainty in technology benefit and technology development estimates, respectively. The purpose of this paper is to describe the uncertainty analysis methodology and to illustrate the results of its use in the TAFAD study. The time-cost tradeoff analysis will be reported elsewhere.

In this paper, we present the risk analysis model used in TAFAD, the analytical procedure to implement the model, and representative computational findings. In each discussion, we draw a parallel between the classical (deterministic) methods of technology benefit assessment and the modern (probabilistic) methods employed in the TAFAD study.

The Mathematical Model

This section describes the mathematical model AFCUE (airlift fleet cost-effectiveness uncertainty estimator), which was developed specifically for the TAFAD study. The model is simply a set of interrelated equations that represent the sequence of variable transformations in the conceptual transport design process. The dynamics of using the model to convert probability distributions on technical variables (for a given design) into probability distributions on figures of merit is explained in the next section.

AFCUE did not replace the established conceptual design steps at Lockheed-Georgia. Rather, AFCUE represents these steps at a less detailed level with the objective of capturing only the significant sensitivity relationships. For each "paper airplane" to be evaluated, the equations in AFCUE are calibrated to match the performance, effectiveness, and cost values that have been calculated for that airplane by the more complex, deterministic conceptual design procedure. The calibration process is explained in the following subsection, followed by descriptions of the performance, effectiveness, and cost equations used in AFCUE.

Sizing, Costing, and Calibration Prior to Use of AFCUE

Sizing a study aircraft to match a mission is accomplished by Lockheed-Georgia's generalized aircraft sizing and performance (GASP) program (Fig. 1). GASP controls the interaction of modules provided by the various technical disciplines and the inputs provided for the specific configuration. GASP then generates a component buildup of drag and weight and integrates these results into total aircraft drag and weight. Propulsion system size is defined by matching cruise thrust requirements or, if required, by mismatching these requirements to oversize the engine at cruise in order to provide additional takeoff thrust. The capability of sizing a configuration with a fixed-size propulsion system is also available. The aircraft size required for the mission is defined by an automated interactive process. GASP has been used in a number of studies to synthesize aircraft for design variables such as wing loading, aspect ratio, cruise power setting, Mach number, range, payload, and field performance, with the objective of identifying aircraft optimized to figures of merit such as minimum direct operating cost, gross weight, acquisition cost, fuel usage, or life cycle cost.

An optimized aircraft is passed on to the systems analysis group for fleet sizing and cost analysis. The results of these detailed, deterministic analyses were needed prior to the use of AFCUE in the TAFAD study in order to obtain calibration constants for the equations in AFCUE. Two types of functional relationships were used to obtain satisfactory equations for use in AFCUE:

Additive	$Y = f(X_1, X_2, \ldots, X_n) + C$
Multiplicative	$Y = C * f(X_1, X_2, \ldots, X_n)$

where f represents a "general" relationship known to hold between Y and the X_i. The calibration constant C ensures that if the design-specific deterministic values for each X_i are entered, the nominal value for Y will result.

Aircraft Performance Estimates

Seven technical variables are the independent variables in AFCUE: airframe unit weight (AUWT), cruise Mach number, cruise specific fuel consumption (sfc), weight empty, cruise lift-to-drag ratio L/D, avionics system weight X_1 and electrical system weight X_8. From these, five other technical variables are derived: maximum thrust per engine at static sea level THR_{max}, maintenance man-hours per flight hour—peacetime (MM/FHP), maintenance man-hours per flight hour—deployment (MM/FHD), ramp weight W_{ramp}, and thrust per engine required in mission sizing routine.

The range and fuel equations used in AFCUE are

$$\mathrm{FBLK} = \mathrm{FCRU} + (\text{fuel to 1500 ft}) + (\text{fuel 1500 ft to alt.}) \qquad (1)$$

$$\mathrm{MF} = \mathrm{FBLK} + \mathrm{RF} \qquad (2)$$

$$\mathrm{CD} = C * \left\{ \frac{\mathrm{MACH} * L/D}{\mathrm{sfc}} \right\} * \ln \left\{ \frac{W_E + W_P + \mathrm{FCRU} + \mathrm{RF}}{W_E + W_P + \mathrm{RF}} \right\} \qquad (3)$$

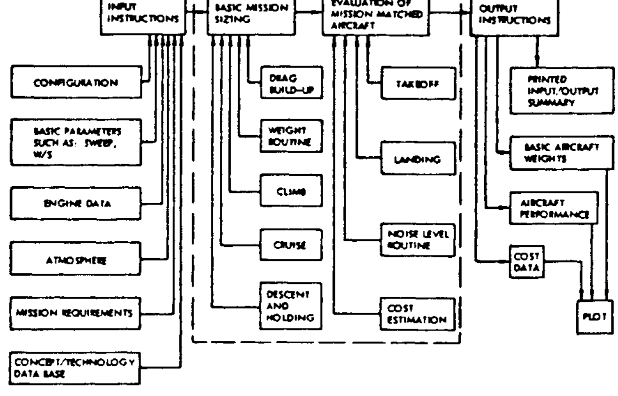

Fig. 1 Generalized aircraft sizing program.

$$R = CD + (\text{distance to 1500 ft}) + (\text{distance 1500 ft to alt.}) \quad (4)$$

Fleet Effectiveness Equations

The mission deployment network used in the technology assessment is illustrated in Fig. 2. The Army units to be deployed within a 30 day closure time total roughly 446,000 tons. Because the closure time and total load are fixed, the productivity of any fleet of conceptual airlifters is the same. The fleet size, then, becomes the key effectiveness measure. The productivity of individual airplanes in the deployment is inversely proportional to the fleet size. The fleet effectiveness equations presented below link the technical and performance values for a given design with the fleet size and fleet fuel burned.

The steps leading to a fleet size are now described. The formula for cycle flight time assumes a half-hour ascent/descent penalty at each of three bases in a route is

$$CFT = \sum_{i=1}^{n} [(0.5) + (D_i/CS)] \quad (5)$$

where CFT is the cycle flight time and D_i the distance for leg i.

Maintenance is assumed to be performed only at the home base (MOB) by nine two-man crews. Some percentage (PER) of the total maintenance man-hours is of such a nature that it cannot be deferred until the end of the deployment. Hence, maintenance downtime at the home base per cycle is given by

$$MT = (MM/FHD/18) * PER * CFT \quad (6)$$

Maintenance man-hours per flight hour for the employment (MM/FHD) are obtained by adjusting the peacetime rate MM/FHP to a wartime rate using the following equation derived by Lockheed maintainability engineers:

$$MM/FHD = \left[MM/FHP * (12/3.33)^{-0.8631}\right] + 3.0 \quad (7)$$

MM/FHP is estimated by parametric relationships, not shown here, that depend on weight estimates and technology complexity factors.

Cycle ground time (CGT) is dependent on the maintenance and taxi times and refueling. The taxi time is assumed to be 13 min/stop. We assume that refueling but not maintenance is performed at each stop concurrently with loading and unloading operations. Time for refueling/loading/unloading at a base depends on what operations occur at that base. At the MOB, loading is the constraining activity; at the en route base, the only activity is refueling; finally, at the DOB, unloading is the constraining activity. The equations for the cycle ground time and total cycle time are

$$CGT = MT + CTT + RLUT \quad (8)$$

$$TCT = CFT + CGT \quad (9)$$

The utilization rate (UR) is the number of hours/day that an aircraft is actually performing its mission.

$$UR = (CFT/TCT) * 24 \quad (10)$$

The steady-state equation used for individual aircraft productivity flying a given cycle is

$$ACP = (PL * UR)/CFT \quad (11)$$

where the payload is set by the critical leg distance in the delivery phase of the cycle. Since the total number of cycles flown by the fleet is divided between six routes, the average productivity (AAP) for an aircraft in the fleet is found by taking a weighted average of the productivities achieved on the routes. The weights are the fraction of total tonnage delivered over the respective routes. The formula for fleet size is then

$$FS = TT/(CT * AAP) \quad (12)$$

Fuel burned on a cycle is built up by calculating the fuel per leg, using a version of Eq. (3), and adding. The number of cycles flown on a given route may be estimated by dividing the total tons flown over that route by an average payload. The fleet fuel (FF) for the deployment is then the sum of the fuel used to deliver the loads over the respective routes.

Cost Estimating Equations

Life cycle cost (LCC) models are built up through a series of equations of the form $Y = f(X_1, X_2, \ldots, X_n)$, where Y is an element of cost (e.g., airframe cost) and the X_is are predictor variables (e.g., weight, state of the art, speed). LCC is the sum of the total acquisition cost (TAC) and the operations and support cost (O&S).

The O&S cost is calculated using Lockheed-Georgia's implementation of the U.S. Air Force CORE model.[7] Two of the seven independent variables in AFCUE (avionics system weight X_1 and electrical system weight X_8) are input to this model, as well as derived distributions for the operating weight, thrust, and fleet size. Unlike the situation with O&S cost estimating, airframe manufacturers use various (often more than one) acquisition cost models. An acquisition cost model based on the Rand equations was created for this risk analysis. The total acquisition cost is calculated in AFCUE by estimating the costs of the total airframe and engine and then

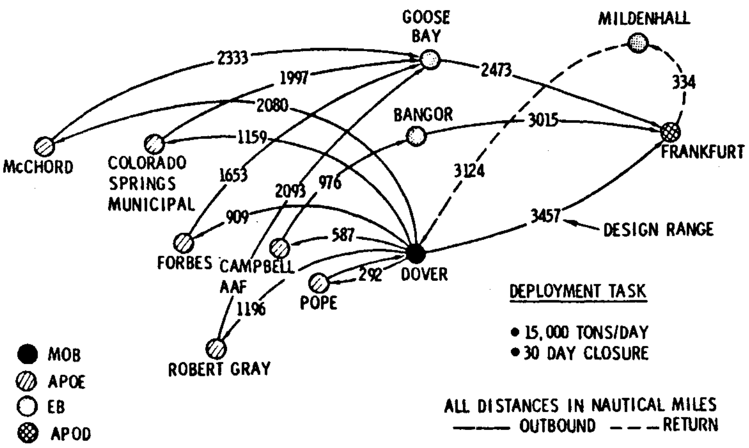

Fig. 2 Mission route structure.

adding to these the cost of spares and initial support, as

$$\mathrm{TAC} = \mathrm{TC}_{\mathrm{BUY}} + \mathrm{TEC} + \mathrm{SIS} \tag{13}$$

The following paragraphs describe the derivation of each term in Eq. (13). A single equation (with a learning curve) is used to estimate the total airframe cost. The equation is an updated version of

$$\mathrm{TC}_{100} = 24.16(\mathrm{AUWT})^{0.96}, \quad 1973\ \$ \tag{14}$$

which appears in Ref. 8. The variable AUWT is the airframe unit weight, also known as AMPR weight. This equation was developed via regression analysis on data from production programs for five large, subsonic aircraft: B-52, C-5, C-130, C-133, and KC-135.

To convert the preceding equation to FY 1982 dollars, 1973 engineering, tooling, manufacturing, and quality control labor rates were compared with the 1982 rates. The increases were very uniform, ranging from a factor of 2.29–2.63 of the 1973 rates. On a 250 aircraft program, the percentage of hours devoted to the four categories is 0.231, 0.159, 0.545, and 0.065, respectively. The weighted average of increase factors gave an average increase in labor rates from 1973 to 1982 of 2.423 for aerospace workers. Therefore, the equation for the airframe cost for 100 units is

$$\mathrm{TC}_{100} = (2.423)(24.16)(\mathrm{AUWT})^{0.96}$$
$$= 58.54(AUWT)^{0.96}, \quad 1982\ \$ \tag{15}$$

To determine the total number of aircraft to be procured (BUY), the formula BUY = FS/0.85 is used to conform with TAFAD study rules. All fleet sizes calculated for the scenario described above fell in the range of 100–200 units. In AFCUE, we assume the learning curve between 100 and 200 units has a slope of 1.4 (exponent = 0.490), which is consistent with historical data. This slope enables the cost for a first production unit to be calculated (TC_1) and is used to obtain an equation for calculating the airframe cost for quantities near 200. For example, if AUWT = 238,976 and BUY = 200 units, then the steps are

$$\mathrm{TC}_{100} = 58.54(238976)^{0.96} = 8{,}524{,}577$$
$$\mathrm{TC}_1 = \mathrm{TC}_{100}/(100)^{0.49} = 892{,}633$$
$$\mathrm{TC}_{200} = \mathrm{TC}_1(200)^{0.49} = 11{,}972{,}301 \tag{15}$$

To calculate the total engine cost, two equations are used: one for the total engine development cost ($\mathrm{ED}_{\mathrm{cost}}$) and one for the cumulative engine production cost ($\mathrm{EP}_{\mathrm{cost}}$). The costs are from the "standard model" developed by Nelson and Timson[9] at Rand. The independent variables are the same for both equations: cruise Mach number, quantity of engines acquired (QTY), and maximum thrust per engine ($\mathrm{THR}_{\mathrm{max}}$). The equations used in AFCUE to derive the latter two values are

$$\mathrm{QTY} = (1.25) * \mathrm{N} * \mathrm{BUY} \tag{16}$$

$$\mathrm{THR}_{\mathrm{max}} = \mathrm{THRUST}/\mathrm{ETA} \tag{17}$$

The use of a 25% ratio of spares to operational engines is a TAFAD study rule and is consistent with DODI 4230.4, "Standard Method for Computation of Spare Engine Procurement Requirements."

Combining the equations for $\mathrm{ED}_{\mathrm{cost}}$ and $\mathrm{EP}_{\mathrm{cost}}$ and taking the antilog of each side allows the following equation for total engine cost (TEC) to be written:

$$\mathrm{TEC} = 2.2199\,(\mathrm{Mach})^{1.2867}(\mathrm{QTY})^{0.08146}(\mathrm{THR}_{\mathrm{max}})^{0.39884}$$
$$+ 0.000036(\mathrm{Mach})^{0.21462}(\mathrm{QTY})^{0.84172}$$
$$\times(\mathrm{THR}_{\mathrm{max}})^{0.84755}, 1973\ \$ \tag{18}$$

To convert Eq. (18) to 1982 dollars, an inflation index of 2.675 for aircraft engines was obtained from Ref. 10.

Finally, the spares and initial support cost (SIS) is a deterministic variable in AFCUE equal to the value calculated in the GASP sizing process adjusted to delete the spare engine cost, which was already accounted for in TEC.

Simulation Procedure and Example

The dynamic process of using AFCUE to convert probability distributions on technical variables into probability distributions on fleet figures of merit is illustrated by the "data flows" in Fig. 3. The ovals numbered 1.0–5.0 are intermediate conversion subprocesses that employ Monte Carlo uncertainty analysis. Rectangular boxes are data stores, either for input to one of the subprocesses or for storage of intermediate output. The arrows represent data transfer. For example, subprocess 4.0 (Quantify uncertainty in cost estimates) uses three data sources: USAF planning factors, distributions on technical variables, and distributions on deployment effectiveness measures. Subprocess 4.0 stores data (distributions) on various costs for the concept under evaluation. It also passes data on to subprocess 5.0.

ACMA Concept

The use of the AFCUE simulation process is illustrated and example results are shown for one of the TAFAD study concepts, the advanced civil/military aircraft (ACMA), sized to match the mission shown previously in Fig. 2. The design objective for the ACMA concept was to provide a configuration typical of current Air Force airlifters. The data base required to develop this type configuration is available and well understood. Therefore, the ACMA concept is used as a comparison baseline when determining the relative benefits of 1) applying different combinations of advanced technologies and 2) other more innovative concepts.

A conventional, high-wing, nose-loading airlifter configuration is used for this concept, as shown in Fig. 4. This configuration was optimized using GASP to minimize the civil direct operation cost. This optimization objective is used to enhance the desirability of the ACMA concept as a civil freighter. The obvious reason for improving the civil desirability of the ACMA concept is that the greater the number of aircraft purchased by commercial carriers, the fewer the number of aircraft required to be purchased by the military for its organic fleet. This reasoning is based on the assumption that each civil aircraft purchased is available for the civil reserve air fleet.

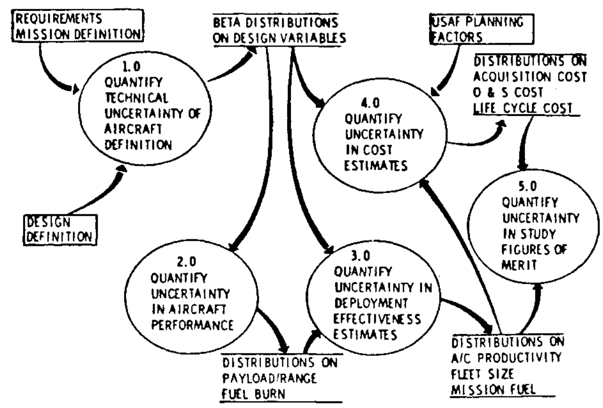

Fig. 3 Data flow diagram for airlift fleet cost-effectiveness uncertainty estimator (AFCUE) model.

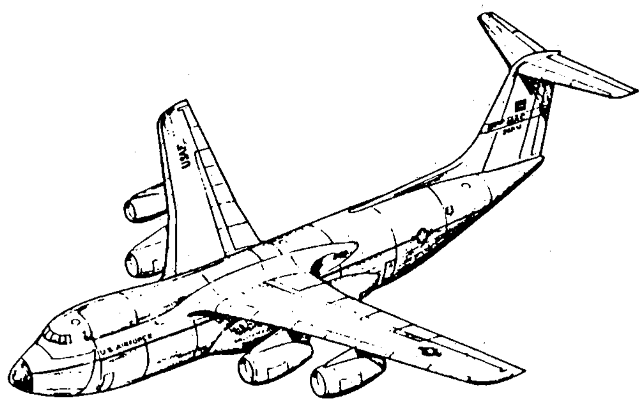

Fig. 4 ACMA conventional configuration.

Uncertainty Analysis Process

Each concept/technology combination in the study was analyzed for uncertainty using the mathematical model AFCUE described above. We will describe the steps in the analysis process using a hypothetical example. Each of the seven input (technical) variables were evaluated by the appropriate discipline for uncertainty in their *actual* value should the airplane concept become a real program. The method used to capture the uncertainty in these input design variables is called subjective probability encoding.[11,12] The method used at Lockheed employs the four-part questionnaire shown in Fig. 5 to convert four responses into a beta probability distribution. The method is due to Stowell[13] and is similar to techniques employed by Rand[14] and the U.S. Navy.[15,16]

Historically, beta distributions have been the most widely used continuous probability densities for quantifying subjective probability (degree of belief). From Fig. 5, the "most likely" value is the point estimate used in the deterministic design calculations. The engineer is free to set the lowest and highest possible values for the mature level of the variable, as well as his degree of confidence in the most likely. His responses are converted to a beta distribution with shape parameters and endpoints that best match his uncertainty assessment.

Figure 6 shows the beta distributions of the four design variables input to the calculation of range in AFCUE [Eq. (3)]. These data are interesting, but the real payoff comes from synthesizing these uncertainty assessments of each discipline into an uncertainty in aircraft range at a given payload.

The Monte Carlo simulation process illustrated in Fig. 7 is used to perform the uncertainty analysis. For example, to generate a sample distribution on range at a given payload, Eq. (3) is used to provide a functional relationship between the range and the probability distributions derived from the questionnaires. The relationship is calibrated for each design by substituting the "most likely" values of the input variables and solving for the multiplicative constant that yields the design point range value.

The range uncertainty analysis is performed for the X-, Y-, and Z-point payloads. As a result, a distribution of the range at each of these three payload conditions is developed. This allows a 99% tolerance interval of the range to be drawn. By connecting the endpoints of these three intervals, minimum to minimum and maximum to maximum, a tolerance band is formed, as shown in Fig. 8. The tolerance interval may be read horizontally (select a payload and determine the uncertainty in maximum payload for that distance).

For each aerial port of embarkation (APOE), a frequency distribution is used to describe the loads at that location based upon the types of Army units there. As shown in Fig. 9, we use the Monte Carlo process to compare this distribution with the uncertainty band on the payload-range curve at the critical leg distance. In the course of the simulation, the payload carried is the minimum of the two randomly sampled variables: the tonnage of the load to be carried at the critical leg distance from the frequency distribution or the allowable tonnage at that distance on the payload-range curve. Using the relations described in the math model, this process leads to the development of probability distributions on aircraft productivity, total fleet fuel, and fleet size.

Life cycle cost (LCC) uncertainty is dependent on technical uncertainty, as described by the beta distributions of the weights and Mach number and the distribution of the fleet size. Table 1 is a brief summary of the AFCUE output for the ACMA conventional concept (Fig. 5) with current technology, which implied a 1988 initial operational capability (go-ahead in 1982 +6 years of development). Four figures-of-merit

FOR THE AIRPLANE ____________________
PLEASE IDENTIFY THE UNCERTAINTY IN THE VARIABLE ____________
BY ANSWERING THE FOLLOWING QUESTIONS. THE PURPOSE OF THESE QUESTIONS IS TO BOUND THE UNCERTAINTY YOU HAVE ABOUT WHAT THE ACTUAL VALUE OF THE VARIABLE WOULD BE IF THE AIRCRAFT WERE BUILT. THE MOST LIKELY VALUE OF THE VARIABLE IS THE SAME AS THE SPECIFICATION VALUE IN THE AIRCRAFT DEFINITION.

A = ____________ MINIMUM VALUE WHICH THE VARIABLE COULD ASSUME (SMALLER VALUES HAVE A NEGLIGIBLE CHANCE OF OCCURRING).

M = ____________ MOST LIKELY VALUE.

B = ____________ MAXIMUM VALUE WHICH THE VARIABLE COULD ASSUME (LARGER VALUES HAVE A NEGLIGIBLE CHANCE OF OCCURRING).

C = ____________ CONFIDENCE THAT MOST LIKELY VALUE WILL OCCUR. USE ONE OF THE FIVE RESPONSES BELOW:

1 = NOT CONFIDENT
2 = SLIGHTLY CONFIDENT
3 = CONFIDENT
4 = VERY CONFIDENT
5 = EXTREMELY CONFIDENT

Fig. 5 Technical uncertainty questionnaire.

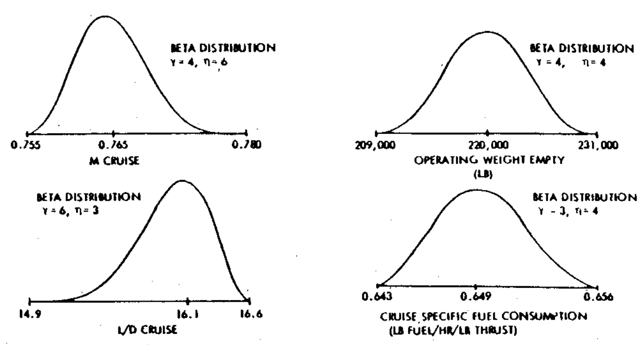

Fig. 6 Probability distributions for the variables on which range is dependent.

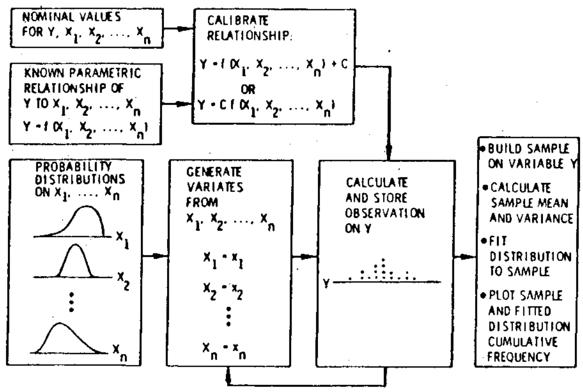

Fig. 7 Monte Carlo simulation process.

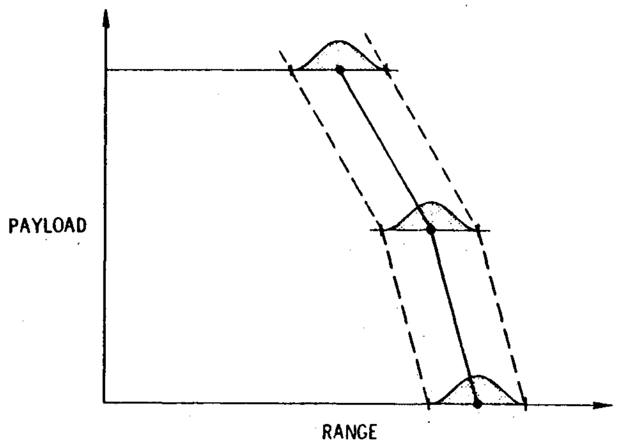

Fig. 8 Construction of confidence band on payload-range curve.

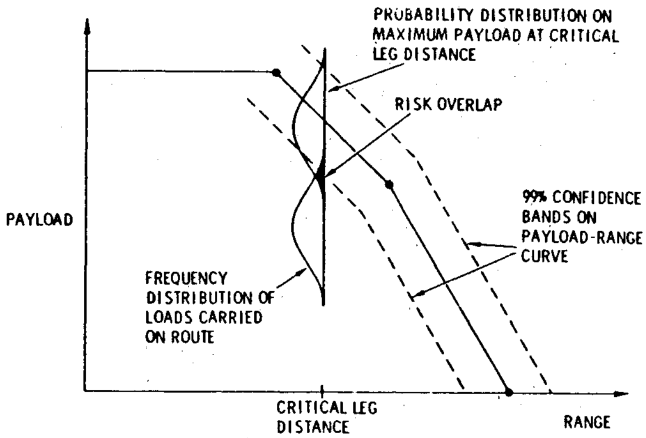

Fig. 9 Area of intersection of distributions of loads carried and maximum payloads.

(FOM) are displayed. The first column of numbers is the point estimate based on the deterministic conceptual design process. The last four columns are the uncertainty data on the same FOM's, calculated by the risk analysis process. The range between the minimum and maximum values represents a 99% tolerance interval centered at the mean value.

All output distributions are assumed normal, an assumption we have verified by performing chi-square goodness-of-fit tests on a variety of AFCUE output data. Thus, the distribution of fleet LCC for the ACMA baseline has a mean of $\$81.856 \times 10^9$ and a 99% tolerance band of [$77.586 B, $86.126 B]. These data show up on Fig. 10 as a solid horizontal line and two dashed horizontal lines respectively.

Study Results

To illustrate the kind of results we were able to obtain in the TAFAD study,[17] consider Fig. 10. The names across the bottom of the figure are abbreviations for the nine "technology sensitivity" aircraft that were analyzed using the same process as the baseline. The terms low and high represent two distinct aircraft initial operational capability dates, 1995 and 1997. The nine aircraft considered were

1) Advanced engine (1995 availability)
2) Advanced engine with exhaust mixer (1995)
3) Second generation supercritical airfoil
4) Advanced materials (primary and secondary structure)
5) Synergistic, low risk
6) Advanced engine (1997)
7) Advanced engine with exhaust mixer (1997)
8) Second generation materials
9) Synergistic, high risk.

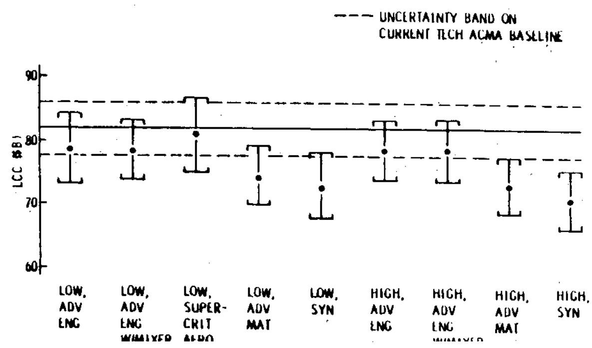

Fig. 10 Uncertainty bands on ACMA technology sensitivity aircraft.

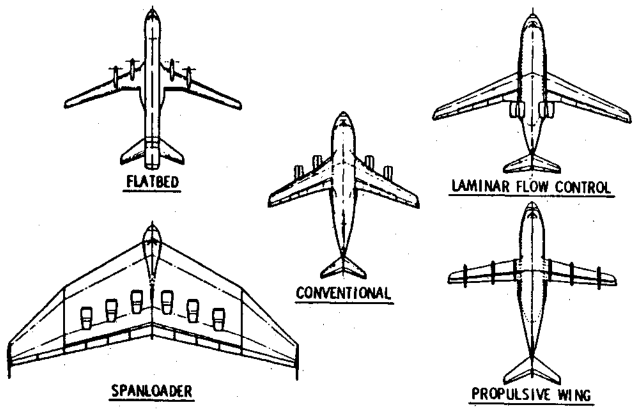

Fig. 11 Concept alternatives.

Table 1 Conventional concept—figure of merit uncertainty

Figure of merit	Point est	Mean	Std dev	Min	Max
Mission fleet	215	215	9.3	191	239
Total fleet (85% avail)	252	253	10.9	225	281
Fleet fuel/day, Mlb	51.4	48.7	3.9	38.8	58.7
Fleet LCC, $\$ \times 10^6$ (FY 82)	82.026	81.856	1.962	77.586	86.126

The low-risk synergistic aircraft includes the application of the second-generation supercritical airfoil, advanced materials, and the advanced engine (1995) with exhaust mixer. The high-risk synergistic aircraft includes these technologies plus second-generation advanced materials and the 1997 advanced engine. Figure 10 shows uncertainty bands on the fleet LCC for these technology sensitivity aircraft in comparison with the current technology baseline described in the previous section. Each dot is a mean fleet LCC calculated by AFCUE; each bracket is a 99% tolerance interval.

Four other more innovative concepts, shown in Fig. 11, were subjected to the AFCUE process as well as the conventional ACMA concept. In addition, a number of technology mixes were examined for each concept. The route structure was adjusted to utilize the performance offered by each concept. Alternate missions were also analyzed, with each concept sized accordingly. Finally, for each concept a compromise configuration was defined offering flexibility over all the mission route structures.

A technology payoff measure was defined to quantify the return on investment for the different technologies applied, either singularly or in various combinations of the five concepts. The measure uses the difference in benefit (LCC or deployment fleet fuel savings) divided by the incremental technology development costs. Three versions of the payoff measure are calculated: point, mean, and risk-adjusted values.

The point value is based upon the estimates developed in the deterministic design process. The mean value is based upon the means obtained in the uncertainty analyses. The risk-adjusted value reflects the uncertainty in the technology benefit and cost by penalizing the benefit and cost according to variances obtained from the uncertainty analyses. Specifically, the 25th percentile value is used for the benefit savings and the 75th percentile value is value for technology development costs, creating a benefit cost ratio that is therefore "risk adjusted." For example, advanced materials has a benefit cost ratio (ΔLCC/Δdevelopment cost) of 51.8 (point value), 52.7 (mean value), and 39.2 (risk-adjusted value). The respective numbers for the 1995 advanced engine are 23.5, 22.5, and 8.1.

In most cases the point values and the mean values of the technology payoff measure did not differ significantly, but there was often a difference between the risk-adjusted values and the point (mean) values. This was true when the magnitude of the uncertainty in the benefit was relatively large with respect to the expected benefit. The unique contribution of the uncertainty analysis to the conceptual design process was that it permitted the calculation of the risk-adjusted technology payoff measure. This measure highlighted those technologies whose projected benefits significantly outweighed the uncertainties in including the technology in a design concept.

Conclusions

A math model containing sufficient detail to capture the significant sensitivities of airlift fleet size and cost to technology uncertainty has been presented. A systematic uncertainty analysis procedure was discussed. The procedure is innovative in that a method that had previously been restricted to use in *cost* uncertainty analysis was expanded and used to quantify uncertainty in performance and effectiveness as well. Furthermore, by applying the method to all combinations of technology considered, a relative measure of technology uncertainty can be obtained. The feasibility and value of considering uncertainty in an aircraft technology assessment study was therefore demonstrated. The appropriate role of risk analysis in a conceptual design study involving the potential application of new technology has been shown.

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