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THE DESIGNER'S IMPACT ON COMMERCIAL AIRCRAFT ECONOMICS

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ABSTRACT

The engineer/designer has a powerful influence not only on the technical quality of the design but also on its economic feasibility. A commercial aircraft program involves the expenditure of large resources and produces an aircraft that must be price competitive and meet airline requirements. The designer uses trade studies and preliminary cost analyses to ensure that the selected design will be the best practical compromise between product quality, production costs, and operating costs.

INTRODUCTION

The ever-changing air transport environment not only redirects the airlines' interests, it also forces manufacturers to redirect their estimate of airlines needs. The commercial aircraft industry is a maturing industry in which the various manufacturers tend to produce similar products; this results in very severe cost competition. It is very difficult to achieve an innovative, technologically superior design that will sell itself.

Therefore, increasing importance is being placed on costs. When the aircraft industry was younger, engineers did not to have to be overly concerned with costs. Aircraft performance was most important, and technology, innovation, and unique designs dominated. Today, with less significant advances in technology and the resulting increase in competition, the designer must assign equal importance to costs. Ignoring costs will quickly lead to a manufacturer's demise.

This discussion of the designer's impact on commercial aircraft economics is arranged in three topics: aircraft and program costs, customer evaluation of aircraft, and design and cost trade studies. A perspective for aircraft costs is provided by defining costs and showing some general relationships. How the airlines, i.e., the customers, evaluate an aircraft is illustrated; an understanding of this is essential for the designer performing cost versus performance tradeoffs. Finally, cost estimating methods and trade study procedures are discussed, and actual trade study examples are shown.

AIRCRAFT AND PROGRAM COSTS

Aircraft design and manufacturing costs can be categorized into two components: (1) nonrecurring or one-time costs and (2) recurring costs related to the continuing production of the aircraft. Engineering, test, and tooling are primarily nonrecurring, while manufacturing labor and manufacturing materials are primarily recurring costs. Figure 1 shows total program costs for different production quantities. Two curves are shown: one for an all-new aircraft and the other for a derivative aircraft.

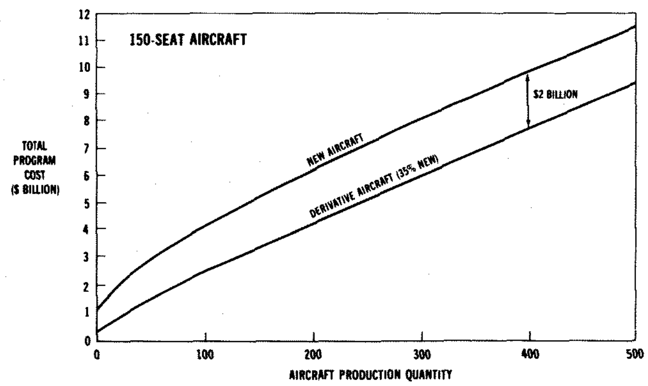


Figure 1. Aircraft Program Costs Are Large

The nonrecurring costs are a small part of the total cost for a large production run. However, since overall program costs are so large even a small part represents a large cost. Nonrecurring costs are represented at the left origin or zero production quantity in Figure 1. Design engineering, in turn, represents a small part of these nonrecurring costs. However, the designer's decision can have major impact on the recurring costs and, therefore, the total program cost. One percent of $9 billion is a lot of money.

Figure 2 shows the average cost of each of the above-noted aircraft as a function of the number of units produced. To compute the values of Figure 2, refer to Figure 1 and divide total cost on the y-axis by the production quantity on the x-axis.

Prices have been included in Figure 2 so that the manufacturer's program quantity break-even point can be determined. The break-even point is where costs equal revenue. Also, profits can be computed by multiplying the difference between cost and price by production quantity.

Note that a lower price has been assumed for the derivative aircraft. Usually, a contemporary new aircraft would have higher technology and performance and command a higher price. Even though the new aircraft price is higher, the program quantity break-even point normally occurs at a larger production quantity.

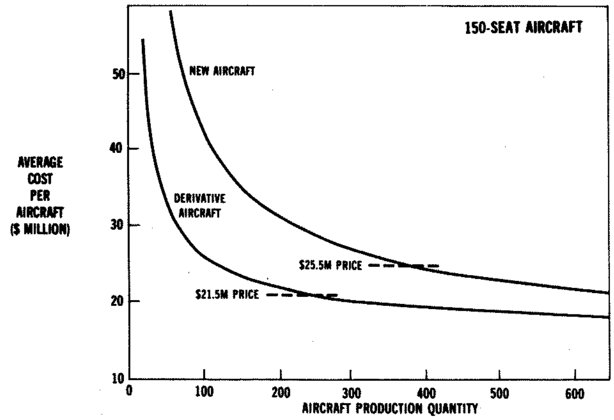


Figure 2. Unit Costs Decline with Large Quantities

Cash flow is shown in Figure 3. Cash flow is the difference between the inflow and outflow of money, or the difference between current costs and revenues. Early in a commercial aircraft program, costs are high, and only minimal revenues are received from airline prepayments. There is a large negative cash flow which must be offset by borrowing from other company resources or from outside sources.

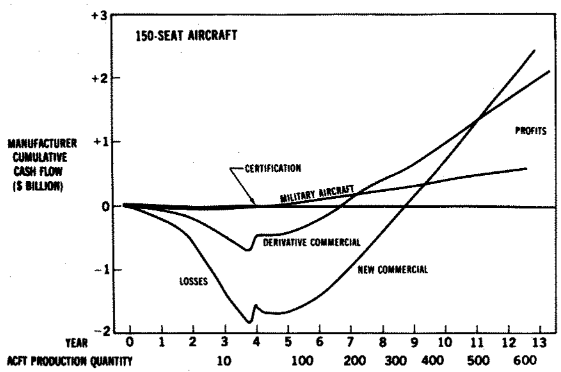


Figure 3. Program Cash Flow

Once deliveries start after certification, revenues increase rapidly. The rapid increase in cash flow at certification results from the delivery of aircraft waiting for certification. When the cumulative costs and revenue are equal, the program is at its cash flow break-even point. After the break-even point has been reached, cumulative positive cash flows represent program profits which can become large if sales are sustained.

There are three curves shown in Figure 3. Two represent the all-new and the derivative commercial programs corresponding to those shown in the previous figures. In addition, there is the all-new aircraft shown as a typical military program. The military has typically contracted to pay all the costs as incurred, plus a fixed profit, plus various incentives. There is some delay in early payments, resulting in a small negative cash flow. Profit potential is less in a military program because profits are limited, but overall financial risk is also significantly less.

The x-axis scale of Figure 3 is time. The approximate production quantity is also indicated on the x-axis. The aircraft prices are the same as used in Figure 2. A change in the prices, the level of airline prepayments, or the manufacturer's costs would greatly affect the shape of the cash flow curve.

CUSTOMER EVALUATION OF AIRCRAFT

The designer wants to reduce the cost of the manufacturer's product, but a cost reduction that degrades performance or excludes important design features may be counterproductive. It is therefore important to understand how the customer (the airline) evaluates an aircraft. The airline procedure for aircraft assessment can be outlined as follows:

- Establish general performance, economic and feature requirements
- Evaluate candidate aircraft performance
  - Payload capability
  - Range capability
  - Field performance
- Evaluate candidate aircraft economics
  - Direct operating cost (DOC)
  - Indirect operating cost (IOC)
  - Return on investment (ROI)
- Evaluate aircraft performance and features not reflected in the economics
- Consider other factors

The designer must make sure that his aircraft meets the airline's performance and feature requirements, has the best possible economics, and has other desirable characteristics.

Airlines use DOC or ROI to evaluate the aircraft. ROI is difficult to use because of nonlinear relationships and more complex computation. Since DOC is simpler and more commonly used for initial evaluation, we shall confine our attention to it.

DOC refers to those costs directly relatable to the aircraft. Airlines and aircraft manufacturers use a variety of methods to calculate DOC. We shall confine our attention to a typical DOC method.

Some performance and feature benefits are not adequately reflected in the DOC method and are considered externally. These include cargo payload, additional range, low noise, loadability, serviceability, reliability, technology image, commonality with aircraft in the airline's fleet, etc.

There are other airline considerations over which the designer has no control. These include other manufacturers' commonality with the airline's fleet, historical airline/manufacturer relationships, political considerations, etc.

The DOC for a 150-seat aircraft is shown in Figure 4. The DOC is subdivided into important aircraft components that drive the DOC results. For example, if there is a 10-percent cost change reflected in the price, trip costs will be changed by \$138 or 3.6 percent.

		TRIP (\$)		PERCENT
AIRCRAFT PRICE		1,381		36
FUEL BURNED		670		17
FLIGHT DECK CREW		625		16
MAINTENANCE — AIRFRAME	324	502	8	13
— ENGINE	178		5	
CABIN CREW		446		11
MAXIMUM TAKEOFF WEIGHT		286		7
TOTAL DIRECT COST		**3,910**		**100**

Figure 4. Direct Operating Cost Causes

The major variables are aircraft price and fuel costs, but other items also contribute to DOC. These other items will be discussed first.

The number of cabin crew is proportional to the number of seats and has little significance for overall aircraft design. The flight-deck crew is only significant as a choice between two- and three-member crews. A third crew member would increase the flight-deck crew costs by 25 percent. We note that there is a great difference between flight-deck crew costs between airlines in this deregulated environment. This DOC method reflects average flight-deck crew costs for the major unionized carriers.

Engines are a large maintenance cost item. In addition, a number of systems included in the airframe are related to the engines. The newer engines may represent as much as 45 percent of the total maintenance cost.

Landing fees and typically 15 percent of flight-deck crew costs are proportional to aircraft maximum takeoff gross weight.

Today, in a medium fuel price environment, aircraft price is the most important DOC driver. The marketplace determines the price a manufacturer will receive for its aircraft. Each manufacturer is part of the marketplace and participates in determining market price level. Each one's cost levels will determine whether its aircraft can be profitably produced and enter the marketplace.

For currently offered aircraft, the prices used in the DOC formula are the actual offered prices. These aircraft with their associated prices represent the competition for a new aircraft. Therefore, a new aircraft must meet two criteria: it must be superior to the competition, and it must be produced at a cost that will permit a reasonable profit. The cost-aware engineer/designer plays a vital role in meeting these criteria.

Advanced engineering studies generally do not use current fuel prices in the DOC formula since the new aircraft being studied will be operational several years in the future when fuel prices may be quite different. Figure 5 shows the volatility in projected fuel prices that have been used in design studies.

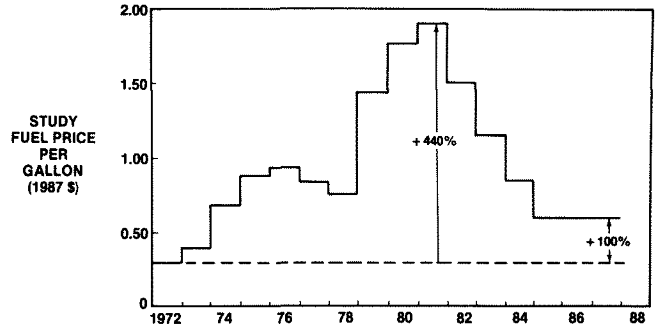


Figure 5. Direct Operating Cost Causes — Fuel Price

Currently, a fuel price of 60 cents per gallon is used. This price approximates the current cost of fuel. This implies that the cost of fuel is expected to rise at a similar rate to the other elements in the DOC formula into the 1990s. It is noteworthy that the fuel price used in 1981 was over three times higher than now.

Figure 6 shows the DOCs for two production aircraft (MD-82 and MD-87) and one 180-seat study aircraft. The aircraft are arranged in order of passenger capacity. Smaller aircraft have better aircraft-mile DOCs, while larger aircraft have better seat-mile DOCs.

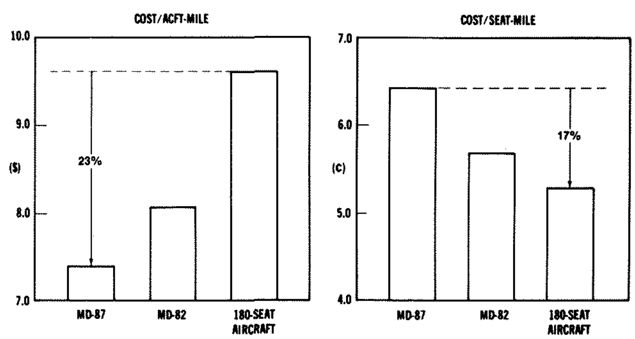


Figure 6. Direct Operating Cost Comparison

If an airline were to use the 180-seat aircraft when it should be using the MD-87 or the reverse, it would be very costly for the airline. Considering the large dollar differences for small changes in DOC, it is clear that the proper matching of aircraft size to the available passenger loads is critical to an airline's profitability. Hence, the need for different aircraft sizes within an airline's fleet.

DESIGN AND COST TRADE STUDIES

The engineer/designer has a critical function in the development of an aircraft program. His activity is one of the most important components of a successful program. As shown in Figure 7, the engineer/designer determines the overall aircraft performance characteristics as well as the basic design with its direct effect on manufacturing costs. These responsibilities directly influence the success of an aircraft program.

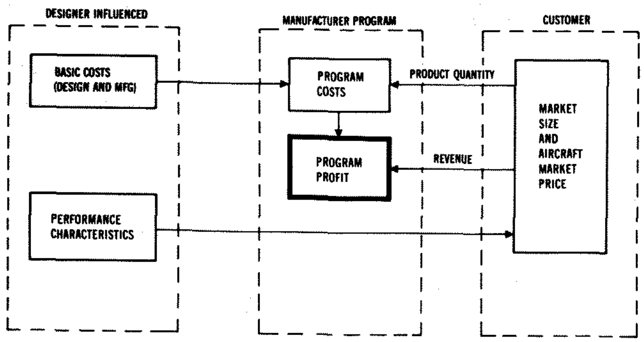


Figure 7. The Designer's Contribution

For the engineer/designer, trade studies are very important tools in determining the optimum aircraft design. These trade studies entail defining alternative designs, quantifying differences in costs and performance, and analyzing the impact on both the manufacturer and the customer.

All design decisions involve some sort of a trade. Most are based upon past experience and do not use trade factors explicitly to choose between design alternatives.

For many problems, the impact on cost and performance is not clear, and a more thorough analysis is needed. Since a decision in one design area may affect another area, a careful and extended analysis is necessary. These analyses may involve engines, structure, and systems design. Alternative designs are defined by preliminary drawings, weight statements, and written technical descriptions.

In trade studies, the differences, not the absolute levels, are important. Small aerodynamic and cost differences are defined that are not meaningful for the total aircraft, but are very important for the individual trade study. A good design represents the summation of the optimized benefits of many design trades.

Trade studies begin by determining the manufacturer's costs (plus necessary profit) and aircraft performance for each alternative configuration. One method of evaluation assumes, for analysis purposes, that the airline pays for these different costs through correspondingly different aircraft prices. Then, differences in airline economics (DOC) will indicate which alternative is better. An alternative method is to vary aircraft price in order to keep the airline economics the same for both aircraft, and then test the effect of these prices on the aircraft manufacturer's economics (profits).

There are two distinct methods of cost estimating: (1) the direct estimate method performed by the designer himself based on the defined tasks and purchased parts cost estimates, and (2) the parametric method which uses an aircraft parameter to estimate costs. A combination of the two methods is usually employed.

The direct estimate method needs an in-depth technical design definition and division of the work into tasks. It can be very time consuming (and therefore expensive) to do this kind of cost estimate. Many of us are familiar with the inadequacies of early or preliminary cost estimates. There is not enough time and not a good enough definition. Also, since cost estimates are used for future allocation of resources, a very careful review is necessary to establish the appropriateness of the estimates.

Weight is the most common parameter used by the parametric method to estimate costs. This method is often necessary because cost estimates are required early in the program, and it is too time-consuming to do a direct estimate. A careful parametric estimate is usually much better than a poor direct estimate. Even though the parametric method is simple to perform and is objective, unfortunately, its accuracy is limited because we don't have a really good parameter and there is not enough uniformity between aircraft development and production programs.

A combination method, therefore, is most frequently used in advanced design studies. The results and applicability must be carefully considered. Designers are contacted for further explanation and clarification of their design. Formal or informal direct estimates are used in critical areas to validate the parametric estimate. The end result is the best estimate possible within the time and manpower constraints. The designer's contribution to this process is critical since only he knows what the design really involves.

Weight is the best cost estimating parameter for preliminary studies. It is common to all aircraft parts, and weight data are required for aircraft performance and center-of-gravity calculations. About half of the weight data required for cost purposes must be generated for other reasons.

This "cost weight" estimating method takes the following into account:

- Component weight
- Component commonality
- Component complexity

For a derivative aircraft, the starting point is the parent aircraft, and the weight of components removed and added is defined (the weight-in and weight-out components). With respect to the derivative aircraft, or in a situation where two related aircraft are being developed at the same time, the degree of similarity between parts of the two aircraft is important for costing and is defined as component commonality. The cost of a part is reduced according to its degree of commonality with a previously produced part. For example, a part with a gauge change is considered to be 25-percent new and 75-percent common. If this part weighs the same, it would be assigned 25-percent of the nonrecurring cost of the original new part. Its recurring cost would also be lower than the all new part: typically 15 to 30 percent for a gauge change.

It is most obvious that the cost-per-pound of the different parts of an aircraft varies greatly according to the complexity of the parts. For example, a flap structure costs 50 percent more per pound than a wing box structure. A typical cost estimating computer model has complexity factors built in for many different parts. Some costs are so unrelated to weight that they must be estimated separately as a direct estimate. Avionics, aerodynamics, and flight test fall into this category.

As an example of a trade study, consider a 110-seat aircraft based on the DC-9-30. The design question is whether to incorporate a 2-foot wing tip extension. Although this addition requires changes to the wing tip sections, there are benefits related to the fact that the tip section would be identical to the MD-80's. This commonality reduces the costs relative to a tip extension of some other length; therefore, the 2-foot tip is the most promising choice for the extension. Figure 8 shows the changes necessary for adding a 2-foot tip.

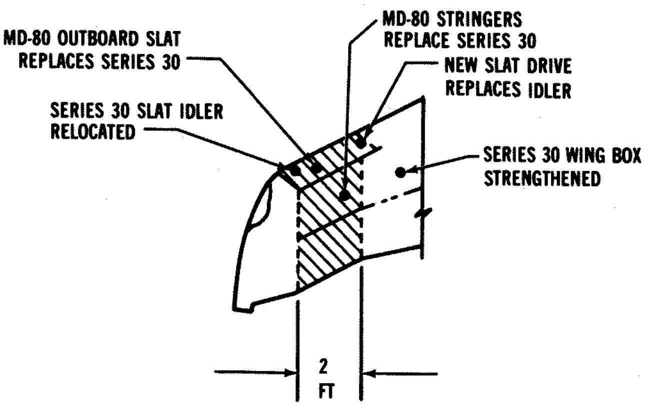


Figure 8. Wing Tip Extension — Changes

Much of the weight increase occurs in the inboard wing because of the loads induced by the tip extension. This illustrates the interactive effect that relatively small design changes can produce.

Figure 9 is a summary of the actual 1982 analysis which accounts for the weight, fuel burn, and incremental costs. The wing tip extension increases weight and cost but provides a 1-percent fuel savings. The 1-percent fuel saving dominates the DOC results and provides a 0.4-percent DOC reduction for a 400-aircraft production quantity. This would save an airline with a 20-aircraft fleet $680,000 per year. Currently, study fuel prices are much less, and all the airline cost savings would disappear.

Δ OEW = +310 LB
Δ FUEL BURNED = −1.0 PERCENT
Δ NONRECURRING COST = +$5.0 MILLION
Δ AIRCRAFT COST = +$100,000 (FOR 200-ACFT PRODUCTION)
= + $60,000 (FOR 400-ACFT PRODUCTION)

AIRLINE ECONOMICS WITH AIRLINE PAYING Δ COSTS
HIGH FUEL COST ENVIRONMENT
Δ DOC = −0.3 PERCENT (FOR 200-ACFT PRODUCTION)
Δ DOC = −0.4 PERCENT (FOR 400-ACFT PRODUCTION)
CURRENT LOWER COST FUEL ENVIRONMENT
Δ DOC = +0.1 PERCENT (FOR 200-ACFT PRODUCTION)
Δ DOC = +0.0 PERCENT (FOR 400-ACFT PRODUCTION)

CONCLUSION: DO NOT INCORPORATE TIP EXTENSION ON SERIES 30 WING UNLESS A HIGH FUEL COST ENVIRONMENT IS PROJECTED

Figure 9. Wing Tip Extension — Analysis

A second trade study example involves a proposal to replace the MD-80 ARINC 570 ADF (Automatic Direction Finder) with the ARINC 712 ADF. The purpose is to save cost and weight while providing a 50-percent improvement in bearing accuracy. The changes are:

- Replace existing ADF with advanced ADF
- Replace loop antenna with loop/sense antenna combination
- Delete four sense antennas in fillet
- Eliminate existing coaxial cables
- Eliminate eight line replaceable units
- Slight decrease in avionics bay cooling requirements

The analysis is shown in Figure 10. The new ADF reduces weight, fuel burned, and cost-per-aircraft and provides a small economic benefit to the airline when the cost benefits are passed through to the airline.

Δ OEW = −70 LB

Δ FUEL BURNED = −0.05%

Δ NONRECURRING COST = + $200,000

Δ AIRCRAFT COST = − $5,000 (FOR 200-ACFT PRODUCTION)
= − $6,000 (FOR 400-ACFT PRODUCTION)

AIRLINE ECONOMICS WITH AIRLINE PAYING Δ COST
Δ TRIP DOC = −.04%

CONCLUSION — INSTALL ADVANCED ADF

Figure 10. Automatic Direction Finder (ADF) Analysis

This trade study was done as part of the studies of a derivative version of the MD-80. The study estimated a small increase in nonrecurring cost with no incremental flight test costs. Later the design change was implemented as part of the MD-80 product improvement program, and some flight test costs were incurred. This illustrates how trade studies are sensitive to the program in which they are a part.

It is also noted that the improvements are very small. But when many are added together, these small improvements can be very significant and make the difference between a successful program and a failure.

A third study example involves the issue of whether a derivative of a 3-man flight-deck crew aircraft should have a 2-man crew. The trade study analysis is shown in Figure 11. The subject is a large, long-range aircraft. There is a big increase in nonrecurring cost, and while there are considerably higher early production recurring costs, the lower parts costs and eventually lower assembly costs result in an unchanged average recurring cost for 300 aircraft.

OEW	=	− 500 LB
MTOGW	=	− 750 LB
FUEL BURNED	=	− 0.15 PERCENT
NONRECURRING COST	=	+ $40 MILLION
RECURRING COST	=	UNCHANGED
COST PER AIRCRAFT	=	+ $0.13 MILLION
AIRFRAME MAINTENANCE COST	=	− 2.1 PERCENT
FLIGHT-DECK CREW COST	=	− 20 PERCENT

Figure 11. Two- Versus Three-Man Flight-Deck Crew — Analysis

The results are shown in Figure 12 where the direct operating costs (DOC) are related to their causes. Note the small effect of aircraft price, weight and fuel burn. While maintenance costs are reduced, the dominant factor is the reduction of one flight-deck crew member. The end result is a significant cost saving per year for a typical aircraft fleet.

DOC CAUSES	THREE-MAN CREW ($/TRIP)	TWO-MAN CREW ($/TRIP)	TWO-MAN BENEFITS ($/TRIP)
AIRCRAFT PRICE	9,251	9,267	+ 17
FUEL BURNED	5,756	5,747	− 8
FLIGHT DECK CREW	3,804	3,040	− 764
AIRFRAME MAINTENANCE	2,425	2,373	− 52
ENGINE MAINTENANCE	1,837	1,837	0
CABIN CREW	3,910	3,910	0
MAXIMUM TAKEOFF WEIGHT	2,681	2,678	− 3
TOTAL	29,617	28,552	− 811 (− 2.7%)

A FLEET OF 10 TWO-MAN CREW AIRCRAFT SAVES AN AIRLINE $7 MILLION PER YEAR

Figure 12. Two- Versus Three-Man Flight-Deck Crew — DOC Comparison

A fourth trade study example illustrates how changes in fuel price affect aircraft design. A fuel price study was performed for an all-new aircraft having mid 1990's certification. Two different configurations are described in Figure 13. One was designed to be economically efficient in a low fuel cost environment, the other in a high fuel cost environment. A 35-percent reduction in fuel consumption is achievable, but at a penalty of a 25 percent increase in aircraft price.

	LOW FUEL COST CONFIGURATION	HIGH FUEL COST CONFIGURATION
DESIGN FEATURES:		
— ENGINES	ADV TURBOFAN	UHB
— AERODYNAMICS	CURRENT	LAMINAR FLOW
— STRUCTURES	CURRENT	COMPOSITE WING BOX
— SYSTEMS	CURRENT	ADVANCED CONTROLS
NUMBER OF SEATS	180	180
DESIGN RANGE (N MI)	3,000	3,000
MTOGW (LB)	190,000	165,000
OEW (LB)	110,000	100,000
FUEL BURNED AT 1,000 N MI PER TRIP (LB)	13,600	8,900 (− 35%)
AIRCRAFT STUDY PRICE ($ MILLION)	40	50 (+ 25%)

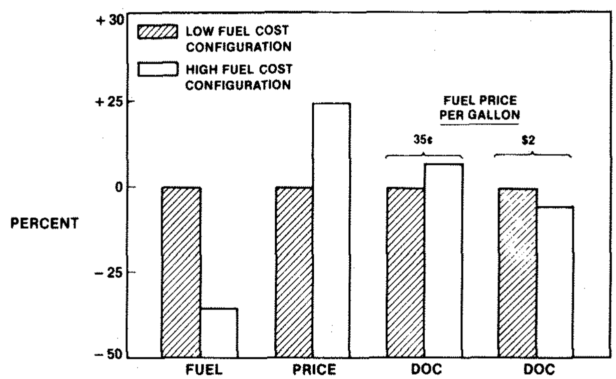
Figure 13. Fuel Price Study — Configurations

In Figure 14, the airline economics (DOC) are compared for the two configurations at two fuel prices. The relatively small changes in airline maintenance costs and those related to takeoff weight compensate for one another. Changes related to aircraft price and fuel price have a major, opposing, and differing effect on DOC.

DOC CAUSES	LOW FUEL COST CONFIGURATION ($/TRIP)	HIGH FUEL COST CONFIGURATION ($/TRIP)	DIFFERENCES ($/TRIP)
AIRCRAFT PRICE	3,145	3,931	+ 786
FUEL BURN (AT 35¢/$2 PER GALLON)	712/4,068	467/2,669	− 245/− 1,398
FLIGHT DECK CREW	1,230	1,230	0
AIRFRAME MAINTENANCE	591	660	+ 69
ENGINE MAINTENANCE	359	363	+ 4
CABIN CREW	1,065	1,065	0
MAXIMUM TAKEOFF WEIGHT	439	376	− 63
TOTAL DOC (LOW/HIGH FUEL PRICE)	7,541/10,896	8,093/10,294	+ 552/ − 602 (+ 7%/ − 6%)

Figure 14. Fuel Price Study — DOC Comparison

The results are summarized in Figure 15 which lead to the conclusion that changes in anticipated fuel price can have a profound effect on aircraft design, and changes in actual fuel price can have a profound effect on an airline's competitive position.



A FLEET OF 25 HIGH FUEL COST CONFIGURATION AIRCRAFT:
SAVES AN AIRLINE $16 MILLION PER YEAR IF FUEL IS $2 PER GALLON
BUT
COSTS AN AIRLINE $15 MILLION PER YEAR IF FUEL IS 35¢ PER GALLON

Figure 15. Fuel Price Study Results

SUMMARY

In today's competitive environment, the designer needs to pay more attention than ever to costs. Other manufacturers can produce similar aircraft which creates intense competitive pressures. Commercial aircraft programs involve very large financial resources − measured in billions of dollars. While an aircraft's design cost is relatively modest, the designer's impact can be critical to the success of the total program.

The designer must give careful consideration to how the airlines evaluate aircraft in order to design the best product. Direct operation cost (DOC) is the most convenient method of aircraft preliminary economic evaluation.

Design trades are performed at all phases of the design process. The advanced design phase is centered on defining the initial configuration where configuration geometry, engine, crew, structure and major system trades are performed. Costing is a major part of this process. To estimate cost, a combination method is employed using direct estimates and a weight-based parametric method. By performing a series of formal and informal trade studies, an optimum design is achieved providing maximum profit for the aircraft manufacturer and the purchasing airline.

Aircraft price has now replaced fuel price as the most important factor in DOC with more than twice the significance of fuel price. While today's modest fuel price level is currently projected to continue, this projection could suddenly be changed. In fact the *perception* of where fuel prices will be in the future has now become a major driver of design decisions.