Abstract

Engineering trade study analyses demand consideration of performance, cost and schedule impacts across the spectrum of alternative concepts and in direct reference to product requirements. Prior to detailed design, requirements are too often ill-defined (only “goals”) and prone to creep, extending well beyond the Systems Requirements Review. Though lack of engineering design and definitive requirements inhibit the ability to perform detailed cost analyses, affordability trades still comprise the foundation of these future product decisions and must evolve in concert. This presentation excerpts results of the recent NASA subsonic Engine Concept Study for an Advanced Single Aisle Transport to demonstrate an affordability evaluation of performance characteristics and the subsequent impacts on engine architecture decisions. Applying the Process Based Economic Analysis Tool (PBEAT), development cost, production cost, as well as operation and support costs were considered in a traditional weighted ranking of the following system-level figures of merit: mission fuel burn, take-off noise, NOx emissions, and cruise speed. Weighting factors were varied to ascertain the architecture ranking sensitivities to these performance figures of merit with companion cost considerations. A more detailed examination of supersonic variable cycle engine cost is also briefly presented, with observations and recommendations for further refinements.
Cost/Effort Drivers & Decision Analysis
(Applications of the Process Based Economic Analysis Tool)

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September 16, 2010
Briefing Contents

- Discussion of decomposition strategies and the limits of conceptual design detail
- PBEAT application to a Subsonic Engine Study showing the breadth of decision analysis
- PBEAT application to a Supersonic Engine Study with expanded subcomponent depth
- Summary Observations
Aircraft Affordability Decomposition to Subsystem Models using the Process-Based Economic Analysis Tool (PBEAT)

**Attributes**

- **Functional Classes within Estimate**
  - Mechanical, Structural, Electrical, Software, etc.
  - Life per functional class (Mech, Struct, Electrical, etc.)
- **Op Hours**
- **Envelop Size**
  - Length
  - Width
  - Height
- **Mass**
  - Non-electrical & electrical
- **Materials**
  - 14,000+ discrete or by class
- **Form Types**
  - Sheet, Prismatic, 3-D body, etc.
- **Feature Count**
  - Based on # of engineering drawings
- **Manufacturing Processes**
  - Cast, forge, compositing, machining, sheet-work, etc.
- **Etc.**
  - # of Parts, TRL & MRL Maturity, Software, etc.

**Subsystems**

1. **Wing**
2. **Horizontal Tail**
3. **Vertical Tail**
4. **Fuselage**
5. **Landing Gear**
6. **Engines**
7. **Fuel System – Tanks and Plumbing**
8. **Surface Controls**
9. **Auxiliary Power (On-Board Power)**
10. **Instruments**
11. **Hydraulics & Pneumatic Systems**
12. **Electrical**
13. **Avionics**
14. **Furnishings and Equipment**
15. **Airconditioning (ECLSS)**
16. **Anti-Icing**

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This numerical experiment using Latin Hypercube depicts the offsetting effect of uncertainty for an increasing number of equally contributing submodels.

These somewhat idealized results (statistically small sample, no bias in variance) demonstrate the large benefit modest decomposition and decreasing benefit afforded by the effort to create ever-increasing detailed submodels.
Engine configurations for a narrow body aircraft, similar to the Boeing B737 and Airbus A320, were parametrically studied by NASA. The following nomenclature identifies the engine configuration trade-space:

- \( Hi \) = High work LPC
- \( Lo \) = Lo work LPC
- \( DD \) = Direct-Drive front Fan
- \( G \) = Geared front Fan
- \( FPR13 \) thru \( FPR17 \) = Fan Pressure Ratio 1.3 thru 1.7
- \( FIXED \) = Fixed area fan nozzle
- \( VAN \) = Variable Area fan Nozzle
- \( Spiral-1 \) = OPR 32, Cruise Mach 0.80
- \( Spiral-2 \) = OPR 42, Cruise Mach 0.80
- \( Spiral-3 \) = OPR 42, Cruise Mach 0.72

The resulting 48 mission-sized engine/aircraft configurations were used to explore the cost-benefit of increased efficiency, reduced noise, and reduced emissions.

PBEAT Benchmark systems (Boeing 747, 777, 737, 787) calibrated using publically available data facilitated analogy estimating at the subsystem-level. Like the Benchmarks, more than 40 PBEAT attribute parameters were used in characterizing the trade space for each of the 17 subsystems.
Outputs from the conceptual design/analysis codes (NPSS/WATE++, FLOPS, PDCYL) augmented by formulas for complexity drivers (detailed part count, design replication, etc.) were used to perform cost estimates using the PBEAT code.
The abbreviated table below shows aircraft performance characteristics (noise, emissions, and flight time) and subsystem results of PBEAT cost analysis aggregated to the system level.

The cost results were later simplified by incorporating fuel usage and O&S cost into a single metric and subsequently expressing development cost, average unit production cost and O&S cost as a cost per flight hour.

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<th>AUPC</th>
<th>Mass</th>
<th>DEV</th>
<th>O&amp;S</th>
<th>FUEL</th>
<th>NITROGEN OXIDES EMISSIONS</th>
<th>Emissions LTO</th>
<th>Noise</th>
<th>Block Time</th>
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The aircraft cost per flight hour provided a concise method for evaluating the varied engine design configurations in this direct Cost/FoM decision approach.
A second decision approach was investigated using surrogate FoM “utility curves” and weighting criteria derived from the Analytic Hierarchy Process (AHP).

The basis of cost benefit in this approach allows for consideration of variation in value referred to as a Figure of Merit (FoM) utility score (worst within dataset = 0 %*weighting score, best within dataset = 100%*weighting score).

<table>
<thead>
<tr>
<th>SPIRAL</th>
<th>FPR</th>
<th>CONFIG</th>
<th>COST/FLT-HR</th>
<th>EMISSIONS</th>
<th>BLOCK TIME</th>
<th>NOISE</th>
<th>Final FoM</th>
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</table>
The shape of each utility curve was derived from engineering judgment and warrants further investigation as to its impact on the decision results.

As related to cost, the first dollar of cost reduction is always easier to obtain than the last dollar of cost reduction and as such might be considered as having less value or utility.

As related to noise, the utility curve concavity shows less benefit for “over achieving” and also demonstrates the pitfalls of using combined FoMs (noise certification is regulated at 3 prescribed points rather than the overall cumulative).
Cost weighted @ 25%
Emission weighted @ 25%
Block Time weighted @ 25%
Noise weighted @ 25%

The trade space plotted – Illustrating the Spiral 1 Hi G FPR15 configuration as the highest rated.
Cost weighted @15%
Emission weighted @ 28.3%
Block Time weighted @ 28.3%
Noise weighted @ 28.3%

The trade space plotted – Illustrating the Spiral 1 Hi G FPR15 configuration as the highest rated.

With only slightly increased noise weighting, lower FPR engines begin to rise in utility.
Cost weighted @ 50%
Emission weighted @ 16.6%
Block Time weighted @ 16.6%
Noise weighted @ 16.6%

The trade space plotted – Illustrating the Spiral 1 Hi G FPR16 configuration as the highest rated.

With decreased noise weighting, higher FPR engines show greater utility (due to reduced ramp weight)
Performance studies are underway examining the impact of variable cycle engine architecture for reconciling supersonic cruise performance with acoustically low takeoff jet velocity.

Using the same/similar tools as the previous subsonic example, a sparse pareto frontier was assembled from performance results of two engine architectures.

For two of these engines meeting a desired jet velocity, engine cost estimates were generated at a subcomponent/part-level using the same attributes formulae derived for the previous subsonic example.
The sample results show the Average Unit Production Cost impact of two cost complexity drivers from these subcomponent results which have been aggregated to the component-level for comparison.

Results indicate generally acceptable results in applying “subsonic” attribute formulae to very different turbine engine architectures using PBEAT (though Turbines, and Controls & Accessories warrant further discussion/investigation).

Interrogation of subcomponent details highlights some areas requiring refinement, such as manufacturing processes assumed for the cooled turbine components.
PBEAT Application using NASA’s Engine Concept Study for a 10-20 Passenger Supersonic Transport

- Refined formulae for variance (least, likely, most) on a subcomponent basis may be required rather than uniform +/- 10%, impacting cumulative distribution.
- Controls & Accessories is too broad a category in NASA’s current conceptual design (high part count overly inflates “off-the-shelf” items), though large amount of electronics rightfully contributes to the high cost.
- Manufacturing processes need greater user specification using PBEAT (e.g. Turbine et al processes should be tied to conceptual design code WATE++).

Sample of Controls & Accessories subcomponents:

- ACC, ACC, Accessories Unit & Gearbox, HPC Tower shaft + Bearing/Sump
- ACC, ACC, Accessories Unit & Gearbox, Torque Converter (Customer Horsepower Extraction)
- ACC, ACC, Accessories Unit & Gearbox, Fuel Boost Pump (Electronic)
- ACC, ACC, Accessories Unit & Gearbox, Lube Pump (Mechanical)
- ACC, ACC, Accessories Unit & Gearbox, Electric Generator Unit
- ACC, ACC, Accessories Unit & Gearbox, Electric Starter Unit
- ACC, ACC, Accessories Unit & Gearbox, Fire Suppression Unit
- ACC, ACC, Propulsion Electrical, FADE/ECU
- ACC, ACC, Propulsion Electrical, Electrical Wiring
- ACC, ACC, Propulsion Electrical, Lighting
- ACC, ACC, Propulsion Electrical, Sensors

Sample of Variable Nozzle subcomponents:

- NOZ-15, NOZ-15, Nozzle (Bypass), Outer Wall Panels & Stiffeners
- NOZ-15, NOZ-15, Nozzle (Bypass), Convergent Inner Wall Panels & Stiffeners
- NOZ-15, NOZ-15, Nozzle (Bypass), Divergent Inner Wall Panels & Stiffeners
- NOZ-15, NOZ-15, Nozzle (Bypass), 2D Sidewall Panels & Stiffeners
- NOZ-15, NOZ-15, Nozzle (Bypass), Transition Panels & Stiffeners
- NOZ-15, NOZ-15, VAR AREA C & A
- NOZ-15, NOZ-15, VAR AREA MSC
- NOZ-15, NOZ-15, Nozzle (Bypass), Plug Panels & Stiffeners
- NOZ-15, NOZ-15, Nozzle Thrust Reverser (Bypass), Clamshell Frames & Skeleton
- NOZ-15, NOZ-15, Nozzle Thrust Reverser (Bypass), Reverse Flow Shrouds
- NOZ-15, NOZ-15, Nozzle Thrust Reverser (Bypass), Crank & Linkage Arms
- NOZ-15, NOZ-15, Nozzle Thrust Reverser (Bypass), Nozzle Outer & Inner Panels Lap Seals
- NOZ-15, NOZ-15, Nozzle Thrust Reverser (Bypass), Actuation
The general ranking of Fan subcomponents costs are as expected.

Fan containment, though a complex Kevlar material system, has excessive production cost prompting more refined specification of manufacturing maturity in the supplemental formulae.

Similarly, highly variable components, such as the vanes, exhibit excessive production cost and warrant investigation (corroborated by highly variable nozzle).
No cost estimate is “right”, though some techniques are better than others. Cost confidence and managing to cost are what matters most, and requires integration with conceptual design tools where ~70% of cost-impacting decisions are made.

Estimates aggregated from decompositions deeper than 2 or 3 levels below aren’t worth the time and effort to create them (co-variance argument). Furthermore, decompositions without some accompanying engineering for complexities (e.g. TRL, manufacturing maturity, etc.) can confuse results and undermine cost confidence (witness “Fan Containment” and “Controls & Accessories”).

Decision Analysis is not a robot optimizer. Robust, flexible solutions are better than true optimums, especially during conceptual design phases of a program when requirements and engineering uncertainties are greatest.

Demonstrated versatility of PBEAT is suited to NASA’s broad charter (aeronautical systems, space launch & satellite systems, green energy, etc.).

- Refinement of supplemental formulae (attribute characterization) continues, to better address Turbine Engine specifics and enforce user-consistency without degrading PBEAT versatility
- Automated linking between improved fidelity Aircraft/Engine design codes and the PBEAT code (via autodata sheets) continues to reduce estimation time/effort and accelerate cost as a decision criteria.

