EAGLE—An Interactive Engine/Airframe Life Cycle Cost Model

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INTRODUCTION

The DoD is placing increased emphasis on predicting and tracking the cost of developing, procuring, and supporting weapon systems over their life cycles. Recent directives have also stressed the importance of reliability/maintainability accounting and prediction for use in estimating their impact on operational effectiveness and ownership costs. In addition, the DoD has begun stating weapon system requirements in terms of mission to be accomplished rather than specific hardware. The net effect of these DoD actions has been to require weapon system contractors to expand their systems analysis capability to ensure that the variables that drive weapon system performance and cost are identified and their interactions known.

Pratt & Whitney Aircraft (P&W) has responded to this challenge by developing the Engine/Airframe Generalized LCC Evaluator (EAGLE) model. This methodology was developed in support of several contracts1 with the purpose of assessing engine technologies that are interactive with airframe size, cost, and performance. Since engine and airframe are scaled to meet the combat mission requirements, the EAGLE model allows trade studies to be accomplished at constant mission performance. It is also possible to fix the size of either engine or aircraft to determine the resulting effect on mission performance. This flexible capability enhances the preliminary evaluation process that eventually leads to optimization of a weapon system for a given mission.

ELEMENTS OF THE EAGLE MODEL

The model is made up of a number of modular subroutines controlled by a supervisory program as shown in the simplified EAGLE model flow chart of Fig. 1. The supervisory program processes the engine and airframe data sets, and delivers information to the mission analysis program. The design (combat) mission is flown iteratively (resizing engine and airframe) until the mission requirements are met. The peacetime missions are then flown and the mission analysis program supplies the scaled airframe and engine characteristics required by the cost modules. Additional nonscaled input is retrieved from the data sets (engine, airframe, force structure) and a total weapon system LCC is developed.

Fig. 1 Simplified flow chart of EAGLE model

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Mission Analysis Program

A critical element of the EAGLE model is the interactive engine/airframe sizing methodology. The mission analysis program (MAP) consists of a group of modular subroutines linked together to simulate flying a mission. Engine and airframe are resized to meet the mission established. The mission analysis process is illustrated in Fig. 2.

![Fig. 2 Engine/airframe resizing in MAP to meet mission requirements](image)

There are three parts to the MAP input: engine definition, aircraft definition, and mission definition. MAP requires a baseline engine definition in terms of installed thrust and TSFC (over the flight envelope), weight, dimension and scaling characteristics. A comparable airframe definition consists of weights, geometry, and aerodynamics is also required. This information is calculated by subroutines based on input aircraft parameters such as wing loading, sweep, tail volume coefficient and fuselage length. A geometry subroutine calculates component areas, characteristic lengths and aircraft volume; then a weights subroutine generates a component weight buildup and determines fuel available. Scaled aircraft aerodynamics is predicted using published procedures contained in the DATCOM and General Dynamics programs sponsored by the Air Force Flight Dynamics Laboratory (References 1 and 2). Total airframe drag is built up from predicted skin friction, interference, subsonic pressure, supersonic wave and lift-induced drags (Fig. 3).

![Fig. 3 Airframe drag buildup procedure](image)

The mission definition combines the flight path description with procedures for simulating required maneuvers such as takeoff, climb, and cruise. These procedures exist as modules or subroutines which mathematically integrate the equations of motion. The determination of takeoff gross weight required to complete a critical mission is an iterative process. Engine size and aircraft weight are calculated for an initial takeoff gross weight at a specified sea-level static (SLS) aircraft thrust-to-weight ratio (Fn/W). This system is “flown” through the mission, and the fuel required is compared with the initially determined fuel available. If the fuel required equals the fuel available, performance parameters (Ps, turn rate, acceleration time, takeoff roll, etc.) are calculated. Otherwise, the process is repeated for the new estimate of takeoff gross weight until fuel required does equal fuel available. The entire process may then be repeated with thrust-to-weight varied parametrically over a specified range. This variation establishes a relation between the calculated performance and thrust-to-weight ratio which is used to choose the value of the thrust-to-weight that meets the performance criteria. At this point, a compatible aircraft/engine system has been sized which satisfies all mission requirements.

While the system is sized for the design mission, actual peacetime usage varies considerably from the design mission. Care must be taken to ensure that operating and support costs (and therefore life cycle cost) reflect a realistic usage. To determine the actual operating and support costs, the aircraft is “flown” for all projected peacetime missions. When the fuel required has been determined for each mission, the fuel usage for the composite of these missions is calculated. In a similar manner, engine duty cycle parameters (cycles, hot time, total operating time) are determined for each mission and a composite of each duty cycle parameter is calculated.

### Engine Cost Elements

In an effort to standardize the elements of LCC and to ensure logical, consistent criteria for future engine source selection, government and industry have developed the Joint Air Force/Industry Engine LCC Model (Reference 3). The model provides a detailed tabulation of engine LCC elements and was used as a guide to ensure that all engine-related cost elements were addressed in EAGLE.

Engine RDT&E costs consider all engine costs that accrue in a full-scale development program through qualification testing (QT). In the EAGLE model, engine RDT&E costs are determined using the Cost Estimating Relationship (CER) shown in Fig. 4 relating normalized development cost and engine test hours. Actual cost data for 17 engine models and their derivatives, shown in Table I, were collected and analyzed.
Fig. 4 Cost estimating relationship for engine RDT&E and CIP costs

Table I. The R&D CER is based on 17 Engine Models and Their Derivatives

<table>
<thead>
<tr>
<th>Demonstrator Engines</th>
<th>Development Engines</th>
</tr>
</thead>
<tbody>
<tr>
<td>JTF10</td>
<td>F100/F401</td>
</tr>
<tr>
<td>JTF10B</td>
<td>JT3/57</td>
</tr>
<tr>
<td>JTF14</td>
<td>JT3D</td>
</tr>
<tr>
<td>JTF16B</td>
<td>JT4/J78</td>
</tr>
<tr>
<td>JTF18C</td>
<td>JT5D</td>
</tr>
<tr>
<td>JTF17</td>
<td>JT9D</td>
</tr>
<tr>
<td>JTF20</td>
<td>TF30</td>
</tr>
<tr>
<td>JTF91</td>
<td>NGW</td>
</tr>
</tbody>
</table>

The major factors which affect overall development cost (engine type, size, complexity, technology level, aircraft application, qualification procedure, etc.) were found to be related primarily to the cost of engine hardware and the number of test hours required to achieve specific milestones. The normalized cost used in the correlation is actual cost divided by the cost of parts for one engine. To discount the effects of inflation, the annual program costs were adjusted to the year of qualification/certification, and the unit experimental engine cost was taken at qualification/certification.

Component Improvement Program (CIP) costs are considered a portion of engine operating and support cost. They include engine modification, support engineering and test costs that result from CIP and Engineering Assistance to Production and Service (EAPS). These costs are estimated using the same CER as was used for RDT&E from QT to maturity.

Engine acquisition cost in the EAGLE model is based on CER's that are sensitive to the design parameters that affect the manufacturing cost of a component. For example, in Fig. 5, the inlet case acquisition cost is expressed as a function of inlet airflow and fan pressure ratio. Individual component costs are combined to obtain total engine unit cost.

To generate these CER's, a matrix of engine configurations was defined that was compatible with the engine sizes, cycles, technology level and design philosophy used in current P&WA parametric performance programs. Manufacturing cost for each design point was determined using a library of historical engine cost data. New part costs were estimated by selecting a similar part from the data bank and assessing it for differences in configuration, material and size. Cost adjustment factors, determined both through analytical development and historical data were then applied to material and labor costs separately.

Fig. 5 Total engine cost based on individual component cost estimates

General and administrative expenses and amortized tooling costs were included to arrive at a cost excluding profit. Components were then combined into modules with cost being correlated against the design parameters that drive the size, configuration and cost of each module.

Experience learning (projected as a function of engine quantity) and projected improvements in manufacturing technology are also considered in the engine costs. Adjustments for manufacturing technology improvements are based on historical trends and are applied using the IOC date to establish the manufacturing time period for the engine.

The engine Support Cost Model (SCM) used in EAGLE is derived from the P&WA F100 Engine Life Cycle Cost model. Although the model was designed specifically for F100 engineering change evaluation, its modular construction (Fig. 6) facilitated the use of the SCM in the EAGLE model.

The support cost model is made up of two parts: the Maintenance Cost Simulator (MCS) and the Fleet Buildup Subroutine (FBS). The first of these, the MCS, uses a Monte Carlo approach to simulate the interaction of scheduled and unscheduled maintenance events. The unscheduled events are input in the form of Weibull curves relating event probability and time. Scheduled events are input at specific intervals. Labor and material costs are determined for each event. The model is run a predetermined number of times to simulate the maintenance activity and collect the maintenance costs. Maintenance events, labor and material costs are determined and reported by year.

The fleet buildup subroutine compiles the output of the MCS model for each engine age (delivery date) into a total fleet. The FBS multiplies the output of each multipass run of the MCS by the
The appropriate number of engines of a particular configuration and delivery date. Yearly totals are then added to determine life cycle totals.

Input
- Failure Modes
- Webull Data
- Cost Data
- Schedueld Maintenance
- Coincidentals

Flight Hour Schedule
- Configuration Dates
- Engine Quantity

Maintenance Costs
- Engine Flight Hour Schedule
- Engine and Model Demands

Delivery Schedule
- Cost Data
- Fuel Consumption
- USAF ILS Factors

Output
- Reliability and Maintainability Parameters
- Maintenance Cost Simulator
- Support Cost Model

Life Cycle Cost Model
- Pipeline Spares Requirements

LCC Summary

Fig. 6 CCD-1180 F100 engine life cycle cost model

A repeatability option is provided in the simulator to allow precisely repeatable answers so that small changes in input can be evaluated. Repeatability is accomplished by freezing the random number sequence for each failure mode line item.

The Engine Duty Cycle Module is used to determine the effect of engine usage on maintenance cost. Each of the components/failure modes available in the SCM is sensitive to one of the duty cycle parameters generated by the duty cycle module. These parameters are used to drive both Weibulls (unscheduled events) and scheduled maintenance for individual components based on mission severity.

Five parameters have evolved as primary drivers of engine part life. The definition of each is shown below:

- **Type I Cycle**
  - Engine transient from shutoff to intermediate power or above to shutoff

- **Type III Cycle**
  - Engine transient from idle to intermediate power or above to idle

- **Hot Time**
  - Time at intermediate power or above

- **Engine Flight Hours**
  - Taxi plus flight time

- **Total Operational Time**
  - Total engine run time (engine flight time + ground time)

The data required to develop these parameters is available primarily from the mission analysis program. Type I cycles, hot time, engine flight hours and total operating time are all based on information generated in the mission summary. Partial throttle transients (Type III cycles) are determined by using a regression of historical data, see Fig. 7. To further simplify, an equivalent TAC cycle has been defined as:

\[ \text{TAC} = \text{Type I's} + 0.25 \times \text{Type III's} \]

**Fig. 7 Engine duty cycle based on mission analysis and historical regression**

High Thrust Loading Aircraft Do More Full Throttle Transients

Doesn't aircraft load more engines per sortie?

Aircraft Thrust Loading - \( \text{Fn/W} \)
Since the weapon system life is generally quoted in terms of “flight hours,” these driving parameters have been normalized by EFH. The ratios TAC/EFH, HT/EFH, TOT/EFH are used as severity factors that impact the probability of occurrence of maintenance events with respect to engine flight hour accumulation. The effect of mission severity on engine maintenance cost is then determined by running the SCM to simulate the fleet maintenance activity over the life cycle.

Airframe Cost Elements

The EAGLE model uses the Modular Life Cycle Cost Model (MLCCM) to predict airframe/avionics and base operating support costs. MLCCM was developed for the Air Force Flight Dynamics Laboratory (FDL) by Grumman Aerospace Corporation and is becoming the airframe industry standard LCC model. The model consists of CER’s regressed against parameters available early in the design of an aircraft. A primary purpose of MLCCM is to provide design engineers with the capability to conduct effective design/cost/performance trade studies during the early conceptual and preliminary design phases of an advanced aircraft system. The cost data sources and methodology used to regress the data are detailed in Modular Life Cycle Cost Model for Advanced Aircraft Systems, Phase III (Reference 4).

The MLCCM requires numerous detailed input data that can be categorized into the three groups shown in Table II. Some of the input required can be standardized for a particular type of aircraft or application. The FDL has been directing an effort in this regard with the members of the Aerospace Industry Working Group. An airframe industry standard list of default values has been compiled for each of the three categories of aircraft (fighter, attack, cargo/transport). Use of these default values greatly reduces the complexity of the MLCCM in EAGLE.

A second category of input required is information that is developed in EAGLE’s mission analysis program. Scaled geometry, weight, aerodynamic and performance parameters are passed through the supervisory control to the MLCCM module.

The third category includes input that does not vary with engine/aircraft/mission changes. Groundrules involving force structure, engine and aircraft quantities, and utilization as well as economic assumptions are passed directly from the input data set to the MLCCM module.

Economics

The economics routine is used to determine the effects of inflation and/or discounting on weapon system life cycle cost. In certain trade comparisons, discounting may be required to account for the time value of money. This is of particular interest when the technologies being compared have different investment and payback periods. In addition, a return-on-investment is calculated to gauge the economic advantage of these engine changes.

An annualization routine was required to spread system cost over the life cycle. Engine support costs are determined on an annual basis in the SCM module and are merely passed on to the annualization module. RDT&E, acquisition, airframe/base operating support and fuel costs are calculated as single values and must be apportioned to the appropriate year. RDT&E is spread linearly over the development period; engine CIP costs follow a historically derived algorithm. Acquisition costs are assumed linear over the production period. Airframe/avionics support and fuel cost follow the production period buildup, assumes full-strength operation until aircraft retirement causes a tapering off of operation and support costs.

EAGLE MODEL CAPABILITY

The model has been designed to assess the impact of engine changes on the aircraft while holding overall vehicle performance constant. For many trades of interest, this involves resizing both engine and airframe. However, in addition to this capability, the option exists to hold either engine or airframe constant. This option was provided in order to determine the impact of engine changes on vehicle performance for fixed engine or airframe designs.

The EAGLE model database currently includes typical fighter and transport aircraft point designs. The fighter is capable of super-sonic cruise, employs a cranked wing and is powered by one or two afterburning engines. The transport is typical of a medium payload, long-range configuration with two or four non-afterburning engines. Design mission variables include aircraft thrust loading, wing loading, radius, payload and Mach number. In addition to the design (sizing) mission, nine peacetime missions are provided for the fighter with three missions for the transport. Peacetime mission mix is a variable as range for each mission.

The baseline engines included in the model are members of PWA JT69 family of engines. The technology level assumed for this family is representative of engines to be qualified in the late 80's and will be substantiated by the PWA JT80 demonstrator engine, scheduled for test in 1985. Component engine costs are determined based on internal engine performance parameters and geometries which are an automatic output of our parametric performance decks.

In addition to determining a weapon system LCC baseline, the model is capable of generating results for up to four sensitivities at a time. For each sensitivity, changes to the baseline are defined in terms of differences in cost, maintenance, weight, TSFC and thrust for input to the model. A revised weapon system LCC is generated for these revised assumptions and compared to the baseline.

VALIDATION

To meet the requirements of the Advanced Technology Engine Studies (ATES), P&WA is being assisted by the airframe contractors shown in Table III. During Task 1 of ATES, a baseline weapon system LCC was developed for each application by one or more of these airframe contractors. In addition, sensitivities of engine performance parameters (weight, TSFC, thrust) were assessed to determine the effect on both aircraft TOGW and Weapon System LCC. These results have been used to compare with and validate EAGLE results for both the fighter and the transport applications.

Table II. Input Requirements for Determining Airframe/Avionics Cost

<table>
<thead>
<tr>
<th>Input Standard (Default)</th>
<th>From Mission Analysis Program</th>
<th>Groundrules</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Typical Aircraft in Each Category)</td>
<td>Aircraft Component Geometry</td>
<td>Life Cycle Years</td>
</tr>
<tr>
<td>• Wing Thickness Ratio</td>
<td>• Takeoff Gross Weight</td>
<td>Engine/Aircraft Quantities</td>
</tr>
<tr>
<td>• Sink Speed</td>
<td>• Thrust</td>
<td>Utilization</td>
</tr>
<tr>
<td>• Number Wheels, Struts</td>
<td>• Maximum Mach Number</td>
<td>Dollar Year</td>
</tr>
<tr>
<td>• Learning Curve Slopes</td>
<td>• Combat Radius</td>
<td>Profit</td>
</tr>
<tr>
<td>• Number Fuel Tanks, Valves</td>
<td>• Etc.</td>
<td>Etc.</td>
</tr>
</tbody>
</table>

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Table III. Multiple Airframe Companies Support Wide Range of Applications for Advanced Technology Engine Studies (ATES)

<table>
<thead>
<tr>
<th>Generic Class</th>
<th>Service</th>
<th>Study Applications</th>
<th>Airframer Responsibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fighter/Attack</td>
<td>USAF ATAMS (CTOL)</td>
<td>X X</td>
<td>Boeing Grumman McDonnell</td>
</tr>
<tr>
<td></td>
<td>USAF ATAMS (STOL)</td>
<td>X</td>
<td>Douglas</td>
</tr>
<tr>
<td></td>
<td>USAF Multi-Role Aircraft</td>
<td>X</td>
<td>Vought</td>
</tr>
<tr>
<td></td>
<td>USN Supersonic V/STOL</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Grumman</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Subsonic Utility</td>
<td>USN Subsonic V/STOL-A</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>USAF Adv Airlifter</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Bomber</td>
<td>USAF Manned Subsonic</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bomber</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

An example of the comparisons that have been made is shown in Fig. 8 for the ATAMS fighter. The resulting P&WA synthesized aircraft results correlated to within 5% TOGW and 10% Weapon System LCC compared to the airframe contractor’s baseline design.

The sensitivity of LCC to engine weight and TSFC was also very close to that predicted by the airframe contractors. Table IV compares EAGLE-generated trade factors to an ATAMS fighter composite of Boeing, Grumman and McDonnell Douglas designs. The TSFC trade factors are presented as a combination of both subsonic and supersonic performance so that a single figure of merit can be used to reflect the impact on the overall weapon system. The small differences between TSFC sensitivities have been attributed to configuration/aerodynamic assumptions and individual costing techniques rather than any major differences in sizing methodology. Wide variations in mission and aircraft configuration between the airframe contractors made a comparison of thrust sensitivity (at a particular sizing condition) impossible.

Table IV. EAGLE-Generated Trade Factors Compare Favorably with ATAMS Composite Baseline Sensitivities

<table>
<thead>
<tr>
<th>Sensitivity</th>
<th>%ΔTOGW/ΔX</th>
<th>%ΔLCC/ΔX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Weight</td>
<td>0.260</td>
<td>0.203</td>
</tr>
<tr>
<td>TSFC (Subsonic Cruise)</td>
<td>0.516</td>
<td>0.484</td>
</tr>
<tr>
<td>TSFC (Supersonic Cruise)</td>
<td></td>
<td>0.297</td>
</tr>
<tr>
<td></td>
<td>0.259</td>
<td></td>
</tr>
</tbody>
</table>

TRADE STUDY EXAMPLE

The first step in evaluating engine technologies is to establish a baseline aircraft, design mission and mission mix. In addition, an engine cycle must be selected and a maintenance baseline established for the particular engine configuration chosen. The engine maintenance parameters required as input to the MCS are assessed at the component failure mode level and reflect the durability/reliability goals designed into the particular engine selected.

In the trade study example shown below, an ATAMS aircraft/mission was used along with twin STJ562 engines which were determined during the ATES studies to be optimum for this mission. The STJ562 is a twin spool, augmented, 16,000 lb (71.2 KN) thrust class turbojet representing an advanced technology level consistent with a late 1980’s qualification.

The baseline engine includes a floatwall combustor design which was selected primarily for its high LCF life, see Fig. 9. The study alternative to the floatwall combustor is a machined ring design. The machined ring combustor saves both weight and production cost but is less durable than the baseline. This reduced durability necessitates an increased frequency of module inspections and an associated part scrappage rate higher than the baseline. In addition, a higher frequency of unscheduled events is projected.

The machined ring combustor also affects the performance characteristics of the engine. This particular design produces a more severe pattern factor which requires additional turbine cooling air (TCA) to maintain turbine blade and vane life. The increase in TCA causes the TSFC and thrust penalties shown in Table V. The effect on performance (weight, TSFC and thrust) results in resizing both engine and airframe in order to maintain constant mission performance. In this example, engine thrust was required to increase 0.8 percent and aircraft TOGW by 0.05 percent. The net impact of the cost, maintenance and performance differences results in a Weapon System LCC advantage of $90 million for the floatwall design.

Table V. Machined Ring Combustor Relative to Floatwall Design

<table>
<thead>
<tr>
<th>ΔPattern Factor</th>
<th>+0.05</th>
<th>ΔLife Cycle Cost for 500 Operational Aircraft:</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔTCA</td>
<td>+0.8%</td>
<td>Development</td>
</tr>
<tr>
<td>ΔTFSC, Avg</td>
<td>+0.2%</td>
<td>Acquisition</td>
</tr>
<tr>
<td>ΔThrust, Avg</td>
<td>−0.8%</td>
<td>−12.8</td>
</tr>
<tr>
<td>ΔWeight</td>
<td>−23 lb</td>
<td>−9.2</td>
</tr>
<tr>
<td>ΔCost</td>
<td>−$10,000</td>
<td>+90.8</td>
</tr>
<tr>
<td>ΔMaintenance</td>
<td>Less durable</td>
<td>Fuel at $1.80/gallon +9.9</td>
</tr>
<tr>
<td>Total</td>
<td>$+90.4 (millions)</td>
<td></td>
</tr>
</tbody>
</table>
SUMMARY AND CONCLUSIONS

The EAGLE model was developed primarily to evaluate the influence of engine design decisions on the total weapon system. To accomplish this, an adequate accounting and understanding of engine/airframe interaction, mission impact, engine performance, maintenance and cost effects was a prerequisite. In addition, P&WA's engineering model has been designed with the flexibility to incorporate expected revisions resulting from future DoD (and other) requirements. Model modularity provides this flexibility.

This modular construction also contributes to EAGLE's growth potential. Growth of the model is anticipated to follow two general paths. The first is an evolutionary growth of the model for a particular engine as it matures from a preliminary to a fixed design. Trade studies evolve from conceptual, "rubber" system evaluation to the detailed level of analysis required for production engines.

The second area of growth potential involves the addition of other engines (and aircraft) of interest to the data base as they are identified. These could include current production and derivative engines as well as advanced engines exhibiting even higher levels of technology than the JT9 engine family.

The EAGLE model is viewed as more a modeling system than a particular weapon system model. With the basic model framework now established, revision of the model can be accomplished quickly and efficiently to meet future requirements for weapon system evaluation.

REFERENCES


