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Preliminary Design of Low Cost Propulsion Systems Using Next Generation Cost Modeling Techniques

Introduction

At GE Aircraft Engines (GEAE), during the preliminary design process for aircraft propulsion systems, the designer has always been concerned about the cost implications of engine architecture and material requirements, which are driven by design specified engine thermodynamic operating conditions. The concern was not only about initial acquisition economics, but about maintenance costs associated with the propulsion life cycle as well as the development costs associated with design and certification of the power plant. The difficulty has been that there was no rapid, accurate cost estimating process to allow the designers ready access to the cost implications of design choices. High cycle pressure ratios and bypass ratios were thermodynamically attractive in reducing SFC. Technology, whether in the form of complex aerodynamic blade shapes to increase efficiency or higher temperature materials to reduce undesirable effects of cooling flows on SFC, was considered without in depth quantitative cost impacts of these design choices.

Unprecedented levels of airline financial losses in the early 1990s provided a clear focus, for both current and future products, indicating cost is a key discriminator. Airline customers demanded engines that are affordable both to buy and to own. Clearly a need had been established to quickly and accurately understand the cost and life implications of preliminary design choices.

Examination of cost models, both inside and outside the company, failed to locate a generic model which satisfied GEAE business needs; i.e., one that

- costed parts based on physical attributes and compared them to production parts in a cost data base
- utilized current production costs for parts and was tied to a system that was periodically updated
- costed development and certification programs associated with engine design choices
- reflected the impact of thermodynamic design choices on maintenance cost associated with long term product utilization

The technical challenge had been established and GEAE launched an initiative in the early 1990s to produce such a code. This paper presents trade studies considering engine cycle trades with cost as a key discriminator.

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Integrated Preliminary Design System

To function in a manner which provides rapid response and system optimization, a preliminary design tool set, capable of being integrated, is required. The specific needs are linkable models that define

- parametric engine cycle performance
- parametric engine weight
- engine cost
- A/C mission analysis

Ideally these programs would be linked and on-line user specified inputs would generate real time system impacts and interdependencies. At a minimum, the programs must provide input to each other with minimal user intervention. Emission and noise considerations must also be assessed in any actual product study. For the purpose of brevity and relative simplicity the emission and acoustic effects are not considered for the study presented here.

The preliminary design system currently in use at GEAE has the above linkable tool set inputs and was utilized to present the results contained in this paper.

Cost Modeling

The following three basic approaches are used in cost modeling: parametric, bottom-up, and comparative.

Parametric Techniques. These techniques use statistical relationships derived from general historical data. Parametrics are a function of one or more cost or noncost related parameters (i.e., weight, size), simplistic, and part specific. Parametrics are generally valid within a narrow technology band; however, for use on emerging technologies, these relationships typically become unreliable.

Bottom-Up Techniques. These techniques estimate costs operation by operation and are based on related parameters. Bottoms-up techniques require applicable historical data and are very time intensive.

Comparative Techniques. These techniques estimate the cost of a new part by adjusting the cost of existing parts to account for the differences in size, materials, configuration, and features. Because comparative costs are rolled up from the part level, they are comparable in accuracy to bottoms up techniques, but are much simpler.

The COMPEAT$™ Cost Model uses the comparative approach automating current manual cost estimating methods. The model takes advantage of advances in software technologies

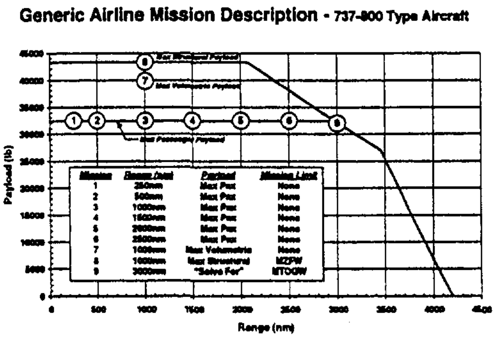

Fig. 1 Mission description

integrating engineering information systems and historical databases, from which comparative data is used as a basis of cost estimating. The COMPEAT$™ Cost Model comparative process provides bottom up accuracy with parametric simplicity.

Application of Surplus Value to Engine Optimization

In the following sections, the surplus value concept and its application to optimization of a medium range commercial aircraft engine will be described. How the maximum surplus value engine differs from the minimum fuel burn engine and the minimum direct operating cost engine will also be discussed.

Surplus Value Concept. The concept of surplus value was documented by Collopy in 1997 [1]. In simple terms, the surplus value of a commercial aircraft is the difference between the present value of the profit stream generated by the aircraft and the cost of manufacturing the aircraft and engines. Therefore, the surplus value represents the total profit potential of the aircraft, which is divided among the airline, airframe manufacturer, and engine manufacturer through the action of a competitive market.

Collopy further demonstrated that in a rational market where profit potential is the airlines' only aircraft selection criteria, two or more competing aircraft can share in the market on a sustained basis only when the sale prices of the aircraft are adjusted such that the net profit available to the airline (i.e., the difference between the present value of the revenue stream generated by the aircraft and the purchase price of the aircraft) is the same for all competing aircraft. Therefore, the airlines get the same surplus value from any of the competing aircraft in this scenario, and the airframe and engine manufacturers divide the difference between the total surplus value and the airlines' share. Hence, the manufacturers of the aircraft and engine combination with the highest total surplus value receive a larger profit than their competitors. By similar reasoning, it follows that when two or more engines compete on the same aircraft, the manufacturer whose engine provides the highest surplus value on the aircraft will receive a larger profit than his competitors. Therefore, it is in the best interests of the engine manufacturers, airframe manufacturers, airlines, and ultimately consumers, to optimize engine designs to achieve maximum aircraft surplus value.

Application of the Surplus Value Concept. To demonstrate the utility of the surplus value method in engine optimization, a typical domestic 160 passenger narrow-body aircraft (fixed not rubber), with a design range of approximately 3000 nm (range capability with max passenger loading) was considered. The aircraft was assumed to be unconstrained by installation issues that would have an adverse effect on engine to wing installation weight or drag. Also, the aircraft was not limited by fuel capacity for any of the engines studied. These were all done to ensure that aircraft specific items would not alter the general engine parameter trends that were being studied in this paper. Also, it is typical of a new aircraft/engine combination.

The Engine Synthesis Program (ESP) and the COMPEAT$™ Cost Model were used to evaluate the performance, weight, and cost of a parametric set of engines designed to the same high pressure turbine rotor inlet temperature limit, 2800°F, and the same takeoff and top of climb thrust levels. All of the engines were two spool turbofans of the following same basic architecture:

— single stage, solid metal, wide chord fan
— three to four stage booster
— seven to nine stage high pressure compressor
— dual annular combustor
— two stage high pressure turbine
— four to seven stage low pressure turbine
— separate flow nacelle

The mission and economic analyses for each of these engines were performed using the methodology described in the following sections.

Mission Mix Scenario. The mission mix scenario was created to model typical domestic aircraft operation. As shown in Fig. 1, nine missions were spread throughout the range/payload envelope.

A distribution of ranges and payloads was then determined from typical operating conditions, which when combined with the missions, yielded the breakdown shown in Fig. 2.

The first six missions are typical of "nonlimited" operations. This means each engine is carrying the same payload (average load of 65 percent pax and 35 percent cargo). The seventh mission is flown with maximum volumetric payload. Again, each engine carries the same payload, but the total payload is higher than that in missions 1–6 (payload is max passengers and max cargo using a typical cargo density). The eighth mission is flown with max structural payload. In this case, since aircraft are certified to a MZFW (max zero fuel weight), the engine weight affects the ability to carry payload. Hence, the heavier the engine, the less cargo that can be carried (each engine carries max passenger load but varying cargo loads). The ninth and final mission in the mix consists of a typical MTOGW (max takeoff gross weight) limited mission. A 3000 nm mission was chosen to allow for approximately a max passenger loading; however, each engine will carry a different payload in this case. The average range of the nine missions studied was ≈1300 nm, which is typical of aircraft in this market category.

Mission Analysis Methodology. The study aircraft was flown with each of the study engines for all of the nine missions described in the mission mix. The missions were executed using typical mission rules and reserves. A particular study engine configuration affects aircraft mission performance through engine SFC, nacelle drag, and engine weight. For the purposes of

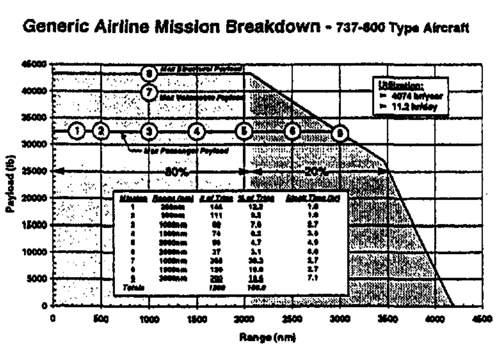

Fig. 2 Mission breakdown

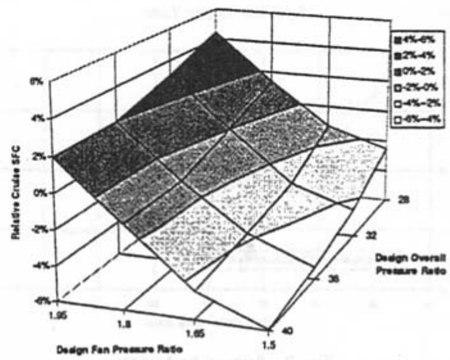

Fig. 3 Effect of fan pressure ratio and overall pressure ratio on cruise SFC

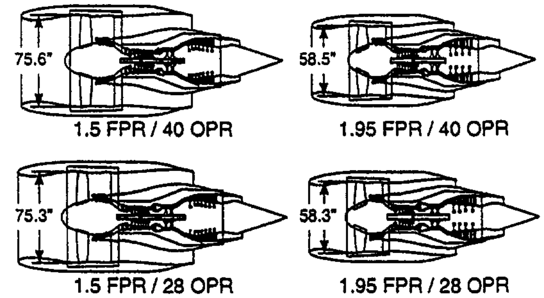

Fig. 5 Effect of engine cycle on size at constant takeoff and top of climb thrust

this study, engine SFC, relative to a given reference engine installation, is reflected in a change to aircraft specific range characteristics. A change in nacelle drag, due to fan diameter (i.e., low FPR = high fan diameter), is also reflected by a change in aircraft specific range characteristics. Propulsion system weight is reflected in aircraft empty weight. Since the study aircraft is a domestic 160 passenger aircraft (i.e., twin-engined) a particular engine's weight, relative to the reference engine, changes the empty weight by a factor of two on engine weight with an additional weight term added to reflect the structure required to mate those engines with the airframe. Each of the missions in the mission mix contributes to operating cost through fuel burn (i.e., a function of weight, drag, and SFC). In addition, operating cost is dependent on the mission results since engine flight hours affect maintenance costs. The major contributor to the overall profitability of the aircraft is revenue, which comes from payload capability in the form of passengers and/or cargo. Therefore, the profitability figures of merit (that vary with each study engine) are fuel burn, flight time, and payload.

Economic Analysis Methodology. In order to analyze the engines in terms of actual airline usage scenarios, an economic analysis has been performed based on the mission analysis results. As described earlier, the surplus value concept is a method which quantifies and ranks the appropriate items to be compared. A modification of this method has been used. This has been done in the interest of better showing the study engine trends as applied to the profit potential of the overall system. The simplification entails utilizing a markup of engine manufacturing cost to determine an engine price, and similarly utilizing the aircraft price, rather than aircraft cost. Inserting these assumptions into the surplus value calculation results in a typical NPV (net present value) analysis. No attempts have been made to study the distribution of the profit between engine manufacturer, airframe manufacturer, and airline. Rather, the study defines the relative profit available assuming the airframe and engine manufacturer have obtained a fixed profit through the markup of cost to price. The study engine trends developed with this simplified method are the same as would be seen with the surplus value method, only the magnitude of the results differ.

The methodology used in performing the economic analysis is a combination of standard DOC (Direct Operating Cost) techniques, coupled with a revenue stream and ultimately results in the NPV analysis. Total DOC+I (direct operating cost + interest) results are made up of flight crew, cabin crew, fuel burn, engine maintenance, airframe maintenance, insurance, landing fees, airframe and engine depreciation, and airframe and engine interest. The "cost" items from the nine missions, coupled with the mission weightings, are totaled to create a yearly "expense". The payload data from each of the nine missions is then divided into passenger and cargo revenue, based on the relevant distributions for each mission. When combined with the mission weightings, a yearly "revenue" is created. Combining the revenues, expense and tax information yields a yearly financial picture. Evaluating these items over a typical service life provides a cash flow stream that, when compared against the initial investment, allows an NPV calculation to be made. The NPV has been determined using a fixed discount rate. The NPV becomes the economic figure of merit used to determine the overall economic "winner" among the study engines. This approach allows the study engines to be ranked by potential economic benefit available to a typical airline customer.

Engine Cycle Trade Study

The basic cycle parameters, fan pressure ratio (FPR), and overall pressure ratio (OPR), are of primary importance in the design of a new turbofan engine. These parameters, which are set very early in the design process, have a major impact on the engine weight, cost, and fuel consumption. To demonstrate

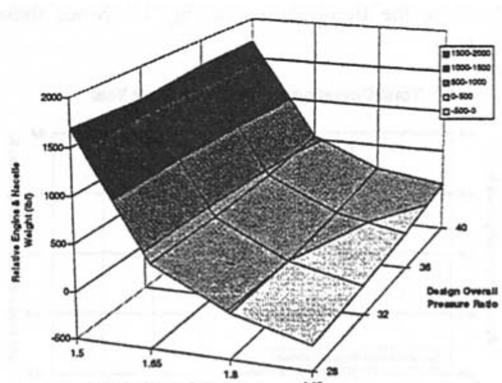

Fig. 4 Effect of fan pressure ratio and overall pressure ratio on engine weight

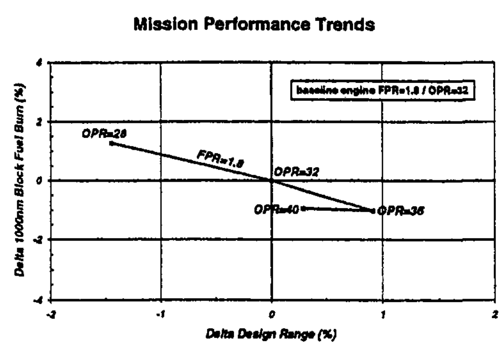

Fig. 6 Mission performance trends

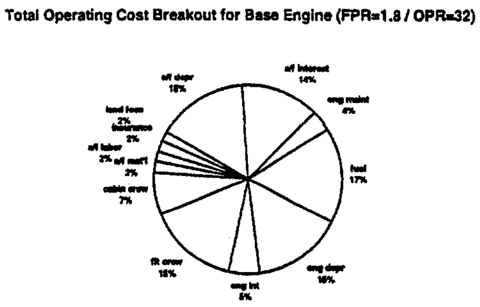

Fig. 7 Operating cost breakout

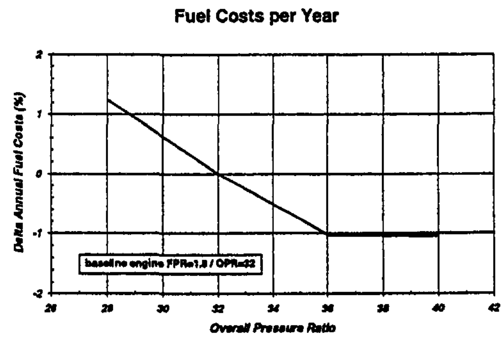

Fig. 9 Annual fuel costs

the surplus value method of optimizing these parameters, we examined the design space defined by a fan pressure ratio range of 1.5 to 1.95 and an overall pressure ratio range of 28 to 40. The results, discussed in the following sections, utilize FPR = 1.8 and OPR = 32 as a baseline.

Engine Characteristics. The specific fuel consumption and engine weight and trends are shown in Fig. 3 and Fig. 4 respectively. As fan pressure ratio is reduced, the bypass ratio and the propulsive efficiency both increase. This results in a significant improvement in specific fuel consumption. However, this also results in a weight increase because fan airflow, and hence diameter, must increase to maintain constant thrust. This effect is illustrated in Fig. 5, where the ESP-generated flowpath drawings are shown for the four corners of the design space. It should be noted that the weight increases rapidly between 1.65 and 1.5 fan pressure ratio because only solid metal fan blades have been chosen for this study. If the lower fan pressure ratio range looked favorable for this application, a weight reduction technology, such as a composite fan blade, could be used to mitigate the weight increase.

Engine specific fuel consumption, weight and cost are influenced by both overall pressure ratio as well. As overall pressure ratio is increased in the range of interest, the thermal efficiency of the cycle increases and the specific fuel consumption decreases. At the same time, the specific power of the core tends to decrease, so the core must be slightly larger to produce the same fan power.

Mission Analysis Results. For the purposes of simplification, the FPR = 1.80 engines have been selected to show the cost and revenue trends with varying OPR. This intermediate FPR was selected as a balance between mission performance and acoustic requirements. Figure 6 depicts mission performance as a function of engine OPR. Delta design range is an indication of MTOGW limited payload capability (mission 9) while 1000 nm delta fuel burn is a reflection of operating cost due to mission weighted fuel burn (missions 1–7). Here it can be seen that, on the study aircraft with the assumed study engine configuration, the high OPR engines offer better design range and fuel burn until that point at which the weight attendant with core size and stage count offsets that improvement in SFC associated with better thermal efficiency. Short haul aircraft are more sensitive to engine weight than SFC due to lower fuel fractions. The aircraft operating costs are based on the integration of fuel burns across the mission mix rather than 1000 nm fuel burn only.

Economic Results. Figure 7 shows the breakdown of individual cost items within the Total DOC+I (total op cost) term for the baseline engine over a one year operation. It must be noted that the engine affects only 35–40 percent of the total aircraft operational cost. Range of variation due to cycle impacts must be significantly less than 35 percent.

Figure 8 shows the relative manufacturing costs for varying OPR. The manufacturing cost trends are similar to the weight trends; larger engines tend to be both heavier and more expensive. However, the cost trends are not as smooth because they are more strongly influenced by discrete changes in materials and numbers of turbomachinery stages. The higher pressure compressor also requires more stages to produce the higher overall pressure ratio. These effects drive both weight and cost up. In addition, as overall pressure ratio rises, more costly materials are required in the compressor and turbines to withstand the resulting temperature increases.

Figure 9 shows the change in annual fuel costs for varying OPR at a constant FPR = 1.80. Essentially, this chart is a reflection of the block fuel burn results shown earlier, although the annual fuel costs are the result of the integration of fuel costs on all nine missions as they are weighted for one year's use.

Figure 10 shows aircraft total operating cost for one year's operation on a relative basis. As was mentioned earlier, engine related items account for about 35 percent of the total operating cost of the aircraft, of which fuel costs are but one contributor. The other engine related cost items, namely engine maintenance, depreciation, and interest, when combined with fuel costs, produce the trend shown in Fig. 10. Since these three

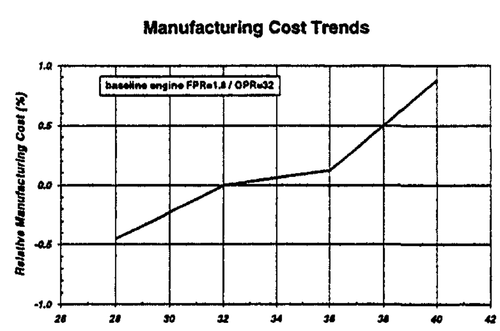

Fig. 8 Effect of overall pressure ratio on manufacturing cost

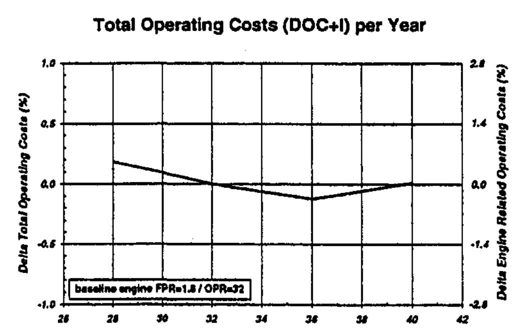

Fig. 10 Annual operating costs

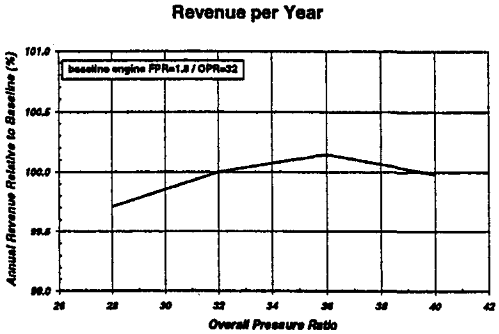

Fig. 11 Annual revenue

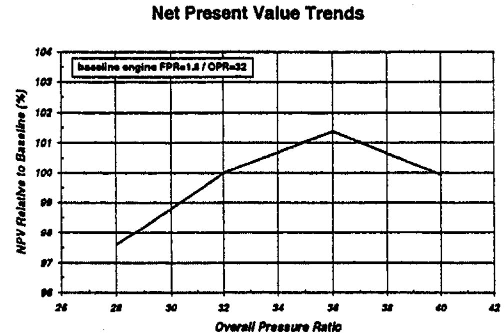

Fig. 12 Net present value trends

items are strong functions of manufacturing cost, the higher OPR engines, with the attendant higher manufacturing costs, are more expensive to operate on a relative basis. The combination of fuel costs, shown in Fig. 9, and manufacturing costs result in an optimal OPR = 36 engine from a total operating cost standpoint.

Figure 11 shows the annual total revenue for varying OPR engines at constant FPR = 1.80. Recall that for missions 1–7, payload (and thus revenue) are the same for all study engines. For mission 8, high engine weight results in lower revenue. For mission 9, payload is a function of engine weight, drag and SFC integrated over the mission. As a result, in Fig. 11, OPR = 36 shows the maximum revenue generating capability.

The integrated effects of total operating cost, acquisition cost, and revenue can be represented by a net present value (NPV) calculation over a fixed period of time. This calculation, for a period of 15 years, is shown in Fig. 12. It should be noted that all of the study engines are a good investment by the standards of the NPV calculation since absolute values are positive. Delta NPV is shown in order to highlight the trends. The combination of low operating costs, moderate acquisition cost, and high revenue result in the OPR = 36 engine having the highest profit potential for the airline.

Summary

A variation of the surplus value method was used to define the optimum engine cycle for a typical 160 passenger narrow-body aircraft. The results indicate that more traditional optimization parameters, such as fuel burn, fail to produce the best engine from an economic perspective, because they focus only on costs without regard to revenue generation potential.

Relative to the specific optimum cycle obtained, it must be remembered that this study has been performed on a 160 passenger narrow-body aircraft, operating over a typical domestic operation. The conclusions on engine FPR, OPR, cost, etc., are not applicable to all aircraft types and operational environments. Due to the short stage lengths that this type of aircraft sees in operation, the importance of SFC and, therefore, fuel burn are not as strong as would be seen in longer range operations. As a result, the impact of items such as maintenance cost and engine cost become much more important on a relative basis, than would be seen on a long range, wide-body application. Each aircraft and engine application should be studied in order to determine the proper relationship between engine parameters. Acoustic and emission requirements could also significantly alter the design choice.

It has also been shown that the basic thermodynamic cycle can have a significant impact on the economic viability of the engine. Although the data to prove it was not shown in this paper, the same is true of the basic engine architecture (i.e., the general engine layout, number of spools, and number and type of stages). Since both the cycle and the engine architecture are set very early in the engine design, an advanced, integrated set of design and analysis tools is required to perform the full engine economic analysis before significant engine design work is completed. The tools must be simple enough to allow rapid design iterations on the cycle and architecture, while having enough fidelity to obviate the need for significant cycle or architecture changes later in the design process.

References

1 Collopy, P. D., 1997, "Surplus Value in Propulsion System Design Optimization," AIAA 97-3159, presented at the AIAA Joint Propulsion Conference, July 6, 1997.