VOL. 27, NO. 2, FEBRUARY 1990 J. AIRCRAFT

Minimizing Life Cycle Cost for Subsonic Commercial Aircraft

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The inclusion of life cycle cost (LCC) as early as possible in the conceptual design process is necessary because of the strong impact early design effort has on the total cost of an aircraft program. Considering LCC for military aircraft is the current industry standard; for commercial aircraft it is also necessary to weigh the merit of decreases in operating costs against increases in acquisition cost and vice versa. A methodology has been developed that makes it possible to identify an aircraft concept that will meet the mission requirements and have the lowest LCC. The methodology consists of an LCC module composed of elements to calculate RDT&E (research, development, testing, and evaluation) cost, production cost, DOC (direct operating cost), IOC (indirect operating cost), and an existing conceptual design and analysis code, the Flight Optimization System (FLOPS). The cost models chosen for the LCC module may produce questionable absolute cost estimates; however, the models chosen permit alternatives to be treated consistently so that relative comparisons are valid. Provision is made in the methodology for sensitivities to advanced technologies to also be investigated. The conceptual design system is applied to short-, medium-, and medium-to-long range subsonic commercial airplanes. The aircraft are optimized for minimum gross weight, fuel burned, acquisition cost, and DOC to show that different concepts result when LCC is considered. Sensitivities of the aircraft to economic and technology variables are illustrated.

Introduction

ENGINEERS have traditionally designed systems that maximize performance while minimizing size and weight. Current practice in the conceptual design process tends toward approximation of minimum cost by using either minimum takeoff gross weight, empty weight, or fuel burned. It is generally accepted that between 70 and 80% of the life cycle cost of a configuration is locked in during the concept stage of development when very little actual money has been spent, as shown in Fig. 1 (from Ref. 1). It is during these early stages of development that commitments are being made to increase performance over existing systems, thus implying the need to consider new technologies.

Conceptual aircraft design is that phase in which the general size, configuration, and estimated performance of the aircraft are determined. The primary purpose at this level is to provide technical and economic feasibility information for guiding larger efforts during more detailed design phases. Recent improvements in computer capabilities and development of codes specifically oriented toward conceptual design make it possible to consider cost at the same time as other conceptual variables, rather than as an afterthought when the potential impact is greatly reduced.

The life cycle cost (LCC) of an aircraft is the total cost associated with that aircraft from initial inception through the aircraft leaving service at the end of its life. Using LCC in the conceptual design process emphasizes the importance of balancing the design between potentially conflicting parameters; for example, an extremely high-performance objective leads to design complexity and high costs, whereas an objective of achieving the ultimate in low cost can lead to substantial penalties on performance and technical specification. The prevailing economic conditions strongly influence how much technology can be introduced on the aircraft. References 2 and 3 contain a more detailed discussion on the rationale and considerations for including life cycle cost in the conceptual design process.

Life Cycle Conceptual Design System

The life cycle cost of an aircraft is the total cost associated with that aircraft from initial inception through the aircraft leaving service at the end of its life. The two major components of LCC are acquisition and operating costs. Acquisition cost is composed of research, development, testing, and evaluation (RDT&E) and production cost and is primarily associated with the manufacturer. Operating cost includes direct operating cost (DOC) and indirect operating cost (IOC) and is primarily associated with the customer or airline. A schematic diagram of the system developed to include LCC in the conceptual design process is shown in Fig. 2. The system includes an existing conceptual design and analysis code called FLOPS (Flight Optimization System) and an LCC model developed for this effort. Input to the system includes a baseline mission, aircraft (geometry and propulsion data minimally), and economic assumptions. The FLOPS and LCC model will be described in more detail in the following discussion.

FLOPS (Ref. 4) is a multidisciplinary system of computer programs for the conceptual and preliminary design and eval-

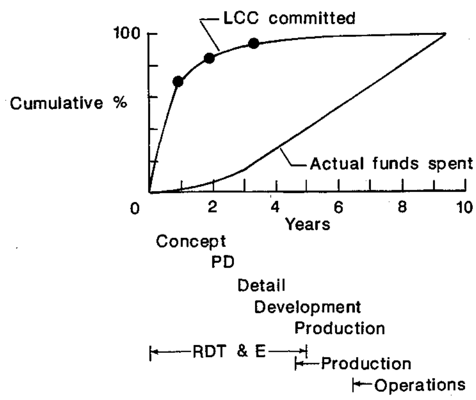

Fig. 1 Cumulative percent of LCC committed and actual funds spent for a typical aircraft (from Ref. 1).

Presented as Paper 88-4402 at the AIAA/AHS/ASEE Aircraft Design Systems and Operations Meeting, Atlanta, GA, Sept. 7–9, 1988; received Nov. 30, 1988; revision received June 27, 1989.

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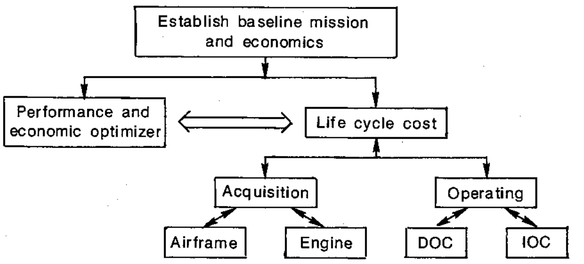


Fig. 2 Life cycle cost conceptual design system organization.

uation of advanced aircraft concepts. FLOPS may be used to analyze a point design, parametrically vary certain design variables, or optimize a configuration with respect to these design variables using nonlinear programming techniques. Additionally, complexity factors can be used to account for advanced technologies in weights, aerodynamics, and propulsion. Previously, optimization could be done for minimum gross weight, minimum fuel burned, maximum range, or some combination of these. The addition of the LCC module to this conceptual design system allows cost to become an additional optimization parameter, making it possible to specify life cycle cost, acquisition cost, direct operating cost, total operating cost, or return on investment as the parameter to be optimized.

The LCC model is composed of elements to calculate RDT&E cost, production cost, DOC, and IOC. Existing cost models were selected for each of these elements based on their applicability to subsonic commercial aircraft and their connection to the conceptual design phase of development. A major area of concern and potential controversy is the accuracy of the cost estimate. Long-range planning is characterized by major uncertainties, a wide range of alternatives that must be considered, a lack of detailed information and data, and the like. This means that highly accurate cost estimates are most unlikely in an absolute sense. Additionally, cost should not be confused with price. Aircraft price is what the manufacturer can sell the aircraft for, whereas cost is what it actually costs the manufacturer to build the aircraft. These cost models do include a profit for the manufacturer. The cost models chosen will permit alternatives to be treated consistently so that relative comparisons are valid.

The Science Applications, Inc. (SAI) airframe model (Ref. 5) is used for airframe acquisition cost. The SAI model is composed of system-level weight and cost-estimating relationships for transport aircraft. This model provides a rapid means for estimating the approximate weight and cost of transport aircraft at the individual system level, exclusive of engines. Weight is estimated based on performance parameters and cost then is estimated as a function of weight.

The model of Ref. 6 is used to estimate the RDT&E cost of the aircraft airframe. The model uses cumulative cost data from 25 separate aircraft programs to derive cost-estimating relationships for engineering, tooling, production, materials, development support, and flight-test operations during the development phase.

The Rand Corporation model for estimating the development and production costs of military engines (Ref. 7) is used for engine acquisition costs. The model predicts the engine cost as a function of the maximum thrust of the engine at sea-level static conditions, weight, specific fuel consumption at sea-level static, turbine inlet temperature, and a pressure term (the product of flight envelope maximum dynamic pressure and the overall pressure ratio of the engine). The model was corrected for commercial engines and pricing policies by correlating predicted costs with actual costs (obtained from Ref. 8) for several commercial engines.

For DOC, the American Airlines modification (Ref. 9) of the Air Transport Association-67 model (Ref. 10) is used. A set of parametric equations to determine commercial air transport aircraft DOC as a function of aircraft design characteristics make up the American Airlines model. The output consists of the aircraft-related operating costs per trip for the different cost categories. Dividing by the average flight time yields the aircraft-related operating costs as cost per flight hour.

The Lockheed-Georgia Company model (Ref. 11) is used for IOC. The model was originally published as a proposed standard method to estimate indirect operating costs. No other models for IOC have surfaced since then and it appears that this model has become the standard. The IOC calculation is primarily a function of empirically derived constants based on airline operating experience and there is very little connection to the aircraft conceptual design parameters being used by the other cost models. Hence, IOC does not play a significant role in the aircraft optimization result but is included to complete the LCC calculation.

Complexity factors to account for the costs associated with advanced technologies were incorporated in each of these models. Factors can be applied to overall airframe RDT&E and engine RDT&E. Factors can also be applied to the manufacturing and operating costs associated with individual aircraft components and systems. Additionally, factors can be used to modify the labor rates associated with RDT&E, manufacturing, and operating. Many of the cost complexity factors associated with individual aircraft components and systems have corresponding technology factors in FLOPS, making it possible to examine the effect of an improvement (or decrement) in a specific technology and a corresponding increase (or decrease) in cost.

A proper index to convert all of the individual models to the same year dollars is required. Reference 12 contains a table of federal price deflators for the aerospace industry for 1963 through estimates for 1988 with a base year of 1982. Included are indexes for aircraft, aircraft engines and parts, aircraft parts, and a composite index. The composite index is used to convert all dollars to the same year.

The life cycle cost is found by summing all of the individual costs found in each of the separate cost models

$$\text{LCC} = \text{AF RDT\&E} + \text{AF ACQ} + \text{ENG RDT\&E} + \text{ENG ACQ} + \text{DOC} + \text{IOC}$$

where AF = airframe, ACQ = acquisition cost, and ENG = engine. The RDT&E and ACQ costs are per aircraft. The DOC and IOC are computed for dollars per block hour ($/BH) and then converted to dollars per airplane over the life of the airplane by

$$\text{DOC} = \text{DOC(\$/BH)}x\text{(BH/FLGT)}x\text{(FLGT/YR)}x\text{YR}$$

where BH = block hours, FLGT = flight, and YR = year. (BH/FLGT) is computed by FLOPS. (FLGT/YR) is the utilization and is calculated in the DOC model based on the flight length and airline experience.

Design Realities

An important part of making effective use of this design tool is understanding what the capabilities and limitations are. The critical realization is that this is a tool to assist the designer, not replace him. It can aid in the examination of alternatives but it cannot design an airplane.

The cost models are appropriate for subsonic commercial transport aircraft with turbofan or turbojet engines. The initial input to the code is a baseline airplane consisting of geometry, propulsion data, mission characteristics, and economic parameters. If desired, aerodynamic drag polars may be input; however, they can be generated by FLOPS. It is assumed that a configuration layout is done in the development of the baseline, that all geometry except the wing and engine size is fixed, and that the configuration has acceptable stability and control. The conceptual design system attempts to maintain the appropriate level of stability and control by maintaining constant horizontal and vertical tail volume coefficients. At the end of the optimization process, the designer should confirm that the stability and control characteristics of the configuration are still acceptable.

Based on the foregoing discussion, it may appear that this methodology is extremely limited. The examples presented here are conventional configurations; however, with a proper understanding, this design tool is limited only by the imagination of the designer. For example, it should be possible to examine a conventional configuration compared to a canard configuration and a twin-fuselage configuration for lowest life cycle cost. This would be done by developing a baseline configuration for each of those concepts and using this system on the individual baselines. FLOPS is very flexible in terms of its capability to handle unique configurations. The results for each baseline can be compared to determine the configuration with the lowest cost.

Results and Discussion

Description of Baselines

For this study, three different classes of subsonic commercial aircraft were used (short-, medium-, and medium-to-long-range). The baseline missions and economic assumptions for the short-range aircraft (SRAC), medium-range aircraft (MRAC), and medium-to-long-range aircraft (LRAC) are shown in Table 1. The missions are intended to be representative of realistic missions; therefore, range is not the only difference. The same economic assumptions were used for all aircraft. Baseline aircraft geometries were developed from existing aircraft of the same class. Scalable engine data appropriate to each vehicle size were used as input to FLOPS. Design variables for these aircraft were aspect ratio, wing area, wing sweep, wing thickness-chord ratio, engine thrust, and takeoff gross weight. In order to see the full effect of the optimization process, the design variables were not constrained to realistic values. The mission requirements (in particular, takeoff field length) did help maintain a certain amount of realism in the designs.

Effect of Optimization Parameter

A comparison of the wing planforms obtained when the aircraft are optimized for minimum acquisition cost (ACQ), takeoff gross weight (TOGW), LCC, DOC, and minimum fuel burned (FUEL) is shown in Fig. 3. The aspect ratio, wing area, and wing sweep are represented in the planform sketches. The wings are drawn with a common root quarter-chord location. In terms of increasing aspect ratio and wing area, all planforms start with minimum acquisition cost, TOGW, LCC, DOC, and end with minimum fuel. For the SRAC (Fig. 3a) and the MRAC (Fig. 3c), the minimum LCC and DOC planforms are identical. Aspect ratio can be used as a measure of technology by recognizing that a larger aspect-ratio wing is going to be more aerodynamically efficient but also

Table 1 Baseline missions, aircraft, and economics

	Short-range aircraft	Medium-range aircraft	Medium-to-long-range aircraft
Range, n.mi.	1,000	2,500	4,500
Cruise Mach	0.78	0.80	0.82
Max. cruise alt., ft	35,000	40,000	45,000
Passengers	100	200	500
TOFL, ft.	6,000	7,000	10,000
No. of engines	2	2	4

Baseline Economic Assumptions
(for all aircraft)

Year for calculations	1987
Spares factor for airframe	0.10
Spares factor for engines	0.30
Airframe production quantity	400
No. of prototype aircraft	2
No. of flight test aircraft	2
Prior no. of engines procured	0
Depreciation period	14 yr
Lifetime	14 yr
Residual value at end of life	15%
Fuel price	$0.50/gal

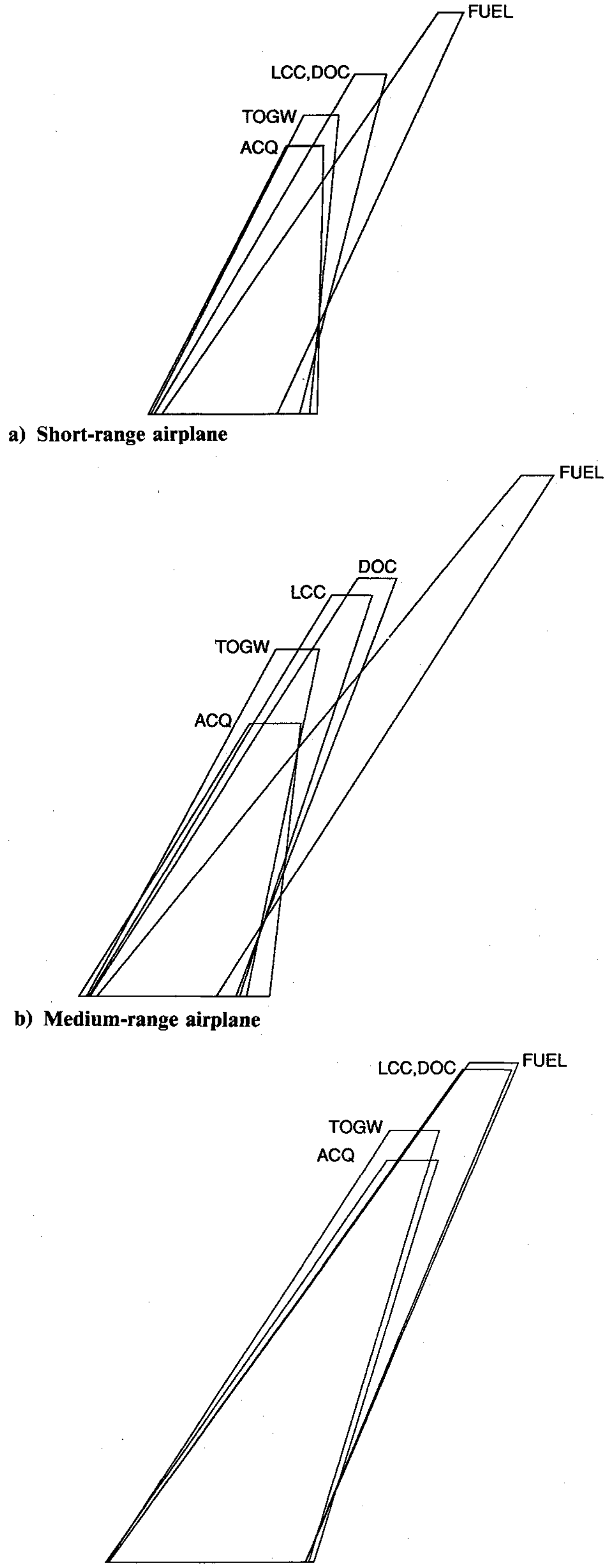
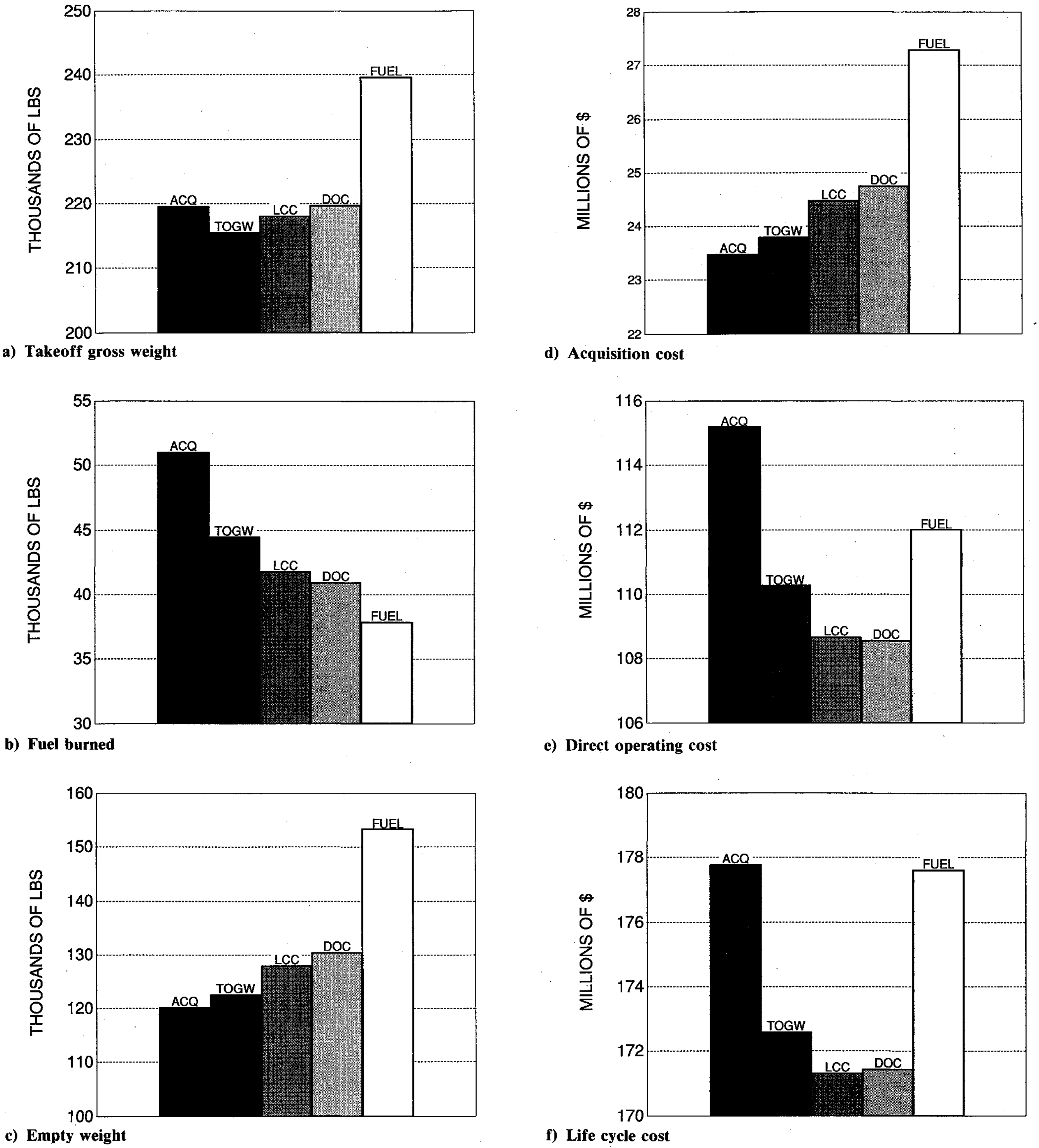


Fig. 3 Effect of optimization parameter on wing planform.



a) Takeoff gross weight
b) Fuel burned
c) Empty weight
d) Acquisition cost
e) Direct operating cost
f) Life cycle cost

Fig. 4 Optimization parameter effect on medium-range airplane.

heavier and more expensive to build. The minimum acquisition cost airplane is dependent primarily on the structural weight of the airplane, the minimum fuel airplane is dependent primarily on the fuel weight, and the minimum TOGW airplane depends on both the structural weight and fuel weight. The minimum DOC airplane is dependent on the cost of fuel, the cost of maintenance, and has a secondary dependence on the acquisition cost of the aircraft. The minimum LCC airplane balances both the operating and acquisition costs of the airplane. For the short- and medium-range aircraft (Figs. 3a and 3b, respectively), the minimum LCC and DOC planforms are closer to the minimum TOGW airplane, whereas for the medium-to-long-range aircraft (Fig. 3c), the minimum LCC and DOC planforms are very close to the minimum fuel planform. The following discussion will investigate the differences between these configurations further. Due to space limitations, only the details for the medium-range aircraft will be presented.

The bars in the graphs of Fig. 4 each represent the values of TOGW (Fig. 4a), fuel burned (Fig. 4b), empty weight (Fig. 4c), acquisition cost (Fig. 4d), DOC over the lifetime of the aircraft (Fig. 4e), and LCC (Fig. 4f) associated with the medium-range aircraft that have been optimized for minimum ACQ, TOGW, LCC, DOC, and FUEL. The minimum fuel airplane has the highest TOGW, whereas the minimum acquisition cost airplane burns the most fuel. With the exception of the minimum acquisition cost airplane, TOGW increases with increasing aspect ratio and wing area. The amount of fuel burned decreases for all cases with increasing aspect ratio. The minimum acquisition cost airplane has the lowest empty weight, whereas, the minimum fuel airplane has both the highest empty weight and highest acquisition cost. The minimum LCC airplane has a slightly higher empty weight and acquisition cost then the minimum TOGW airplane. With the exception of the minimum fuel airplane, DOC decreases with increasing aspect ratio. The LCC of the configuration follows the technology trends with the extremes (minimum fuel and acquisition cost airplanes) having very high LCC and the minimum TOGW, LCC, and DOC airplanes having lower LCC. Both the short- and medium-to-long-range airplanes show similar results, although fuel played a much more important role in the medium-to-long-range airplane. The minimum LCC and DOC airplanes are dependent on the economic assumptions. The DOC and LCC airplanes are very similar because with these economic conditions the elements that determine DOC (fuel, maintenance, salaries, acquisition cost, and so on) are of equal importance with the elements that determine LCC (acquisition cost and DOC). In the following section, the effects of economic assumptions such as fuel cost and lifetime on the medium-range aircraft will be examined.

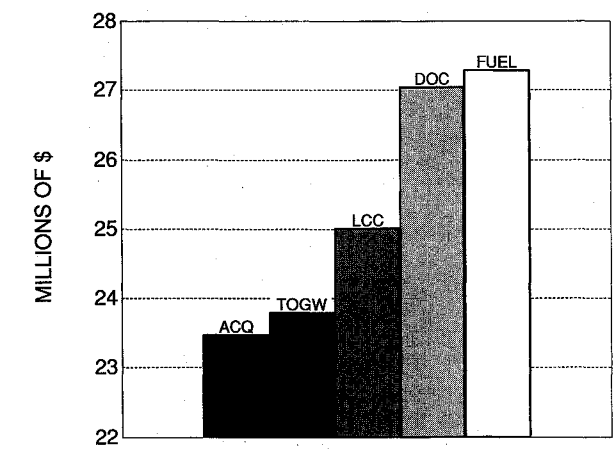
Economic Condition Effects

Figure 5 shows results from optimization runs for minimum LCC and DOC for the medium-range airplane with fuel at \$2.00 per gallon. The effect of increasing fuel price is to increase the amount of technology that can be included for both the minimum LCC and DOC airplanes. Once again, acquisition cost (Fig. 5a) increases with an increasing technology level. The minimum LCC and DOC airplanes have higher acquisition costs than before. As might be expected, the minimum DOC and minimum fuel aircraft have nearly identical acquisition and life cycle costs (Fig. 5b). This is because the fuel cost has become a much more important factor than acquisition cost in determining DOC. The amount of technology that can be included on the minimum LCC airplane is restricted by the balance between increases in acquisition cost and decreases in direct operating cost. Additionally, the differences in life cycle cost between the minimum LCC, DOC, and FUEL airplanes is not that great.

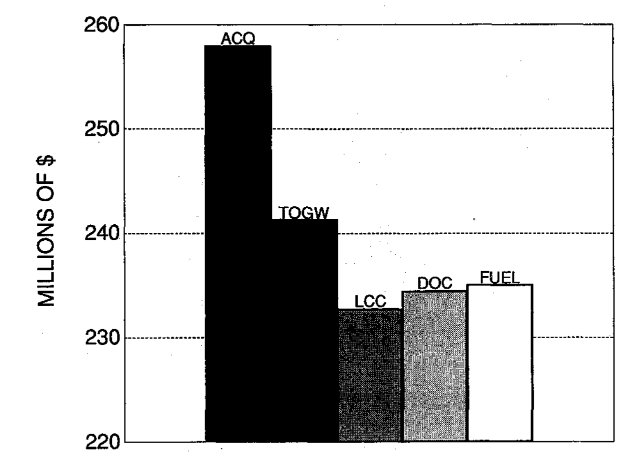
Another important set of economic assumptions is the lifetime of the aircraft and its residual value at the end of that lifetime. To illustrate these effects, results are shown (Fig. 6) for the medium-range aircraft when optimized for minimum DOC and LCC with a lifetime of eight years and a residual of 30%. Utilization of these aircraft in terms of number of flights per year is identical to the baseline. In this case, the LCC and DOC airplanes are identical. The trends for acquisition cost (Fig. 6a) and LCC (Fig. 6b) are the same as before, but the reduced lifetime makes a lowered acquisition cost and technology level more important than saving fuel in order to keep the LCC low for both the minimum LCC and DOC airplanes.

Number of Engines Study

Table 2 illustrates one of the real payoffs of including cost in conceptual design. Each of the three classes of aircraft was optimized for minimum LCC with two, three, and four engines. If the number of engines is selected based on minimum TOGW, empty weight, or fuel burned, in all cases four en-

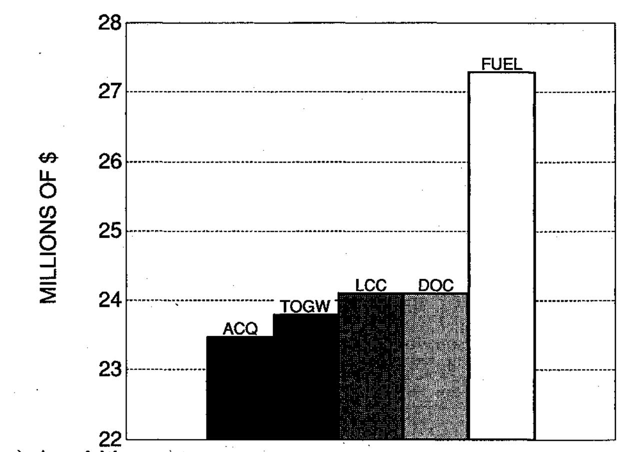


a) Acquisition cost

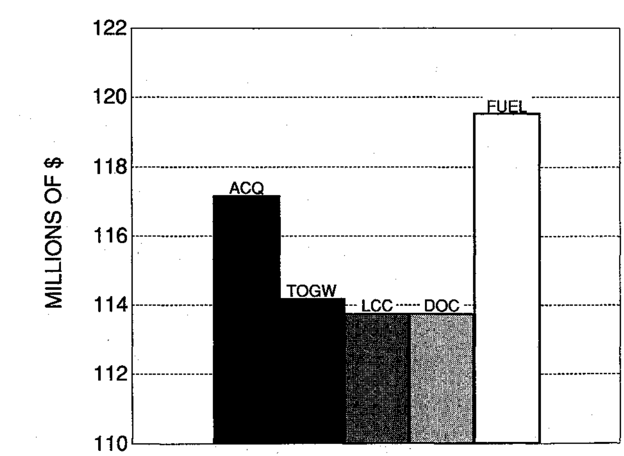


b) Life cycle cost

Fig. 5 Medium-range aircraft fuel price sensitivity (fuel = \$2.00/gal).



a) Acquisition cost



b) Life cycle cost

Fig. 6 Lifetime and residual effects on the medium-range aircraft (lifetime = 8 yr, residual = 30%, fuel = \$0.50/gal).

Table 2 Effect of number of engines

No. of engines:	4	3	2
Short-range airplane			
TOGW, lb	86,705	92,014	90,064
Empty weight, lb	50,386	54,939	52,613
Fuel, lb	12,402	13,031	13,541
Thrust, lb	5,218	8,184	13,839
Thrust-to-weight	0.24	0.27	0.31
LCC, M$	114.50	118.36	114.14
DOC, M$	79.20	81.62	78.37
ACQ., M$	11.90	12.92	11.81
Cost/engine, M$	0.38	0.51	0.72
Total engine cost, M$	1.52	1.53	1.44
Medium-range airplane			
TOGW, lb	201,616	215,645	216,086
Empty Weight, lb	113,551	125,856	127,938
Fuel, lb	39,686	41,212	41,784
Thrust, lb	14,384	21,437	34,542
Thrust-to-weight	0.29	0.30	0.32
LCC, M$	173.11	176.25	171.32
DOC, M$	111.28	112.39	108.67
ACQ, M$	23.49	25.44	24.48
Cost/engine, M$	0.71	0.86	1.15
Total engine cost, M$	2.84	2.58	2.30
Medium-to-long-range airplane			
TOGW, lb	753,658	807,769	948,147
Empty Weight, lb	389,740	409,937	497,152
Fuel, lb	251,055	274,610	327,932
Thrust, lb	33,750	54,994	122,863
Thrust-to-weight	0.18	0.20	0.26
LCC, M$	395.40	414.28	457.42
DOC, M$	250.03	264.55	301.71
ACQ, M$	55.92	59.48	64.14
Cost/engine, M$	1.14	1.49	2.26
Total engine cost, M$	4.56	4.47	4.52

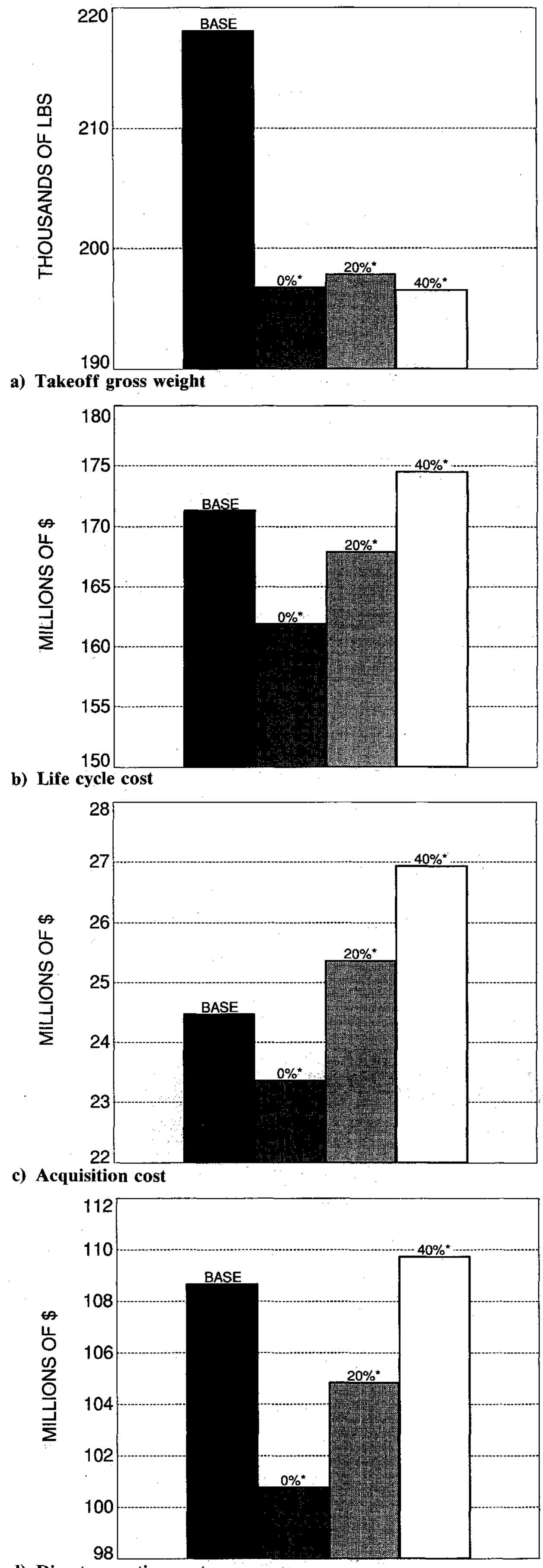
Table 3 Technology effect assumptions

Performance improvements in aerodynamics

Advanced technology airfoil
40% Laminar flow on wing, horizontal tail, vertical tail, body, and nacelles

Cost increases			
0%	20%	40%	In airframe R&D
0%	20%	40%	In manufacturing of wing, body, nacelles, and tail
0%	20%	40%	In operating of wing, body, and nacelles
0%	20%	40%	In maintenance labor rate

gines would be chosen. However, if the number of engines is based on minimum LCC or DOC, only in the case of the medium-to-long-range aircraft would four engines be chosen. The short- and medium-range aircraft both have minimum DOC and LCC with two engines. If minimum acquisition cost is the criterion for selection, four engines would be chosen for the medium- and medium-to-long-range aircraft; once again, two engines would be selected for the short-range aircraft. For the short- and medium-range aircraft, the total cost for two engines is less than the cost for four engines. Additionally, the maintenance cost is a much greater function of the number of engines than it is of engine size. Therefore, from an economic viewpoint, two engines is the logical choice. For the medium-to-long-range aircraft, however, the total engine cost is approximately constant. The one-engine out requirements drive this very large airplane to very large engines. All costs increase



a) Takeoff gross weight

b) Life cycle cost

c) Acquisition cost

d) Direct operating cost

Fig. 7 Effect of aerodynamic technology and cost assumptions on the medium-range aircraft (fuel = $0.50/gal, lifetime = 14 yr, residual = 15%). *Cost for advanced aerodynamics technology.

with the decreasing number of engines, making four the correct choice. This exercise was also conducted based on minimum TOGW aircraft; the results were identical. This type of application makes a very strong argument for considering cost in the conceptual design process.

Technology-Level Study

As mentioned earlier, FLOPS has the capability to account for advanced technologies through the use of complexity factors. Similar factors were included in the LCC module. Complexity factors can be applied to airframe RDT&E, engine RDT&E, and manufacturing and operating costs associated with the individual aircraft components and systems. With these factors, it is possible to specify a technology improvement (or decrement) and a corresponding cost increase (or decrease). If these increments are known, they may be used to determine their effect on the configuration. However, one of the true values of this conceptual design system is the capability to evaluate the sensitivities of the aircraft to these technology and cost increments. An example is presented for an increase in aerodynamic technology for the medium-range aircraft. Table 3 shows the aerodynamic performance improvements assumed and the corresponding cost increments. Three sets of cost increments (no additional cost, 20% additional cost, and 40% additional cost in each element shown) were used to evaluate the sensitivity of this configuration to the change in cost. (All other economics are the baseline assumptions.)

The TOGW of the medium-range aircraft when optimized for minimum LCC is shown in Fig. 7a. Applying aerodynamics technology results in a large decrease in TOGW. The small differences in TOGW for the various cost increments are real (i.e., not functions of an unconverged optimization). When there is no associated cost increase, the LCC is also dramatically reduced as seen in Fig. 7b. With a 20% cost increase the LCC is still less than the baseline. If the cost increase is as much as 40%, the resulting LCC is greater than the baseline. For this set of economic conditions, a cost increase of up to approximately 30% appears to be tolerable for this technology set. The acquisition cost and direct operating cost for this configuration are shown in Figs. 7c and 7d, respectively. As would be expected, for no increase in cost associated with advanced technology, the acquisition and direct operating costs are less than for the baseline aircraft. For a 20% increase in cost, the acquisition cost is somewhat greater than the baseline and the direct operating cost is still significantly less. A 40% increase in cost leads to higher acquisition and direct operating costs. Similar results were obtained for the configuration when optimized for minimum takeoff gross weight. The point at which advanced technology is affordable is highly dependent on the assumed economic conditions. In addition to aerodynamics, this system can handle weight, propulsion, and systems technologies and costs. They may be evaluated individually or combined.

Conclusions

A conceptual aircraft design system had been developed to include LCC in the design of subsonic commercial transports. With this system, a configuration can be optimized for minimum LCC, DOC, or acquisition cost, in addition to minimum TOGW, fuel burned, or maximum range. Absolute cost estimates produced may be questionable; however, alternatives are treated consistently so that relative comparisons between configurations are valid. Extensive use of the methodology on short-, medium-, and medium-to-long-range aircraft has demonstrated that the system works well. Results from the study show that optimization parameter has a definite effect on the aircraft, and that optimizing an aircraft for minimum LCC results in a different airplane than when optimizing for minimum TOGW, fuel burned, DOC, or acquisition cost. Additionally, the economic assumptions can have a strong impact on the configurations optimized for minimum LCC or DOC. Also, results show that advanced technology can be worthwhile, even if it results in higher manufacturing or operating costs. Examining the number of engines on a configuration demonstrated a real payoff of including LCC in the conceptual design process: the minimum TOGW or fuel aircraft did not always have the lowest LCC when considering the number of engines.

Acknowledgments

The work described in this article was conducted in partial fulfillment of the requirements for the Doctor of Philosophy Degree from the University of Kansas. The author would like to express special appreciation to her advisor, Jan Roskam, of the Aerospace Engineering Department at the University of Kansas. The author would also like to thank the NASA Langley Research Center staff, and the Advanced Vehicles Division in particular, for their support of this graduate study and research effort. In addition, the author is indebted to L. Arnold McCullers of the Planning Research Corporation for supplying FLOPS, the Flight Optimization System, without which this research would not have been possible. Last but not least, deep gratitude is expressed to the special women of Zonta International for their generous support of this effort through two Amelia Earhart Fellowships (1985–86 and 1986–87).

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