LIFE CYCLE COST IN THE CONCEPTUAL DESIGN
OF SUBSONIC COMMERCIAL AIRCRAFT
VOLUME 1 - DISCUSSION

Dissertation
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ABSTRACT

A methodology has been developed which makes it possible to identify an aircraft concept that will meet the mission requirements and have the lowest life cycle cost (LCC). Provision is made in the methodology for sensitivities to advanced technologies to also be investigated. The methodology consists of:

1) a LCC module composed of elements to calculate RDT&E (research, development, testing, and evaluation) cost, production cost, DOC (direct operating cost), and IOC (indirect operating cost), and

2) an existing conceptual design and analysis code, the Flight Optimization System (FLOPS).

Using this methodology, a configuration can be optimized for minimum life cycle cost, direct operating cost, or acquisition cost, in addition to minimum takeoff gross weight (TOGW), fuel burned, or maximum range.

Use of the methodology on short-, medium-, and medium-to-long range subsonic commercial aircraft has demonstrated that optimization parameter has a definite effect on the aircraft; optimizing 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 and operating costs.
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LIST OF SYMBOLS

ACQ  Acquisition cost, millions of dollars
ADV  Advanced
AERO Aerodynamics
AF   Airframe
AMPR Airframe unit weight, pounds
AR   Aspect ratio
ATA  Air Transport Association
BASE Baseline
BH   Block hour
CER  Cost estimating relationship
c/4  Wing quarter chord
DOC  Direct operating cost, millions of dollars
E    Endurance, hours
ENG  Engine
EW   Empty weight, pounds
FLGT Flight
FLOPS Flight Optimization System
FUEL Fuel burned, pounds
G    Constraints for FLOPS optimization process
IOC  Indirect operating cost, millions of dollars
LCC  Life cycle cost, millions of dollars
LIFE Lifetime, years
LRAC Medium-to-long range aircraft
ltr  loiter
L/D  Lift-to-drag ratio
$M_{ff}$  Mission fuel fraction
MQT  Model qualification test
MRAC  Medium-range aircraft
M$\$  Millions of dollars
OBJ  Objective function for FLOPS optimization process
OWE  Operating weight empty, pounds
PROP  Propulsion
R  Range, nautical miles
R&D  Research and development
RDT&E  Research, development, testing and evaluation
REF  Reference
RESID  Residual value at the end of the lifetime, percent of acquisition cost
RK  penalty function factor for FLOPS optimization process
ROI  Return on investment, percent
sfc  Specific fuel consumption, pounds/hour/pound
S_{ref}  Reference wing area, square feet
SRAC  Short-range aircraft
SUMT  Sequence of Unconstrained Minimizations Technique
SYS  Systems
T  Thrust per engine, pounds
TOA  Time of arrival
TOC  Total operating cost, millions of dollars
TOFL  Takeoff field length, feet
TOGW  Takeoff gross weight, pounds

t/c  Thickness-to-chord ratio

T/W  Thrust-to-weight ratio

V  Velocity, knots

V/STOL  Vertical/short takeoff and landing

W  Weight, lb

WBS  Work breakdown structure

W_{crew}  Weight of crew, pounds

W_{E}  Weight empty, pounds

WER  Weight estimating relationship

W_{F}  Fuel weight, pounds

W_{PL}  Payload weight, pounds

W_{tfo}  Weight of trapped fuel and oil, pounds

W_{TO}  Takeoff gross weight, pounds

WTS  Weights

W/S  Wing loading, pounds per square foot

\( \Lambda \)  Sweep angle, deg
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 (ref. 1) that between 70 and 80 percent 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, making it critical to consider cost in the conceptual design process.

Considering LCC for military aircraft is the current industry standard; it is also necessary for commercial aircraft to weigh the merit of decreases in operating costs against increases in acquisition cost and vice versa. In addition to the obvious benefits to manufacturers and customers through the reduction of life cycle cost, society will ultimately benefit since it must bear the final cost of all activity undertaken by man. Recent improvements in computer capabilities and development of codes specifically oriented toward conceptual design make it possible to consider cost simultaneously with other conceptual design variables.

1.1 PURPOSE AND OBJECTIVES

The purpose of this research effort was to develop methodology to incorporate life cycle cost in the conceptual design process of
subsonic commercial aircraft. Investigation determined that considering life cycle cost for military aircraft is currently the industry standard; no information was found in the open literature relating life cycle cost to commercial aircraft. Specific objectives of this research effort were:

1) to investigate the current status of cost estimation, particularly related to conceptual aircraft design;
2) to develop methodology to include cost in the conceptual design process so that an aircraft concept can be identified that will meet the mission requirements and have the lowest life cycle cost, and
3) to demonstrate the value of the methodology by showing:
   a) that designing an aircraft concept for minimum life cycle cost yields a different concept than designing the concept for minimum takeoff gross weight, empty weight, or fuel burned;
   b) the effect of economic conditions on the final concept;
   c) the advantages of using cost instead of the traditional design parameters (takeoff gross weight, empty weight, fuel burned), and
   d) the sensitivity of the configuration to advanced technologies and their costs.

1.2 APPROACH

The approach used to accomplish the research objectives is as follows:

1) Conduct a literature search about cost estimating methods and conceptual design.
2) Develop a methodology by:
   a) identifying appropriate cost models and developing a life cycle cost module;
   b) identifying appropriate existing design and analysis code that includes conceptual design variables; and
   c) integrating the life cycle cost module into the conceptual design code.

3) Demonstrate the methodology by:
   a) using three different aircraft,
   b) examining the effect of the objective function,
   c) examining the effect of economic variables,
   d) identifying the benefits of using life cycle cost instead of traditional conceptual design parameters, and
   e) examining the sensitivities of the aircraft to advanced technologies and their associated costs.

The results of the literature search on cost estimation and conceptual design are presented in Chapters 2 through 6. Chapter 7 describes the methodology developed and Chapter 8 contains a discussion about the assumptions, limitations, and realities in using the methodology. The study conducted to demonstrate the use of the methodology is documented in Chapter 9. Conclusions are summarized in Chapter 10. Volume 2 of this report contains specific details about the computer codes.
CHAPTER 2
CONCEPTUAL DESIGN

Conceptual aircraft design is that phase wherein the general size, configuration, and estimated performance of the aircraft is determined (ref. 2-7). The primary purpose at this level is to provide technical and economic feasibility information for guiding larger efforts during the detailed design phase (ref. 8). According to reference 7, until about 1955-1960 conceptual aircraft design studies were generally based on relatively simple criteria and methods. Although published contributions (e.g., refs. 9-11) have not always been representative of industrial practice, they do indicate that early parametric studies were made on a limited scale, frequently by highly competent and experienced designers with a thorough insight into what could be considered as realistic optimization opportunities in the conceptual design process. The situation changed drastically when high-speed digital computers were introduced, enabling the designer to analyze a virtually unlimited number of parametric variations.

Present computerized design programs have materially aided in developing aircraft in the early design phases so that risk is reduced and there is greater assurance of meeting the design objectives when hardware is built. Nevertheless, there are still some obvious problems in structuring conceptual design that prevents completely computerized designs (ref. 12). The evolving design concepts must be integrated, hopefully in a synergistic or
complimentary way but more usually in a compromise. The conceptual design problem is composed of a large number of interacting technical factors drawn from several different engineering and scientific disciplines, and is complicated by the need to satisfy numerous mission requirements and constraints. The difficulties are further compounded by the rapid rate of technical progress in the aeronautical sciences, which forces the designer to either work with uncertain data from the frontiers of knowledge or to use proven technology and risk producing an obsolescent aircraft (ref. 13). The process involves innovation and inventiveness. Applications of judgement are required if the design is to be successful.

One phase of the conceptual design process is vehicle sizing where an estimate of the aircraft size and weight is made based on its design, mission, and payload. It has inherent capability to trade off various geometric and aerodynamic parameters and is sensitive to the payload and mission profile of a configuration (ref. 2-6, 14). In the past, parametric studies in which one or two of the principal design characteristics (e.g., wing loading, thrust-to-weight ratio) were varied to discover how the variation affected the aircraft design and performance. These limited parametric studies did help designers with imagination and sound technical insight to improve aircraft design, but they were not entirely satisfactory because varying only a few of the design characteristics did not reveal the entire range of potential improvements. Additionally, the results obtained by varying a
single design characteristic while others remain fixed can be misleading, as the fixed values are necessarily most appropriate to one value of the varying characteristic and this value may not be the best (ref. 13).

Recent developments in computer capability and mathematical modeling of aircraft design and performance parameters have resulted in the development of conceptual design optimization computer codes. However, contributions to design optimization were made long before the computer-aided design era (ref. 7). Göthert, in 1939, made one of the first comprehensive attempts to optimize the span and wing area of propeller aircraft (ref. 15). In 1949, Pearson made an elementary derivation of the optimum engine thrust and Mach number for long-range jet aircraft (ref. 16). Ashkenas (1948) studied optimum cruise conditions for constant engine ratings and devised an aerodynamic criterion for the optimum wing area (ref. 17). Backhaus, in 1958, attempted a comprehensive optimization of jet transports (ref. 18) while Sanders, in 1961, made various analytical studies involving wing weight variation and demonstrated the importance of differences in the figures of merit (ref. 19). Bagby and Anderson (1965) isolated the engine optimization problem from the overall airplane design cycle (ref. 20). In 1968, Küchemann and Weber made an important contribution to the optimization of cruise altitude and engine thrust, based on maximum payload fraction (ref. 21).

The need to provide optimization and tradeoff-type calculations that result in the best performance for a vehicle concept is an
important requirement in computerized conceptual design. Reference 8 presents the case of a remotely piloted vehicle which was constrained to a specified level of performance in terms of sustained turn rates at two different Mach numbers and altitudes. The optimization process selected the best combination of wing area, sweep, thickness ratio, taper ratio, vehicle thrust-to-weight ratio, body diameter, and body fineness ratio for the minimum gross weight vehicle capable of performing the mission with its constraints. The design variables did not change significantly, yet the gross weight was reduced by 27 percent. Unless these types of optimizations are performed, the study concepts have poorer performance than necessary and make comparisons between concepts less valid.
Traditionally engineers have designed systems that maximize performance and have minimum 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 percent of the life cycle cost of a configuration is locked in during the concept stage of development (refs. 1, 22-29), as illustrated in figure 3.1 (taken from ref. 1). During this early stage, commitments are made on aircraft performance, thus implying a technology level. Based on past cost investigations of commercial programs at the Boeing Company, reference 30

Figure 3.1 - Cumulative percent of LCC committed and actual funds spent for a typical military aircraft (taken from ref. 1).
illustrates the same concept from a different perspective.

Figure 3.2 (taken from ref. 30) shows the management leverage on

and total cost of a program as a function of time. Management action taken after program go-ahead, when less than three percent of the eventual program cost has been spent, can influence the total program cost by 20 percent at most. The program cost is largely determined by the time the market is identified and the airplane concept formulated.

These examples show that the early consideration of cost is important. Reference 31 suggests that costs are important only if tradeoffs exist; if there are no choices (e.g., among alternative systems, designs, manufacturing processes, production rates, etc.) then cost is not meaningful. The importance of considering cost and making tradeoffs is not new to the field of aeronautics or to the world in general:
When we mean to build,  
We first survey the plot, then draw the model;  
And when we see the figure of the house,  
Then we must rate the cost of the erection;  
Which if we find outweighs ability,  
What do we do then but draw anew the model,  
In fewer offices or at least desist,  
To build at all.

William Shakespeare  
King Henry IV Part II (1597-8)  
(From ref. 32)

The choice of the appropriate type of cost to be considered in the conceptual design phase for commercial aircraft is crucial. In past commercial aircraft conceptual design studies where cost has been considered at all, the operating economics (either direct operating cost or return on investment) have typically been used as the comparison between different concepts (refs. 33-35 to name a few). Considering operating costs accounts for the airlines' point of view but ignores the considerations of the manufacturer.

The military world functioned in the opposite mode in the past - the acquisition cost (development and production) was heavily emphasized and operating costs were virtually ignored. Then, for a variety of reasons, the operations costs began to make up a majority of the total cost on specific aircraft systems (refs. 36-38). Since the same source of funding had to cover both acquisition and operating costs, the importance of both costs was noticed and acted on. The military now places major emphasis on the total (or life cycle) cost of an aircraft system. References 7 and 39 both recognize the minimization of life cycle costs (LCC) for military aircraft while direct operating cost (DOC) or return on investment (ROI) are used for commercial aircraft.
The life cycle cost of an aircraft is the total cost to transition the aircraft from "cradle to grave" (ref. 1). It includes the cost of development, acquisition, operations, support, and where applicable, disposal (ref. 40). 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, while an objective of achieving the ultimate in low cost can lead to substantial penalties on performance and technical specification (ref. 41). The fundamental problem appears to be the requirement to spend large dollars now in order to acquire a potential future savings. Use of the conceptual design process to assess the future savings is useful in permitting a more balanced judgement.

The commercial world has recently recognized the importance of considering life cycle costs. Discussions with personnel at Boeing Commercial Aircraft Company have indicated that there are as many people involved with the life cycle cost issues of the 7J7 program as are involved with the technology issues. Reference 27 also notes that cost is becoming more important than technology requirements during design and development. These reasons make clear that it is important to consider life cycle cost in the conceptual design of commercial transport aircraft. Additionally, regardless of whether military or commercial, the cost is borne by society.
Until recently, efforts to include cost in the conceptual
design process have either examined only a piece of the total cost
(i.e., acquisition or operating), or used the result of the sizing
process to estimate the cost, or both. There are many existing
computer codes which will estimate some portion of the cost for a
given concept (refs. 24, 42-62). These codes do not, however,
provide the designer with any insight into methods to reduce the
cost. Instead he must use trial and error to find the concept with
the lowest cost and there is no guarantee that the actual minimum
has been found. Appendix A contains a description of each of these
codes. Recently optimization has been proposed to consider cost in
the conceptual design process and computer codes have been
developed to minimize different pieces of the cost (refs. 13,
63-68). These codes are described in Appendix B. One of these
codes (ref. 68) is capable of minimizing the LCC for V/STOL
military aircraft for either maximum speed at best altitude,
minimum gross weight, or maximum thrust. The program in
reference 13 is capable of considering a combination of different
costs but the authors deemed it inappropriate to look at anything
more than direct operating cost (DOC).

Using LCC as the objective function (parameter to be minimized)
in the conceptual design process should yield a different aircraft
than using takeoff gross weight, empty weight, fuel burned, or
direct operating cost. Figure 3.3 (taken from reference 69)
illustrates the differences obtained when using takeoff gross
weight, empty weight, and fuel burned as the objective function to
Figure 3.3 - Effect of constraint parameter on optimum design (taken from ref. 69).

find the optimum aspect ratio. Aspect ratio is presented as the design variable only as an example and in this case no constraint was placed on the realistically achievable maximum aspect ratio. Generally low aspect ratio is associated with low technology levels and reduced weight, manufacturing costs, and performance; the reverse is true of high aspect ratios. The minimum OWE occurs at a low aspect ratio while the minimum mission fuel occurs at high aspect ratio. The minimum takeoff gross weight occurs at a mid aspect ratio. This figure suggests introducing economics as the objective function. References 70 and 71 discuss the differences obtained when transports are optimized for minimum fuel burned versus minimum DOC. The final aircraft are different and the primary difference is due to the fuel price used to calculate direct operating cost. For high fuel costs, the weight and cost penalties associated with high aspect ratio are compensated for by the reduced amount of fuel burned. Using LCC as the objective
function would include both aircraft structure (manufacturer's view point) and performance (operator's view point) in comparable units (dollars).

Life cycle costing is a method of forecasting the cost of future events, and is much like forecasting the weather (ref. 27). Engineers tend to be uncomfortable dealing with future unknowns that cannot be estimated from a scientific basis and, left to their own desires, would avoid the consideration of cost completely. Much time is sometimes wasted in refined analysis of the purely technological end of a problem, to a degree quite absurd in relation to the irreducible uncertainties in the marketing situation. Consequently, the engineer feels betrayed when calculations are upset by a perfectly ordinary market change, while the economist feels that the engineer spends too much time on irrelevancies (ref. 72). Increases in the cost of aircraft programs over time and recognition of the importance of cost consideration early in the design process have made it necessary for engineers to become more concerned with economics. Systems analysis techniques and a conceptual design (mission analysis) process provide a powerful tool for the exploration and tradeoff of system alternatives (ref. 27). The following chapter will define the systems analysis process and the role of cost in systems analysis.
CHAPTER 4
SYSTEMS ANALYSIS

Systems analysis may be defined as inquiry to help decision-makers in choosing preferred future courses of action by:

1) systematically examining the relevant objectives and the alternative strategies for achieving them, and

2) comparing quantitatively where possible the economic costs, effectiveness (benefits), and risks of the alternatives.

Systems analysis is more a research strategy than a method or technique. It is more an art than a science, although scientific methods are utilized wherever possible. In sum, systems analysis may be viewed as an approach to, or a way of looking at, complex problems of choice, usually under conditions of uncertainty (ref. 73).

Before launching into how cost can be considered in systems analysis, it is first worthwhile to define costs, benefits, and the relationship between the two. "Economic costs" are benefits lost. For this reason, economic costs are often referred to as "alternative costs" or "opportunity costs" (ref. 73). The real meaning of cost must be found in alternatives or forgone opportunities. (The only reason that you hesitate to spend a dollar is because of the alternative things that it could buy.)

Minimizing costs and maximizing benefits are opposite sides of the same coin. The task is never as simple as just doing one or the other. Neither the cheapest nor the most expensive is always
the best. The aim is either to minimize the costs of accomplishing a certain mission or to maximize the benefits achieved at a certain level of cost. If the cost of attaining a certain level of output is minimized, it inevitably follows that the level of output attainable for that given level of cost is maximized. Hence, costs and benefits have the same dimensions.

The analysis process usually proceeds by a series of iterations through five main phases. They are (ref. 73):

1) Formulation (The Conceptual Phase) - The objectives of the analysis are defined, issues related to the objectives are identified, the scope of the problem is limited to keep the analysis manageable, and the appropriate criteria for choosing between alternatives are identified.

2) Search (The Research Phase) - Data and relationships are sought, along with alternative actions that are believed to have some chance of solving the problem.

3) Evaluation (The Analytical Phase) - Various models are built, they are used to predict the consequences from each choice of alternatives, and alternatives are compared in terms of consequences.

4) Interpretation (The Judgemental Phase) - The predictions obtained from the models along with whatever other information or insight is relevant are used to compare the alternatives further, derive conclusions, and indicate a course of action.
5) Verification (The Testing Phase) - The conclusions are tested where possible.

It is difficult to say which of these phases is most important. However, the first should receive particular emphasis. Many analyses flounder right here, simply because of the failure to devote enough time for a study to deciding what the problem really is. The formulation should identify the subproblems involved, isolate the major factors, develop a vocabulary for dealing with them, sketch out relationships between the variables as they appear, and even arrive at a tentative set of conclusions. The idea is to make clear the structure of the analysis. But more importantly, it offers a concrete hypothesis for others to probe.

As mentioned above, the evaluation phase involves building models. The main purpose in designing the model is to develop a meaningful set of relationships among the objectives, the relevant alternatives available for attaining the objectives, the costs of the alternatives, and the utility of each of the alternatives. Model building is an art, not a science. It is often an experimental process. The goal is to try to include and highlight those factors which are most relevant to the problem at hand, and to suppress (judiciously) those which are relatively unimportant. Unless the latter is done, the model is likely to be unmanageably large. Also, provision must be made in the model for the explicit treatment of uncertainty. Finally, since by definition a model is an abstraction from reality, the model must be built on a set of assumptions. These assumptions must be made explicit.
Since the model is only a representation of reality, it is desirable to do some sort of checking to see if the analytical procedure used is a reasonably good representation, within the context of the problem at hand. This is difficult to do, especially in dealing with systems analysis problems having a time horizon 5, 10, or more years into the future. However, questions such as the following might help establish the validity of the model:

1) Can the model describe known facts and situations reasonably well?
2) When the principal parameters involved are varied, do the results remain consistent and plausible?
3) Can the model handle special cases where there are already some indications as to what the system should be?
4) Can the model assign causes to known effects?

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, for the most part, highly accurate cost estimates are most unlikely in an absolute sense. A significant body of opinion seems to believe the fallacy that a high degree of accuracy can be obtained by going into a greater amount of detail. It is not at all clear, especially for long-range planning, that a higher degree of accuracy can be attained by trying to force the analysis into a finer and finer grain of
detail. With a limited data base, it becomes very easy to use essentially fictitious numbers to fill in the overly detailed categories, with the result that the output of the analysis is no better than that obtained by working at higher levels of aggregation. In such instances, concentrating the analytical effort at an appropriate (relatively high) level of aggregation and using carefully derived statistical estimating relationships are the most likely means of producing fruitful results.

The level of detail included in the estimates should correspond to the level of detail required by the decision to be made (ref. 31). For example, if a choice must be made between two alternatives, the one with the lowest LCC should be selected if all else is equal. A simple bottom line estimate would suffice for that purpose. However, if a decision concerning subsystem level design options must be made, then greater detail is required. The inputs for a more detailed model may not be available or they may be obtained only through an effort that is not warranted for a gross estimate.

The most practical position is to assume that no one estimate is correct, but that a range of costs is possible due to possible variances in the forecast conditions and ground rules (ref. 74). For long-range planning studies, relative comparisons of alternatives are desired and there is no real need for a high degree of accuracy in absolute terms. There is, however, a critical need for analytical techniques that will permit alternatives to be treated consistently.
One of the major problems in systems analysis is the treatment of uncertainty. One significant source of uncertainty involves uncertainty about the state of the world in the future. Major factors here are technological uncertainty, future economic conditions, etc. Reference 73 describes three ways to treat uncertainty:

1) Sensitivity Analysis - Instead of using mean values for parameters in the analysis that have uncertainty associated with them, successively use several values (high, medium, and low) in an attempt to see how sensitive the results (the ranking of alternatives being considered) are to variations in the uncertain parameters. If a certain alternative is superior in all of these sensitivity investigations, it is referred to as a dominant solution. Dominance is a desired characteristic, but its existence is rare.

2) Contingency Analysis - This type of analysis investigates how the ranking of the alternatives under consideration holds up when a relevant change in criteria for evaluating the alternatives is postulated, or a major change in the general environment is assumed.

3) A Fortiori Analysis - Sometimes in a particular analysis the generally accepted judgement favors one alternative (e.g., A). However, if certain assumptions about uncertainty are used, another alternative (B) may be better. The major uncertainties are resolved in favor of
B and then A is compared under the adverse conditions. If A still looks good, there is a very strong case to support its selection.

While these techniques may be useful in a direct analytical sense, they may also contribute indirectly. For example, a good understanding of the really critical uncertainties in a given problem area may be gained through sensitivity and contingency analysis. On the basis of this knowledge, it might then be possible to come up with a newly designed alternative that will provide a reasonably good hedge against a range of the more significant uncertainties. This is often difficult to do; but when it can be accomplished, it offers one of the best ways to compensate for uncertainty.

Reference 8 reports on three categories of parameters for which sensitivity information is usually desired in the conceptual design of aircraft. The first category includes the mission parameters such as range, payload, turn radius, endurance, etc. The second includes the vehicle design parameters such as wing loading, wing aspect ratio, body fineness ratio, etc. The third category includes the efficiency parameters such as engine compressor efficiency, span load efficiency, minimum drag coefficient, etc. Sensitivity to mission parameters indicates the ease or difficulty with which the general concept can perform the specified mission (i.e., feasibility). Sensitivity to parameters in the second category provides information for optimizing the vehicle, since this is essentially gradient information indicating
the direction of improved performance measure. Sensitivity information from the third category is used to identify overall improvement in the vehicle due to changes in the technology of a specific area. This type of information helps focus research on the most significant areas.

To conclude this section on systems analysis, it is appropriate to look at the principles of good analysis and some of the common pitfalls. A good analysis should make efficient use of expert judgement, choose the right objectives, and conduct sensitivity testing. Additionally, failure to obtain the complete answer is not necessarily bad; partial answers to relevant questions are more useful than full answers to empty questions. Finally, estimates of cost are essential to a choice among alternatives. A few of the more common pitfalls include failing to allocate and to spend enough of the total time available for a study deciding what the problem really is, examining an unduly restricted range of alternatives, trying to do too big a job, and determining objectives and criteria carelessly. Other pitfalls include using improper costing concepts, becoming more interested in the details of the model than in the real world, forcing a complex problem into an analytically tractable framework by overemphasizing ease of computation, and failing to take proper account of uncertainty.
A cost model may be viewed as a device designed to facilitate the analytical process by bringing together the various factors on the input side and relating them to some type of output-oriented capability in the future (ref. 73). There are essentially three ways to calculate life cycle costs (ref. 24):

1) bottom-up or build-up approach,
2) comparison, and
3) parametric analysis.

1) The bottom-up approach involves determining the price and quantity of each type of material and each type of labor required for fabrication of the system under consideration. The individually determined costs are then summed (refs. 24, 58, 75-76). This method is typically used by the aircraft manufacturer and is reasonably accurate, but requires an inordinate amount of time and manpower and a data base only a manufacturer would have. For purposes such as conceptual development programs or tradeoff studies, such accuracy is not required and such a large expenditure of time and manpower is not warranted (ref. 77).

2) Comparison is possible when the new item has functions, physical, and performance characteristics similar to an existing item. The current costs on the similar item can be gathered and modified appropriately to account for the differences in configuration. The accuracy of this method is very dependent on
the level of similarity between the new and existing items, making it very limited. It is often used to calibrate parametric methods (ref. 24).

3) The parametric or top down model is, typically, an aggregate of cost estimating relationships (CERs) which have been statistically derived from historical data containing some non-cost parameters. The primary use of such a model is to predict the cost of a new product or service by extrapolating from the historical data base. A distinct advantage of this parametric approach to estimating is relief from dependency upon drawings and detailed parts list, which are not available during the program's conceptual phase (refs. 38 and 78). A parametric analysis can be done very quickly and correlates closely (two to three percent) with the bottom-up method (ref. 24).

A critical step in the development and analysis of system concepts is to identify the relationships between aircraft performance parameters and each of the elements that make up the parameter (ref. 58). Such relationships are necessary for quantitative assessment of the impact of a specific system concept. A second use for analytical relationships is in identifying "leverage" points in the various aircraft operating parameters - that is, factors that have the strongest influence on a particular improvement area. By identifying those factors which have the largest leverage, efforts can be concentrated in areas offering the largest potential payoff.
CERs are at the heart of parametric estimating. They express cost relationships among both cost and noncost variables in mathematical terms, sometimes as linear or polynomial equations regressed as historical data (ref. 25). An aggregate of CERs comprise a cost estimating model. CERs must be fine-tuned when incorporated into estimating models for at least three reasons (ref. 38):

1) to better match the product,
2) to accommodate conditions not inherent in the original data, and
3) to guard against the model becoming technologically obsolete.

Parametric models are well-suited to the conceptual design phase because of the reasonably good estimates that may be obtained with surprisingly little information. On the other hand, parametric models have many limitations. It is necessary to understand these limitations or very misleading results may be obtained (ref. 79). One limitation is the lack of sensitivity to detailed vehicle design characteristics, which is a result of the failure to report costs to the detail level in past programs and an over-reliance on weight in the cost model. Often there is a lack of adequate and relevant empirical data to build the parametric model with (ref. 31). This is true for many reasons:

1) manufacturers closely guard all cost related information (commercial cost information is never released),
2) manufacturers generally do not maintain information with the intent of developing models,

3) manufacturer may keep records in a manner that is not consistent with other manufacturers, and

4) definitions of cost elements and other variables may change over time making it difficult to compile a consistent data base spanning many years.

In determining the CERs, there are additional problems including omission of a variable, faulty measurement of variables, and misspecification of variable to variable relationships. Another limitation is the difficulty with estimating the cost of vehicles which advance the state of the art, since by definition there is usually no historical data upon which to base the estimates. This is a problem with nearly all estimating techniques. Partial solutions can be achieved through the use of "complexity factors" but only when data exist to establish the value of such factors (ref. 44). It is often difficult to find two sources which agree on the value of the complexity factor for a particular condition.

A major deficiency of past cost-estimating methods has been the result of an overreliance on the vehicle gross weight, or estimate of major airframe component weights, as the cost-driving variable (ref. 80). By assuming the use of conventional materials and structural methods, gross weight has been an important parameter in cost studies. However, recent advances in technology have produced components with increased specific strengths (hence
greater structural efficiencies and decreased weights), but with increasingly exotic materials and fabrication complexities (hence greater costs). Thus, cost is sometimes an inverse function of weight, and estimates based solely on gross weight predictions cannot accurately predict costs, especially in changing technology. A second deficiency of previous cost-estimating models has been the use of oversimplified cost models that lacked the depth necessary to provide a sensitivity to design tradeoff choices in terms of structural materials and methodology.

Cost estimating is an art form and subjectivity is a vital component. It should be recognized that there is nothing sacred about cost models (ref. 31). The objective of the model and the assumptions used should be specified to enable the user to make adjustments when the case of interest does not conform with them. Great differences in costs and relevant variables are the norm in the aircraft industry as experience within a particular firm and among similar firms varies widely.

One conclusion reached in attempting to validate airframe cost models against existing aircraft was that probably no one will ever know what they really cost anyway. The commercial transport aircraft price is particularly difficult. Reference 81 contains the following quote from the president of The Boeing Aircraft Company: "In the transport airline business, the price of the aircraft is determined in the marketplace... The price the aircraft will bring on the market is not really fixed by the manufacturer. Furthermore, it has little direct relationship to the design and
production cost of the vehicle." One of the complicating factors in arriving at the price of the aircraft is the use of new technology which leads to an increase in manufacturing costs and a decrease in DOC. Assessing the impact of cost on price should be a simple matter of calculating the cost of manufacturing and defining a selling price to provide the proper income for the company. In reality, that's not the way it works. The selling price of transport aircraft is the result of a definition process which cannot be described rationally and which is dependent on the price of existing equivalent aircraft, the various economic trends, competition, negotiation, etc., that is, finally, on the ancient law of supply and demand (ref. 39). Reference 82 points out that the ultimate cost of an aircraft will depend on the number built, which will depend on the number sold. However, the number sold will depend on their price, which is partly dependent on what they cost.

In the light of all this uncertainty, it might appear that it is hopeless to attempt predict cost for commercial transport aircraft using any kind of cost model. However, as pointed out in Chapter 5, accuracy is really secondary; what matters is consistent treatment of all parameters and a model sensitive to important cost factors. With these qualities, a cost model will allow relative comparisons between concepts.

The estimation of LCC involves estimates of acquisition and operating costs. Appendix C contains a description of several models capable of estimating acquisition cost. Many of these
models are built from military aircraft data bases and are for high-performance aircraft, leading to a question about how applicable military models are for commercial aircraft. It is necessary to understand the composition of the data base and to be aware of the limitations of the CERs but reference 77 concludes that CERs developed for military aircraft may very well be valid when they are applied to determine the cost of an entire aircraft. Appendix D contains a description of operating costs models and Appendix E describes the few models found that will determine entire LCC.
CHAPTER 6
ADVANCED TECHNOLOGIES

One way of meeting the challenge of lower LCC is by recognizing the fact that successful airplanes use mature equipment and systems. Maturity can be defined as being fully developed or perfected (ref. 29). However, to be successful an aircraft must be competitive, not outdated or obsolete. Airlines must receive a reasonable return on investment to survive. Operation of new equipment must provide enough working capital to continue purchasing additional new aircraft. To allow this self-regeneration to succeed, there must be a substantial improvement in operating economics resulting from new technologies. In a nutshell, the problem is not only developing new technologies, but developing cost-effective technologies and utilizing them in the most effective mix (ref. 83).

Technology is defined as "the application of scientific knowledge to practical purposes" (ref. 71). Practical purposes involve the economic ability to use the product. In this light, the Concorde is a magnificent technical achievement but an economic failure. The conceptual design process offers a powerful means of assessing the payoff of technical innovations and emerging technologies on system capabilities. Emphasis can be given to development and application of technologies which can reduce cost. Baseline designs and associated analyses, with and without the new technology, provide a clear means of obtaining good comparisons and
determining the impact of the new technology on the design characteristics, capabilities, cost, and timing (ref. 84).

The benefits of new technology are primarily in aircraft performance (lower fuel consumption), but may also come from reduced manufacturing expenditures and maintenance costs. In most cases, however, an emerging technology will have development, tooling, and incremental facilities costs. These nonrecurring costs must be amortized and become a significant factor in the cost-effectiveness of a new technology or technology mix (ref. 83).

For aircraft, advanced technologies will fall in the areas of aerodynamics, propulsion, structures, controls, and electronics/avionics. Many papers have been written discussing these technologies, their likely development and their potential impact on the aircraft (refs. 22, 24, 58, 71, 77, 83, 85-90). Quantitative estimates of the costs/benefits of the application of some of these technologies are available in these references. In other cases, the estimates are completely subjective. The challenge in cost modeling of new technologies is to account for these uncertainties is a reasonable, relative, and repeatable manner.
CHAPTER 7
LIFE CYCLE COST CONCEPTUAL DESIGN SYSTEM

A system has been developed to include life cycle cost in the conceptual design process as depicted in figure 7.1. The system includes a LCC module developed for this effort and an existing conceptual design and analysis code called FLOPS (Flight Optimization System). The LCC Conceptual Design System will be described in more detail in the following discussion.

Figure 7.1 - Life cycle cost conceptual design system schematic diagram.
7.1 FLOPS

The Flight Optimization System (ref. 69) is a multidisciplinary system of computer programs for conceptual and preliminary design and evaluation of advanced aircraft concepts. It originally consisted of four primary modules: weights, aerodynamics, mission performance, and takeoff and landing. Figure 7.1 shows the overall FLOPS organization; also shown is the cost module addition which will be described in detail in the next section.

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. The available design variables are wing area, wing sweep, wing aspect ratio, wing taper ratio, wing thickness-chord ratio, gross weight, thrust (size of engine), cruise Mach number, and maximum cruise altitude. 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 optimization in FLOPS uses a penalty function method also known as the Sequence of Unconstrained Minimizations Technique (SUMT). The goal of the optimization process is to find the set of
design variables which minimize the objective function (OBJ) subject to a set of constraints. There are two types of constraints: compatibility and behavioral. The compatibility constraints are upper and lower limits on each active design variable. The behavioral constraints are:

1) lower limit on range,
2) upper limit on approach speed,
3) upper limit on takeoff field length,
4) upper limit on landing field length,
5) lower limit on missed approach climb gradient thrust, and
6) lower limit on second segment climb gradient thrust.

The constraints are of the form:

\[ G = 1. - \frac{\text{value}}{\text{upper limit}} \text{ or } G = 1. - \frac{\text{lower limit}}{\text{value}} \]

The form of the unconstrained minimization problem equation is:

\[ F = \text{OBJ} + \text{RK} \left[ \frac{1.}{G(J)} \right] \]

where \( F \) is the function to be minimized, \( \text{OBJ} \) is the objective function, \( \text{RK} \) is the penalty function factor, and \( G(J) \) is the value of the \( J \)th constraint. The optimization is performed as a series of minimizations of \( F \) (called drawdowns) with the value of the penalty function factor \( \text{RK} \) successively lowered so that the constraints have less and less effect on \( F \). A drawdown consists of several finite difference gradient calculations and corresponding one-dimensional searches. The nonlinear programming technique used modifies the gradient to determine the direction for the one-
dimensional search. There are several FLOPS inputs that control the optimization process; in most cases the default values work well. Additional details about the FLOPS optimization process and inputs are contained in Appendix A of Volume 2.

7.2 LIFE CYCLE COST MODULE

A schematic diagram of the LCC module is shown in figure 7.2. It is composed of elements to calculate RDT&E cost, production cost, DOC, and IOC. These costs are calculated on a per aircraft basis for a specified production quantity. Existing cost models

Figure 7.2 - Conceptual design system cost flowchart.
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.

Input to the module comes from the FLOPS calculations and from a cost namelist input with the other FLOPS namelists. In FLOPS it is possible to specify either the inclusion or exclusion of cost calculations. If cost calculations and optimization are requested, it is then possible to specify cost as the objective function to be optimized. The models, their design variables, and the input will be described in the following sections. Validation of the cost models is contained in Appendix F.

7.2.1 Input from FLOPS

A portion of the conceptual design variables necessary to calculate cost are either used by FLOPS or calculated in FLOPS. These variables are automatically transferred from FLOPS to the LCC Module through a common block. The common block also contains a variable called COST that is returned from the LCC Module to FLOPS. This is the variable used as the objective function in optimization in FLOPS if optimization has been requested. The cost returned can be any one of several costs as will be described in the section on cost calculations. Table 7.1 shows the variables in that common block and their definitions.

7.2.2 Input from Cost Namelist

Variables related to calculating cost that do not change as the optimization proceeds are input to the LCC module through a
TABLE 7.1 - CONCEPTUAL DESIGN VARIABLES FROM FLOPS.

where:
WTS(1) = wing weight, lbs
WTS(2) = horizontal tail weight, lbs
WTS(3) = vertical tail weight, lbs
WTS(4) = fuselage weight, lbs
WTS(5) = landing gear structural weight, lbs
WTS(6) = landing gear controls weight, lbs
WTS(7) = wheels and brakes weight, lbs
WTS(8) = tires weight, lbs
WTS(9) = nacelle weight, lbs
WTS(10) = thrust reverser weight, lbs
WTS(11) = fuel system weight, lbs
WTS(12) = engine system weight, lbs
WTS(13) = flight controls weight, lbs
WTS(14) = hydraulic system weight, lbs
WTS(15) = electrical system weight, lbs
WTS(16) = pneumatic system weight, lbs
WTS(17) = air conditioning weight, lbs
WTS(18) = anti-icing system weight, lbs
WTS(19) = auxiliary power system weight, lbs
WTS(20) = furnishings and equipment weight, lbs
WTS(21) = instruments - equipment weight, lbs
WTS(22) = instruments - other weight, lbs
WTS(23) = avionics - equipment weight, lbs
WTS(24) = avionics - other weight, lbs
WTS(25) = total weight of engines, lbs
NENG = number of engines per aircraft
SMACH = maximum Mach number at best altitude
THRMAX = maximum thrust per engine, lbs
QMAX = maximum dynamic pressure during climb, lb/ft^2
RANGE = block distance, st. mi.
FUELBL = block fuel, lbs
TBLOCK = block time, hr.
SPEED = cruise speed, st. mi. per hr.
NS = number of seats
TGNDMAN = time in ground maneuver, hr
NCREW = total number of crew
WLDGMX = maximum landing weight, lbs
FUELCP = maximum total fuel capacity, lbs
CARGO = cargo weight, lbs
SREF = wing reference area, ft^2
COST = final result returned to FLOPS, dollars
namelist called $COSTIN$. The variables and their definitions are presented in Table 7.2.

7.2.3 **Cost Models**

7.2.3.1 **Airframe RDT&E**

The model of reference 91 (Appendix C) is used to estimate the RDT&E cost of the aircraft airframe. The design variables used in the model are shown in Table 7.3. The variables are defined in section 7.2.2.

7.2.3.2 **Airframe Production**

The Science Applications Incorporated (SAI) airframe model (ref. 92) is used for airframe production cost. The SAI model is described in detail in Appendix C. The model includes equations to calculate the component weights and equations to calculate the costs based on those weights. FLOPS also includes the capability to calculate component weights. In integrating the LCC Module into FLOPS, weights were calculated by FLOPS and those weights used in the airframe production cost calculations. Design variables used by the model are summarized in Table 7.4.
<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>DEFAULT</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>350.</td>
<td>Airconditioning total pack air flow, lb/min</td>
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<td>APULFW</td>
<td>400.</td>
<td>Auxiliary power unit flow rate, lb/min</td>
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<tr>
<td>APUSHIP</td>
<td>170.</td>
<td>Auxiliary power unit shaft horsepower, hp</td>
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<td>DEPER</td>
<td>14.</td>
<td>Depreciation period, years</td>
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<tr>
<td>DEVST</td>
<td>1980</td>
<td>Development start time, year</td>
</tr>
<tr>
<td>DEVTI</td>
<td>1986</td>
<td>Development time, quarters</td>
</tr>
<tr>
<td>DYEAR</td>
<td>1986</td>
<td>Desired year for dollar calculations</td>
</tr>
<tr>
<td>EPR</td>
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<td>Engine pressure ratio at sea level static</td>
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<td>F</td>
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<td>Spares factor for production aircraft</td>
</tr>
<tr>
<td>FAFMSP</td>
<td>0.1</td>
<td>Spares factor for production airframes</td>
</tr>
<tr>
<td>FARE</td>
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<td>Fare, dollars per passenger per seat</td>
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<tr>
<td>FENGSP</td>
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<td>Spares factor for production engines</td>
</tr>
<tr>
<td>FPPFT</td>
<td>0.5</td>
<td>Spares factor for prototype and flight test</td>
</tr>
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<td>FUELPR</td>
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<td>Fuel price, dollars per gallon</td>
</tr>
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<td>HYDGM</td>
<td>150.</td>
<td>Gallon per minute flow of hydraulic pumps</td>
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<td>IACOUS</td>
<td>0</td>
<td>Acoustic treatment in nacelle</td>
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<td>IBODY</td>
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<td>Body type indicator</td>
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<td>=1, yes</td>
</tr>
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<td>ICIRC</td>
<td>1</td>
<td>Circuit indicator - fire detection</td>
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<td>=1, single circuit</td>
<td>=2, dual circuit</td>
</tr>
<tr>
<td>IOOREV</td>
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<td>Thrust reverser</td>
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<tr>
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<td>=0, no core reverser</td>
<td>=1, core reverser</td>
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<tr>
<td>ICOSTYP</td>
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<td>Cost type calculation desired</td>
</tr>
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<td>=1, life cycle cost (LCC)</td>
<td>=2, acquisition cost</td>
</tr>
<tr>
<td></td>
<td>=3, direct operating cost (DOC)</td>
<td>=4, indirect operating cost (IOC)</td>
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<td>=5, total operating cost (DOC + IOC)</td>
<td>=6, fare for a given return on investment</td>
</tr>
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<td>=7, return on investment for a given fare</td>
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<td>=1, data link</td>
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<tr>
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<td>Multiplex indicator</td>
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<td>=1, multiplex</td>
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<td>Value</td>
<td>Description</td>
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<td>-------</td>
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<td>Nozzle type indicator</td>
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<td></td>
<td></td>
<td>=2, simple target type reverser with separate flow exhaust nozzle</td>
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<tr>
<td></td>
<td></td>
<td>=3, simple target type reverser with mixed flow exhaust nozzle</td>
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<td></td>
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<td></td>
<td>=5, short duct engine without thrust reverser</td>
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<td>Print controller for Cost Module</td>
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<td></td>
<td></td>
<td>=0, only print major cost elements</td>
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<tr>
<td></td>
<td></td>
<td>&gt;0, print all details</td>
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<td>IRAD</td>
<td>1</td>
<td>Indicator to include research and development</td>
</tr>
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<td></td>
<td></td>
<td>=0, ignore R &amp; D costs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>=1, include R &amp; D costs distributed over entire program</td>
</tr>
<tr>
<td>IRANGE</td>
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<td>Range indicator</td>
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<td></td>
<td>=0, short range</td>
</tr>
<tr>
<td></td>
<td></td>
<td>=1, medium range</td>
</tr>
<tr>
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<td></td>
<td>=2, long range</td>
</tr>
<tr>
<td>ISPOOL</td>
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<td>Auxiliary power unit complexity indicator</td>
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<td></td>
<td>=1, double spool, variable vane APU</td>
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<td>Transfer operation indicator</td>
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<td></td>
<td>=0, through (no transfer) operation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>=1, transfer operation</td>
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<td>Windshield type indicator</td>
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<td></td>
<td>=1, curved windshield</td>
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<td>KVA</td>
<td>200.</td>
<td>KVA rating of full-time generators (100-300)</td>
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<td>LF</td>
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<td>Passenger load factor, percent</td>
</tr>
<tr>
<td>LIFE</td>
<td>14.</td>
<td>Number of years for Life Cycle Cost calculation</td>
</tr>
<tr>
<td>NAPU</td>
<td>1</td>
<td>Number of auxiliary power units</td>
</tr>
<tr>
<td>NCHAN</td>
<td>1</td>
<td>Number of channels (1, 2, or 3; 1 most common)</td>
</tr>
<tr>
<td>NFLITTST</td>
<td>2</td>
<td>Number of flight test aircraft</td>
</tr>
<tr>
<td>NGEN</td>
<td>3</td>
<td>Number of inflight operated generators (3 or 4)</td>
</tr>
<tr>
<td>NINS</td>
<td>0</td>
<td>Number of inertial navigation systems (3 or 4)</td>
</tr>
<tr>
<td>NP0D</td>
<td>4</td>
<td>Number of podded engines</td>
</tr>
<tr>
<td>NPROTYP</td>
<td>2</td>
<td>Number of prototype aircraft</td>
</tr>
<tr>
<td>PCTFC</td>
<td>10.</td>
<td>Percent of seats for first class</td>
</tr>
<tr>
<td>PLMQT</td>
<td>1984.</td>
<td>Planned MQT (150-hour Model Qualification Test or FAA certification), year</td>
</tr>
</tbody>
</table>
TABLE 7.2 - CONTINUED.

| PRPROC | 0. | prior number of engines procured |
| Q      | 100. | airframe production quantities |
| RESID  | 2. | Residual value at end of lifetime, percent |
| ROI    | 10. | Return on investment, percent |
| SFC    | 0.6 | engine specific fuel consumption, lb/hr/lb |
| TEMP   | 1800. | Maximum turbine inlet temperature, degrees F |

TECHNOLOGY SENSITIVITY PARAMETERS IN NAMELIST COSTIN
(1.0 = no change)

| R&D     |       |   |
| FAFRD   | 1.0   | airframe R&D |
| FENRD   | 1.0   | engine R&D   |

MANUFACTURING
- FMAC  1.0  air conditioning
- PMAI  1.0  anti-icing
- FMAPU 1.0  auxiliary power unit
- FMAV  1.0  avionics
- FMBODY 1.0  fuselage
- FMCOMP 1.0  composite materials
- FMEL  1.0  electrical systems
- FMENG 1.0  engine
- FMENSY 1.0  engine systems
- FMFCS  1.0  flight control system
- FMFEQ  1.0  furnishings and equipment
- FMFUSY 1.0  fuel systems
- FMEAR  1.0  landing gear
- FMHYD  1.0  hydraulic systems
- FMINS  1.0  instruments
- FMAC  1.0  nacelles
- FMNPW  1.0  pneumatics
- FMTAIL 1.0  tail
- FMTIRV 1.0  thrust reversers
- FWING  1.0  wing

OPERATING
- FOAC  1.0  air conditioning
- FOAI  1.0  anti-icing
- FOAPU 1.0  auxiliary power unit
- FOAV  1.0  avionics
- FOBODY 1.0  fuselage
- FOCCOMP 1.0  composite materials
- FOEL  1.0  electrical systems
- FOFCM  1.0  flight control system
- FOFEQ  1.0  furnishings and equipment
- FOFSU  1.0  fuel systems
- FOGEAR 1.0  landing gear
- FOINS  1.0  instruments

41
TABLE 7.2 - CONCLUDED.

<table>
<thead>
<tr>
<th>Code</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FONAC</td>
<td>1.0</td>
<td>nacelles</td>
</tr>
<tr>
<td>FOPNM</td>
<td>1.0</td>
<td>pneumatics</td>
</tr>
<tr>
<td>FOPROP</td>
<td>1.0</td>
<td>propulsion system</td>
</tr>
<tr>
<td>FOWING</td>
<td>1.0</td>
<td>wing</td>
</tr>
</tbody>
</table>

**ECONOMICS**

<table>
<thead>
<tr>
<th>Code</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEACSR</td>
<td>1.0</td>
<td>aircraft servicing</td>
</tr>
<tr>
<td>FECFEE</td>
<td>1.0</td>
<td>control fee</td>
</tr>
<tr>
<td>FECRW</td>
<td>1.0</td>
<td>flight crew</td>
</tr>
<tr>
<td>FEDEP</td>
<td>1.0</td>
<td>depreciation</td>
</tr>
<tr>
<td>FEFLITA</td>
<td>1.0</td>
<td>flight attendants</td>
</tr>
<tr>
<td>FEINS</td>
<td>1.0</td>
<td>insurance</td>
</tr>
<tr>
<td>FEIABR</td>
<td>1.0</td>
<td>R&amp;D labor rate</td>
</tr>
<tr>
<td>FELDFE</td>
<td>1.0</td>
<td>landing fee</td>
</tr>
<tr>
<td>FEMAIN</td>
<td>1.0</td>
<td>maintenance man hours increase</td>
</tr>
</tbody>
</table>

TABLE 7.3 - CONCEPTUAL DESIGN VARIABLES IN THE AIRFRAME RDT&E MODEL.

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>WIS(1)-WIS(25)</td>
<td>FMFCS</td>
</tr>
<tr>
<td>Q</td>
<td>FMHYD</td>
</tr>
<tr>
<td>DYEAR</td>
<td>FMENM</td>
</tr>
<tr>
<td>IACOUS</td>
<td>FMAC</td>
</tr>
<tr>
<td>INOZ</td>
<td>FMAI</td>
</tr>
<tr>
<td>FMWING</td>
<td>FMAPU</td>
</tr>
<tr>
<td>FMTAIL</td>
<td>FMEL</td>
</tr>
<tr>
<td>FMBODY</td>
<td>FMFEQ</td>
</tr>
<tr>
<td>FMGEAR</td>
<td>FMINS</td>
</tr>
<tr>
<td>FMTRV</td>
<td>FMAV</td>
</tr>
<tr>
<td>FMNAC</td>
<td>FMCOMP</td>
</tr>
<tr>
<td>FMFUSY</td>
<td>FMENSY</td>
</tr>
</tbody>
</table>

TABLE 7.4 - CONCEPTUAL DESIGN VARIABLES IN THE AIRFRAME PRODUCTION COST MODEL.

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DYEAR</td>
<td>NFLITST</td>
</tr>
<tr>
<td>AMPR</td>
<td>FAFRD</td>
</tr>
<tr>
<td>SPEED</td>
<td>FEIABR</td>
</tr>
</tbody>
</table>
7.2.3.3. Engine RDT&E and Production

The Rand Corporation model (Appendix C) for estimating the development and production costs of engines (ref. 93) is used for engine acquisition costs. The model was corrected for commercial engines and pricing policies by correlating predicted costs with actual costs (obtained from ref. 81) for several commercial engines. RDT&E costs are divided equally over the entire production run when RDT&E is included in the cost calculation. Table 7.5 summarizes the conceptual design variables used in the engine development and production cost model.

7.2.3.4 Direct Operating Cost

For DOC the American Airlines modification (ref. 94) of the ATA-67 model (ref. 95) is used. An in-depth description of this model is presented in Appendix D. The conceptual design variables used in the model are presented in Table 7.6.

<table>
<thead>
<tr>
<th>TABLE 7.5 - CONCEPTUAL DESIGN VARIABLES IN THE ENGINE RDT&amp;E AND PRODUCTION COST MODEL.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DYEARN</td>
</tr>
<tr>
<td>WIS(25)</td>
</tr>
<tr>
<td>NEA</td>
</tr>
<tr>
<td>FPPFT</td>
</tr>
<tr>
<td>FPRROC</td>
</tr>
<tr>
<td>NPROTYP</td>
</tr>
<tr>
<td>NFIITST</td>
</tr>
<tr>
<td>THRMAX</td>
</tr>
<tr>
<td>SMACH</td>
</tr>
<tr>
<td>DPRESMX</td>
</tr>
</tbody>
</table>
TABLE 7.6 - CONCEPTUAL DESIGN VARIABLES IN THE DIRECT OPERATING COST MODEL.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Code</th>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DYEAR</td>
<td>NAPU</td>
<td>FONAC</td>
<td>DIRECT OPERATING COST</td>
</tr>
<tr>
<td>TOGWMX</td>
<td>NINS</td>
<td>FOCOMP</td>
<td></td>
</tr>
<tr>
<td>WLDGMX</td>
<td>THENG</td>
<td>FOAC</td>
<td></td>
</tr>
<tr>
<td>TEMP</td>
<td>ISPOOL</td>
<td>FOINS</td>
<td></td>
</tr>
<tr>
<td>GIS(25)</td>
<td>NPOD</td>
<td>FOEL</td>
<td></td>
</tr>
<tr>
<td>NENG</td>
<td>IOCREV</td>
<td>FOFEQ</td>
<td></td>
</tr>
<tr>
<td>AMPR</td>
<td>PLRDPH</td>
<td>FOAPU</td>
<td></td>
</tr>
<tr>
<td>AC</td>
<td>AFMCST</td>
<td>FOPRO</td>
<td></td>
</tr>
<tr>
<td>FUELCP</td>
<td>AFMSP</td>
<td>FOPCS</td>
<td></td>
</tr>
<tr>
<td>HYDCPM</td>
<td>ENGCT</td>
<td>FOFUS</td>
<td></td>
</tr>
<tr>
<td>THRMX</td>
<td>ENGSP</td>
<td>FOHYD</td>
<td></td>
</tr>
<tr>
<td>APUSHIP</td>
<td>RESID</td>
<td>FOAI</td>
<td></td>
</tr>
<tr>
<td>APUBLW</td>
<td>DEPPER</td>
<td>FOPNM</td>
<td></td>
</tr>
<tr>
<td>SREF</td>
<td>IDTINK</td>
<td>FEMAIN</td>
<td></td>
</tr>
<tr>
<td>FL</td>
<td>IBODY</td>
<td>FEDEP</td>
<td></td>
</tr>
<tr>
<td>NCHAN</td>
<td>FUEBL</td>
<td>FEINS</td>
<td></td>
</tr>
<tr>
<td>IMUX</td>
<td>FUELPR</td>
<td>FECFEE</td>
<td></td>
</tr>
<tr>
<td>NSEATS</td>
<td>RANGE</td>
<td>FELDFE</td>
<td></td>
</tr>
<tr>
<td>NGEN</td>
<td>LIFE</td>
<td>FEACSR</td>
<td></td>
</tr>
<tr>
<td>KVA</td>
<td>FOWING</td>
<td>FEČRW</td>
<td></td>
</tr>
<tr>
<td>RANGE</td>
<td>FOGEAR</td>
<td>FEFLTA</td>
<td></td>
</tr>
<tr>
<td>ICIRC</td>
<td>FOBODY</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

7.2.3.5 **Indirect Operating Cost**

The Lockheed-Georgia Company model (ref. 96) is used for IOC. Appendix D presents a description of this model. Table 7.7 summarizes the conceptual design variables used in the model.

Changes in the aircraft during the optimization process do not have a strong impact on the IOC. It is, however, necessary to include IOC in the determination of life cycle cost.
TABLE 7.7 - CONCEPTUAL DESIGN VARIABLES IN THE INDIRECT OPERATING COST MODEL.

<table>
<thead>
<tr>
<th>IDOM</th>
<th>TOGWMX</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSEATS</td>
<td>TBLOCK</td>
</tr>
<tr>
<td>PCIFC</td>
<td>RANGE</td>
</tr>
<tr>
<td>NPCs</td>
<td>ITTRAN</td>
</tr>
<tr>
<td>LF</td>
<td>FEFLTA</td>
</tr>
<tr>
<td>CARGO</td>
<td>FEACSR</td>
</tr>
</tbody>
</table>

7.2.4 Price Index

A proper index to convert all of the individual models to the same year dollars is required. Reference 97 contains a table of federal price deflators for the aerospace industry for 1963 through estimates for 1987 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.

7.2.5 Complexity Factors

Complexity factors to account for the costs associated with advanced technologies were incorporated in each of these models. A complexity factor of 1.0 represents no change while a value less than 1.0 represents a cost decrement and a value greater than 1.0 represents a cost increment. For example, a complexity factor of 0.8 would represent a 20 percent improvement in the cost and 1.2 a 20 percent cost increase. 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.

7.2.6 Cost Calculation Options and Procedures

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

\[ \text{LOC} = \text{AF RDT&E} + \text{AF ACQ} + \text{ENG RDT&E} + \text{ENG ACQ} + \text{DOC} + \text{IOC} \]

The RDT&E and ACQ costs are per aircraft. The DOC and IOC are computed for dollars per block hour and then converted to dollars per airplane over the life of the airplane by:

\[ \text{DOC} = \text{DOC}(\$/\text{BH}) \times (\text{BH}/\text{FLGT}) \times (\text{FLGT}/\text{YR}) \times \text{YR} \]

\((\text{BH}/\text{FLGT})\) is computed by FLOPS. \((\text{FLGT}/\text{YR})\) is the utilization and is calculated in the DOC model based on the flight length and airline experience.

It is possible to specify a subpart of the life cycle cost as the cost parameter. Direct operating cost, indirect operating cost, or total operating cost (TOC) can be requested, where:

\[ \text{TOC} = \text{DOC} + \text{IOC} \]

It is also possible to examine just acquisition cost, either with or without the RDT&E. This provides a great deal of flexibility in the cost calculation. Any of the subparts specified may also be
used as optimization objective functions. The requested cost is placed into the variable COST in the FLOPS COSTDAT common block and returned to FLOPS.

7.3 SOFTWARE DOCUMENTATION

Documentation of all of the software for the LCC Conceptual Design System is contained in Volume 2. The FLOPS User's Manual is presented in Appendix A and a listing of the FLOPS computer program is in Appendix B. These two items were supplied by L. Arnold McCullers of PRC Kentron. Appendix C contains the documentation of the LCC Module. A listing of the LCC Module is presented in Appendix D. Specific details about the integration of the LCC Module into FLOPS are contained in Appendix E.
CHAPTER 8
CONSIDERATIONS IN USE OF THE METHODOLOGY

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.

8.1 STARTING POINT

The initial input to the code is a baseline airplane consisting of geometry, installed propulsion data, and mission and economic parameters. Obtaining satisfactory propulsion data is the most difficult part of the baseline development. FLOPS requires a very detailed set of performance points (Mach number, altitude, gross thrust, ram drag, and fuel flow) throughout the flight envelope. 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 is fixed, and that the baseline 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.

8.2 THE NEXT STEP

At the end of the optimization process, the designer must examine the resulting aircraft concept for physical reality. For
example, the fuel volume must be sufficient for the amount of fuel required; if it is not, an effort should be made to find space in the fuselage for fuel tanks. If significant changes are made to arrive at the final concept, it should be used as a baseline and the process repeated to verify the result. In addition, the designer should confirm that the stability and control characteristics of the configuration are still acceptable. Again, if major changes are required, the optimization process should be repeated with the new baseline.

8.3 MODEL LIMITATIONS

8.3.1 Cost Models

The cost models are appropriate for subsonic commercial transport aircraft with turbofan or turbojet engines. The airframe models are all based on existing conventional aircraft. Extending to extremely unconventional configurations using these models is possible but it must be done very carefully. Applications for unconventional configurations will be discussed later in this chapter.

Due to a lack of cost data, it was not possible to include CERs for turboprop or propfan engines. Another propulsion system consideration that could not be included was the effect of noise requirements on engine cost. According to sources in the propulsion industry the data has not been collected to relate noise requirements to engine cost. When starting with a new design, work progresses until the noise requirement is met; there is no luxury of designing the best engine without noise requirements to
determine the sensitivity of cost to noise. In addition, the high bypass ratios of newer engines helps the noise problem while improving engine performance.

8.3.2 FLOPS

The FLOPS code is very flexible allowing many options to be explored. Output from FLOPS includes the takeoff gross weight, fuel burned, engine thrust, tail areas, and wing planform variables of the configuration that will meet the mission requirements and satisfy the optimization objective function. The resulting configuration is still closely tied to the baseline. There have been no changes in the fuselage geometry or propulsion system characteristics. In order to investigate the effect of changes like these, new baseline configurations must be developed and analyzed.

8.4 UNCONVENTIONAL CONFIGURATIONS

Based on the above 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.

To compare the life cycle cost of the conventional, canard, and twin-fuselage configurations mentioned above, the first step is the development of physically valid baseline configurations for each of the concepts. Care must be taken to insure that each configuration contains sufficient volume for the payload and landing gear stowage, has acceptable balance, and has sufficient control surface area to maintain acceptable stability and control levels. The next step is to run each of the baseline configurations in the LCC Conceptual Design System to determine the physical characteristics of each configuration when optimized for minimum life cycle cost. FLOPS can accommodate both canard and twin-fuselage configurations. The LCC module would have no problem with the conventional and canard configuration. If there is a change in the aircraft systems cost due to the operation of the canard, that could be included using the appropriate complexity factors. The twin-fuselage concept would require slightly more imagination with the use of complexity factors in the LCC module. The fuselage cost is a function of the fuselage weight, production quantity, and complexity factor. The weight would come from FLOPS as the weight of both fuselages. To attempt to be accurate the designer would have to develop a relationship between weight, production quantity, and cost. In addition, the airframe R&D cost could be increased through the use of a complexity factor.
The final step in the process of comparing these configurations is to examine the resulting configurations for physical realism. It is necessary to insure that the stability and control levels are still acceptable and that there is still sufficient volume for the payload and retracted landing gear. If the configurations are still physically viable, then the best configuration based on minimum life cycle cost can be selected. If a resulting configuration is no longer physically realistic, then constraints should be applied to the optimization process and the entire process repeated until the final concept is physically valid. Only when all configurations are realistic can the costs be compared.
This chapter covers the baseline conditions for the short-, medium-, and medium-to-long range aircraft and results from the various studies conducted using these aircraft. The studies include the effect of optimization parameter, the effect of economic conditions, the proper number of engines from a cost perspective, and technology level studies.

9.1 BASELINE CONDITIONS

For this study, three different classes of subsonic commercial aircraft were used (short, medium, and medium-to-long range). The baseline missions are shown in Table 9.1. The missions are intended to be representative of realistic missions; therefore, range is not the only difference. Baseline aircraft geometries were developed from existing aircraft of the same class. The short-range aircraft is based on the Boeing 737, the medium-range aircraft on the Boeing 767, and the medium-to-long range aircraft on the Boeing 747. Three-view drawings of these aircraft taken from reference 98 are shown in figure 9.1.

<table>
<thead>
<tr>
<th>TABLE 9.1 - BASELINE MISSIONS.</th>
</tr>
</thead>
<tbody>
<tr>
<td>RANGE, nmi</td>
</tr>
<tr>
<td>CRUISE MACH</td>
</tr>
<tr>
<td>MAX. CRUISE ALT., ft</td>
</tr>
<tr>
<td>NO. OF PASSENGERS</td>
</tr>
<tr>
<td>TOFL, ft</td>
</tr>
</tbody>
</table>
a) Boeing 737 (short-range aircraft).

Figure 9.1 - Three-view drawings of baseline aircraft (copied from ref. 98).

b) Boeing 767 (medium-range aircraft).

Figure 9.1 - continued.
c) Boeing 747 (medium-to-long range aircraft).

Figure 9.1 - concluded.

The general characteristics of the baseline configurations modeled in FLOPS are shown in Table 9.2 and weight statements generated by FLOPS are presented in Table 9.3. A check of the zero-lift aerodynamic characteristics of the configurations generated by FLOPS is shown in figure 9.2 (copied from ref. 5). Economic assumptions used in this study for all aircraft are shown in Table 9.4.

Scalable engine data appropriate to each vehicle size was 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.
<table>
<thead>
<tr>
<th></th>
<th>SRAC</th>
<th>MRAC</th>
<th>LRAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>WING SPAN, ft</td>
<td>93.0</td>
<td>155.1</td>
<td>195.7</td>
</tr>
<tr>
<td>WING REF. AREA, ft</td>
<td>1005.0</td>
<td>2961.0</td>
<td>5500.0</td>
</tr>
<tr>
<td>WING ASPECT RATIO</td>
<td>8.61</td>
<td>8.12/</td>
<td>6.96</td>
</tr>
<tr>
<td>WING TAPER RATIO</td>
<td>0.22</td>
<td>0.27/</td>
<td>0.25</td>
</tr>
<tr>
<td>WING THICKNESS RATIO</td>
<td>0.12</td>
<td>0.11/</td>
<td>0.08</td>
</tr>
<tr>
<td>WING SWEEP AT c/4, deg</td>
<td>25.0</td>
<td>31.5/</td>
<td>37.5</td>
</tr>
<tr>
<td>HORIZONTAL TAIL AREA, ft²</td>
<td>312.0</td>
<td>623.5</td>
<td>1470.0</td>
</tr>
<tr>
<td>VERTICAL TAIL AREA, ft²</td>
<td>224.9</td>
<td>632.6</td>
<td>830.0</td>
</tr>
<tr>
<td>FUSELAGE LENGTH, ft</td>
<td>96.9</td>
<td>152.4</td>
<td>225.0</td>
</tr>
<tr>
<td>MAX. FUSELAGE DIAMETER, ft</td>
<td>13.1</td>
<td>17.0</td>
<td>22.4</td>
</tr>
<tr>
<td>NACELLE LENGTH, ft</td>
<td>18.4</td>
<td>19.2</td>
<td>43.4</td>
</tr>
<tr>
<td>NACELLE DIAMETER, ft</td>
<td>4.5</td>
<td>7.6</td>
<td>8.4</td>
</tr>
<tr>
<td>THRUST PER ENGINE, lb</td>
<td>14,000</td>
<td>46,000/</td>
<td>35,000</td>
</tr>
<tr>
<td>NO. OF ENGINES</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>TAKEOFF W/S, lb/ft²</td>
<td>90.2</td>
<td>81.1</td>
<td>151.4</td>
</tr>
<tr>
<td>TAKEOFF T/W</td>
<td>0.31</td>
<td>0.38/</td>
<td>0.23</td>
</tr>
<tr>
<td>AVG. CRUISE L/D</td>
<td>11.6</td>
<td>14.6</td>
<td>15.4</td>
</tr>
<tr>
<td>AVG. CRUISE SFC</td>
<td>0.82</td>
<td>0.57</td>
<td>0.68</td>
</tr>
</tbody>
</table>
TABLE 9.3 — WEIGHT STATEMENT FOR BASELINE CONFIGURATIONS.

a) Short-range aircraft.

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>WEIGHT, LBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>WING</td>
<td>8,809</td>
</tr>
<tr>
<td>HORIZONTAL TAIL</td>
<td>1,401</td>
</tr>
<tr>
<td>VERTICAL TAIL</td>
<td>748</td>
</tr>
<tr>
<td>FUSELAGE</td>
<td>12,503</td>
</tr>
<tr>
<td>LANDING GEAR</td>
<td>3,647</td>
</tr>
<tr>
<td>NACELLE</td>
<td>1,414</td>
</tr>
<tr>
<td>STRUCTURE TOTAL</td>
<td>28,522</td>
</tr>
<tr>
<td>ENGINE</td>
<td>6,204</td>
</tr>
<tr>
<td>MISCELLANEOUS SYSTEMS</td>
<td>402</td>
</tr>
<tr>
<td>FUEL SYSTEM</td>
<td>330</td>
</tr>
<tr>
<td>PROPULSION TOTAL</td>
<td>6,936</td>
</tr>
<tr>
<td>SURFACE CONTROLS</td>
<td>1,432</td>
</tr>
<tr>
<td>AUXILIARY POWER</td>
<td>597</td>
</tr>
<tr>
<td>INSTRUMENTS</td>
<td>458</td>
</tr>
<tr>
<td>HYDRAULICS</td>
<td>669</td>
</tr>
<tr>
<td>ELECTRICAL</td>
<td>1,327</td>
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<tr>
<td>AVIONICS</td>
<td>1,008</td>
</tr>
<tr>
<td>FURNISHINGS AND EQUIPMENT</td>
<td>9,192</td>
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<td>AIR CONDITIONING</td>
<td>1,118</td>
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<tr>
<td>ANTI-ICING</td>
<td>106</td>
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<td>SYSTEMS AND EQUIPMENT TOTAL</td>
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<td>FLIGHT, 2</td>
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<tr>
<td>CABIN, 3</td>
<td>465</td>
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<td>UNUSABLE FUEL</td>
<td>141</td>
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<td>ENGINE OIL</td>
<td>100</td>
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<tr>
<td>PASSENGER SERVICE</td>
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<td>CARGO CONTAINERS</td>
<td>875</td>
</tr>
<tr>
<td>OPERATING WEIGHT</td>
<td>54,775</td>
</tr>
<tr>
<td>PASSENGERS, 100</td>
<td>16,500</td>
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<tr>
<td>PASSENGER BAGGAGE</td>
<td>4,000</td>
</tr>
<tr>
<td>ZERO FUEL WEIGHT</td>
<td>75,275</td>
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<tr>
<td>MISSION FUEL</td>
<td>15,411</td>
</tr>
<tr>
<td>RAMP (GROSS) WEIGHT</td>
<td>90,686</td>
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</tbody>
</table>
TABLE 9.3 - CONTINUED.

b) Medium-range aircraft.

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>WEIGHT, LBS</th>
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</thead>
<tbody>
<tr>
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<td>31,678</td>
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<tr>
<td>HORIZONTAL TAIL</td>
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<tr>
<td>VERTICAL TAIL</td>
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</tr>
<tr>
<td>FUSELAGE</td>
<td>30,911</td>
</tr>
<tr>
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<td>11,355</td>
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<tr>
<td>NACELLE</td>
<td>3,605</td>
</tr>
<tr>
<td>STRUCTURE TOTAL</td>
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</tr>
<tr>
<td>ENGINE</td>
<td>17,532</td>
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<tr>
<td>THRUST REVERSERS</td>
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<tr>
<td>MISCELLANEOUS SYSTEMS</td>
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</tr>
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<td>FUEL SYSTEM</td>
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<tr>
<td>PROPULSION TOTAL</td>
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<td>SURFACE CONTROLS</td>
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<td>AUXILIARY POWER</td>
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<td>AVIONICS</td>
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<td>AIR CONDITIONING</td>
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<td>SYSTEMS AND EQUIPMENT TOTAL</td>
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<td>675</td>
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<td>CABIN, 5</td>
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<td>UNUSABLE FUEL</td>
<td>776</td>
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<td>ENGINE OIL</td>
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<td>PASSENGER SERVICE</td>
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<td>CARGO CONTAINERS</td>
<td>1,575</td>
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<td>OPERATING WEIGHT</td>
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<td>PASSENGERS, 100</td>
<td>33,000</td>
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<td>PASSENGER BAGGAGE</td>
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<tr>
<td>ZERO FUEL WEIGHT</td>
<td>189,218</td>
</tr>
<tr>
<td>MISSION FUEL</td>
<td>50,864</td>
</tr>
<tr>
<td>RAMP (GROSS) WEIGHT</td>
<td>240,082</td>
</tr>
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</table>
TABLE 9.3 - CONCLUDED.

c) Medium-to-long range aircraft.

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>WEIGHT, LBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>WING</td>
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<tr>
<td>HORIZONTAL TAIL</td>
<td>8,875</td>
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<tr>
<td>VERTICAL TAIL</td>
<td>7,659</td>
</tr>
<tr>
<td>FUSELAGE</td>
<td>71,928</td>
</tr>
<tr>
<td>LANDING GEAR</td>
<td>40,103</td>
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<tr>
<td>NACELLE</td>
<td>20,329</td>
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<td>STRUCTURE TOTAL</td>
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<tr>
<td>ENGINE</td>
<td>48,605</td>
</tr>
<tr>
<td>THRUST REVERSERS</td>
<td>6,396</td>
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<td>MISCELLANEOUS SYSTEMS</td>
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<td>FUEL SYSTEM</td>
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<td>PROPULSION TOTAL</td>
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<td>SURFACE CONTROLS</td>
<td>7,590</td>
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<td>INSTRUMENTS</td>
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<td>AVIONICS</td>
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<td>FURNISHINGS AND EQUIPMENT</td>
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<td>AIR CONDITIONING</td>
<td>4,599</td>
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<tr>
<td>ANTI-ICING</td>
<td>307</td>
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<tr>
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<td>WEIGHT EMPTY</td>
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<tr>
<td>CREW AND BAGGAGE</td>
<td></td>
</tr>
<tr>
<td>FLIGHT, 3</td>
<td>675</td>
</tr>
<tr>
<td>CABIN, 15</td>
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<td>1,205</td>
</tr>
<tr>
<td>ENGINE OIL</td>
<td>500</td>
</tr>
<tr>
<td>PASSENGER SERVICE</td>
<td>9,587</td>
</tr>
<tr>
<td>CARGO CONTAINERS</td>
<td>4,200</td>
</tr>
<tr>
<td>OPERATING WEIGHT</td>
<td>419,244</td>
</tr>
<tr>
<td>PASSENGERS, 500</td>
<td>82,500</td>
</tr>
<tr>
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<td>22,000</td>
</tr>
<tr>
<td>ZERO FUEL WEIGHT</td>
<td>523,744</td>
</tr>
<tr>
<td>MISSION FUEL</td>
<td>308,718</td>
</tr>
<tr>
<td>RAMP (GROSS) WEIGHT</td>
<td>832,462</td>
</tr>
</tbody>
</table>
Figure 9.2 - Validation of study aircraft zero-lift drag as predicted by FLOPS (figure copied from ref. 5)
TABLE 9.4—BASELINE ECONOMIC ASSUMPTIONS.

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 YEARS
LIFETIME = 14 YEARS
RESIDUAL VALUE AT END OF LIFE = 15%
FUEL PRICE = $0.50/GALLON

9.2 EFFECT OF OPTIMIZATION PARAMETER

A comparison of the wing planforms obtained when the aircraft are optimized for minimum acquisition cost, takeoff gross weight, life cycle cost, direct operating cost, and minimum fuel burned is shown in figure 9.3. The aspect ratio, wing area, and wing sweep a) Short-range airplane.

Figure 9.3—Effect of optimization parameter on wing planform.
b) Medium-range airplane.

Figure 9.3 - continued.
c) Medium-to-long range airplane.

Figure 9.3 - concluded.
are represented in the planform sketches. The wings are drawn with a common root quarter-chord location. The conceptual design variables for these wing planforms are shown in Table 9.5. 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 short-range aircraft (fig. 9.3a) and the medium-to-long range airplane (fig. 9.3c), the minimum LCC and DOC planforms

**TABLE 9.5 - AERO DESIGN VARIABLES FROM OPTIMIZATION PARAMETER RESULTS.**

a) Short-range aircraft.

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>MIN ACQ</th>
<th>MIN TOGW</th>
<th>MIN LCC</th>
<th>MIN DOC</th>
<th>MIN FUEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR</td>
<td>5.218</td>
<td>6.190</td>
<td>7.675</td>
<td>7.673</td>
<td>11.434</td>
</tr>
<tr>
<td>$S_{ref}$, ft$^2$</td>
<td>1033.2</td>
<td>1082.4</td>
<td>1127.8</td>
<td>1128.3</td>
<td>1056.8</td>
</tr>
<tr>
<td>$\Lambda_{c/4}$, deg</td>
<td>21.39</td>
<td>22.20</td>
<td>26.86</td>
<td>26.85</td>
<td>32.37</td>
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<tr>
<td>t/c, %</td>
<td>0.1030</td>
<td>0.0856</td>
<td>0.0885</td>
<td>0.0885</td>
<td>0.0821</td>
</tr>
</tbody>
</table>

**TABLE 9.5 - CONTINUED.**

b) Medium-range aircraft.

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>MIN ACQ</th>
<th>MIN TOGW</th>
<th>MIN LCC</th>
<th>MIN DOC</th>
<th>MIN FUEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{ref}$, ft$^2$</td>
<td>1937.0</td>
<td>2069.1</td>
<td>2254.4</td>
<td>2278.2</td>
<td>2314.5</td>
</tr>
<tr>
<td>$\Lambda_{c/4}$, deg</td>
<td>26.42</td>
<td>24.68</td>
<td>28.07</td>
<td>29.74</td>
<td>37.15</td>
</tr>
<tr>
<td>t/c, %</td>
<td>0.0650</td>
<td>0.0791</td>
<td>0.0799</td>
<td>0.0818</td>
<td>0.0877</td>
</tr>
</tbody>
</table>
TABLE 9.5 - CONCLUDED.

c) Medium-to-long range aircraft.

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>MIN ACQ</th>
<th>MIN TOGW</th>
<th>MIN LOC</th>
<th>MIN DOC</th>
<th>MIN FUEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{ref}, \text{ ft}^2$</td>
<td>5430.9</td>
<td>5643.4</td>
<td>6294.7</td>
<td>6294.7</td>
<td>6386.2</td>
</tr>
<tr>
<td>$\Lambda_{c/4}, \text{ deg}$</td>
<td>31.01</td>
<td>29.48</td>
<td>32.76</td>
<td>32.76</td>
<td>32.96</td>
</tr>
<tr>
<td>t/c, %</td>
<td>0.0896</td>
<td>0.0784</td>
<td>0.0817</td>
<td>0.0817</td>
<td>0.0768</td>
</tr>
</tbody>
</table>

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 more expensive to build. The minimum acquisition cost airplane is primarily dependent on the structural weight of the airplane, the minimum fuel airplane is primarily dependent on the fuel weight, and the minimum TOGW airplane depends on both the structural weight and the 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. 9.3a and 9.3b, respectively), the minimum LCC and DOC planforms are closer to the minimum TOGW airplane while for the medium-to-long range aircraft (fig. 9.3c) 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.
The bars in the graphs of figure 9.4 each represent the values of TOGW associated with the aircraft which have been optimized for minimum acquisition cost, TOGW, LCC, DOC, and fuel burned. The minimum fuel airplane has the highest TOGW for all aircraft. With the exception of the minimum acquisition cost airplane, TOGW increases with increasing aspect ratio and wing area. The amount of fuel burned (fig. 9.5) decreases for all cases with increasing aspect ratio. Similarly the empty weight of each configuration increases with increasing aspect ratio and wing area as seen in figure 9.6. The minimum acquisition cost airplane has the lowest empty weight while the minimum fuel airplane has the highest empty weight for all cases. The minimum LCC airplane has a slightly higher empty weight than the minimum TOGW airplane.

Figure 9.4 - Effect of optimization parameter on takeoff gross weight.

a) Short-range airplane.
b) Medium-range airplane.

Figure 9.4 - continued.

c) Medium-to-long range airplane.

Figure 9.4 - concluded.
a) Short-range airplane.

Figure 9.5 - Effect of optimization parameter on fuel burned.

b) Medium-range airplane.

Figure 9.5 - continued.
c) Medium-to-long range airplane.

Figure 9.5 - concluded.

a) Short-range airplane.

Figure 9.6 - Effect of optimization parameter on empty weight.
b) Medium-range airplane.

Figure 9.6 - continued.

c) Medium-to-long range airplane.

Figure 9.6 - concluded.
Figure 9.7 shows the engine thrust (size) for each of the configurations when optimized for the various objective functions. For the short- and medium-range aircraft (figs. 9.7a and 9.7b, respectively) the minimum acquisition cost and minimum fuel burned aircraft have the largest engines. The minimum fuel airplane can afford a larger engine to carry more weight in order to increase the aerodynamic efficiency and reduce the fuel burned. For the case of the minimum acquisition cost airplane, a larger (and hence more expensive engine) is affordable to reduce the empty weight, thereby reducing the acquisition cost. The minimum fuel medium-to-long range aircraft (fig. 9.7c) has an engine size much closer to the minimum LCC and DOC airplanes showing that for the longer range

![Thrust Chart]

a) Short-range airplane.

Figure 9.7 - Effect of optimization parameter on engine thrust.
b) Medium-range airplane.

Figure 9.7 - continued.

c) Medium-to-long range airplane.

Figure 9.7 - concluded.
the weight penalty of a larger engine burning more fuel cannot be tolerated. Acquisition cost (shown in fig. 9.8 for all aircraft) follows the same trend as empty weight as might be expected.

With the exception of the minimum fuel airplane, DOC (fig. 9.9) decreases with increasing aspect ratio. As seen in figure 9.10 the LCC of the configurations 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. The minimum LCC and DOC airplanes are dependent on the economic assumptions. The DOC and LCC airplanes are very similar (or identical) because with these economic conditions the elements that determine DOC (fuel, maintenance, salaries, acquisition cost, and so on) are of equal importance with

![Bar chart showing the effect of optimization parameter on acquisition cost.](a) Short-range airplane.

**Figure 9.8 - Effect of optimization parameter on acquisition cost.**
b) Medium-range airplane.

Figure 9.8 - continued.

c) Medium-to-long range airplane.

Figure 9.8 - concluded.
a) Short-range airplane.

Figure 9.9 - Effect of optimization parameter on direct operating cost.

b) Medium-range airplane.

Figure 9.9 - continued.
c) Medium-to-long range airplane.

Figure 9.9 - concluded.

a) Short-range airplane.

Figure 9.10 - Effect of optimization parameter on life cycle cost.
b) Medium-range airplane.

Figure 9.10 - continued.

c) Long-range airplane.

Figure 9.10 - concluded.
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.

9.3 ECONOMIC CONDITIONS EFFECTS

Figure 9.11 shows results from optimization runs for minimum LCC and DOC for the medium-range airplane wing planforms with fuel at $2.00 per gallon. For reference the baseline minimum fuel, LCC, and DOC planforms are also shown. The conceptual design variables from this exercise are shown in Table 9.6. 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. In fact, the minimum DOC wing planform becomes nearly identical to the

Figure 9.11 - Medium-range airplane planform sensitivity to fuel price.
TABE 9.6 - MRAC DESIGN VARIABLES FOR FUEL PRICE SENSITIVITY.

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>MIN LCC</th>
<th>MIN DOC</th>
<th>MIN FUEL</th>
<th>FUEL=$2.00/gal</th>
</tr>
</thead>
<tbody>
<tr>
<td>S_ref', ft²</td>
<td>2254.4</td>
<td>2278.2</td>
<td>2314.5</td>
<td>2269.8</td>
</tr>
<tr>
<td>h_c/4'</td>
<td>28.07</td>
<td>29.74</td>
<td>37.15</td>
<td>30.71</td>
</tr>
<tr>
<td>t/c, %</td>
<td>0.0799</td>
<td>0.0818</td>
<td>0.0877</td>
<td>0.0809</td>
</tr>
<tr>
<td>T, lbs</td>
<td>34542</td>
<td>34835</td>
<td>40747</td>
<td>35443</td>
</tr>
</tbody>
</table>

minimum fuel planform. Once again acquisition cost (fig. 9.12) increases with increasing technology level. The minimum LCC and

Figure 9.12 - Medium-range airplane acquisition cost for a fuel price of $2.00 per gallon.
DOC airplanes have higher acquisition costs than before. As might be expected, the minimum DOC and minimum fuel aircraft have nearly identical acquisition cost and life cycle cost (fig. 9.13). This is because the fuel cost has become a much more important element 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 difference in life cycle cost between the minimum LCC, DOC, and fuel airplanes is not that great.

Another important set of economic assumptions are the lifetime of the aircraft and its residual value at the end of that lifetime. The wing planform resulting from optimizing the medium-range aircraft for minimum DOC and LCC with a lifetime of eight
years and a residual of 30 percent is shown in figure 9.14. For reference the baseline minimum TOGW, LCC, and DOC airplane planforms are shown. Utilization of these aircraft in terms of number of flights per year is identical to the baseline. Table 9.7 presents the associated conceptual design variables. In

![Figure 9.14 - Medium-range airplane planform sensitivity to lifetime and residual.](image)

**Table 9.7 - MRAC Design Variables for Life and Residual Sensitivity.**

<table>
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<tr>
<th>VARIABLE</th>
<th>MIN</th>
<th>MIN</th>
<th>MIN</th>
<th>MIN</th>
<th>MIN</th>
</tr>
</thead>
<tbody>
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<td>$S_{ref}$, ft$^2$</td>
<td>2069.1</td>
<td>2254.4</td>
<td>2278.2</td>
<td>2256.3</td>
<td>2256.3</td>
</tr>
<tr>
<td>$\alpha_c/4'$, deg</td>
<td>24.68</td>
<td>28.07</td>
<td>29.74</td>
<td>35.77</td>
<td>35.77</td>
</tr>
<tr>
<td>t/c, %</td>
<td>0.0791</td>
<td>0.0799</td>
<td>0.0818</td>
<td>0.0650</td>
<td>0.0650</td>
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<tr>
<td>T, lbs</td>
<td>36877</td>
<td>34542</td>
<td>34835</td>
<td>34135</td>
<td>34135</td>
</tr>
</tbody>
</table>

81
In this case, the LCC and DOC airplanes are identical. They have greater sweep but less aspect ratio than the baseline DOC and LCC aircraft. Wing areas are nearly identical. The trends for acquisition cost (fig. 9.15) and life cycle cost (fig. 9.16) are the same as before but the reduced lifetime makes lowered acquisition cost and technology level more important than saving fuel in order to keep the life cycle cost low for both the minimum LCC and DOC airplanes.

![Figure 9.15](image_url)

Figure 9.15 - Medium-range airplane acquisition cost for a life of 8 years and residual of 30 percent.
Figure 9.16 - Medium-range airplane life cycle cost for a life of 8 years and residual of 30 percent.
9.4 **NUMBER OF ENGINES STUDY**

Table 9.8 illustrates one of the real payoffs of including cost in conceptual design. Each of the three classes of aircraft was optimized for minimum life cycle cost with two, three, and four engines. If the number of engines is selected based on minimum

<table>
<thead>
<tr>
<th>TABLE 9.8 - EFFECT OF NUMBER OF ENGINES.</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Short-range airplane.</td>
</tr>
<tr>
<td>NO. OF ENGINES</td>
</tr>
<tr>
<td>T/OGW, lbs</td>
</tr>
<tr>
<td>EW, lbs</td>
</tr>
<tr>
<td>FUEL, lbs</td>
</tr>
<tr>
<td>THRUST, lbs</td>
</tr>
<tr>
<td>T/W</td>
</tr>
<tr>
<td>LCC, M$</td>
</tr>
<tr>
<td>DOC, M$</td>
</tr>
<tr>
<td>ACQ, M$</td>
</tr>
<tr>
<td>COST/ENG, M$</td>
</tr>
<tr>
<td>TOT ENG COST, M$</td>
</tr>
</tbody>
</table>

| TABLE 9.8 - CONTINUED. |
| b) Medium-range airplane. |
| NO. OF ENGINES | 4 | 3 | 2 |
| T/OGW, lbs | 201,616 | 215,645 | 218,086 |
| EW, lbs | 113,551 | 125,856 | 127,938 |
| FUEL, lbs | 39,686 | 41,212 | 41,784 |
| THRUST, lbs | 14,384 | 21,437 | 34,542 |
| T/W | 0.29 | 0.30 | 0.32 |
| LCC, M$ | 173.10 | 176.25 | 171.32 |
| DOC, M$ | 111.28 | 112.39 | 108.67 |
| ACQ, M$ | 23.49 | 25.44 | 24.48 |
| COST/ENG, M$ | 0.71 | 0.86 | 1.15 |
| TOT ENG COST, M$ | 2.84 | 2.58 | 2.30 |
TABLE 9.8 - CONCLUDED.


c) Medium-to-long range airplane.

<table>
<thead>
<tr>
<th>NO. OF ENGINES</th>
<th>4</th>
<th>3</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOGW, lbs</td>
<td>753,658</td>
<td>807,769</td>
<td>948,147</td>
</tr>
<tr>
<td>EW, lbs</td>
<td>379,740</td>
<td>409,937</td>
<td>497,152</td>
</tr>
<tr>
<td>FUEL, lbs</td>
<td>251,055</td>
<td>274,610</td>
<td>327,932</td>
</tr>
<tr>
<td>THRUST, lbs</td>
<td>33,750</td>
<td>54,994</td>
<td>122,863</td>
</tr>
<tr>
<td>T/W</td>
<td>0.18</td>
<td>0.20</td>
<td>0.26</td>
</tr>
<tr>
<td>LCC, M$</td>
<td>395.40</td>
<td>414.28</td>
<td>457.42</td>
</tr>
<tr>
<td>DOC, M$</td>
<td>250.03</td>
<td>264.55</td>
<td>301.71</td>
</tr>
<tr>
<td>ACQ, M$</td>
<td>55.92</td>
<td>59.48</td>
<td>64.14</td>
</tr>
<tr>
<td>COST/ENG, M$</td>
<td>1.14</td>
<td>1.49</td>
<td>2.26</td>
</tr>
<tr>
<td>TOT ENG COST, M$</td>
<td>4.56</td>
<td>4.47</td>
<td>4.52</td>
</tr>
</tbody>
</table>

TOGW, empty weight, or fuel burned, in all cases four engines 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 (Table 9.8c) would four engines be chosen. The short- and medium-range aircraft (Tables 9.8a and 9.8b, respectively) 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 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 extremely
large engines. All costs increase with 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.

9.5 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. Using 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. Examples are presented for an increase in aerodynamic, weights, systems, and propulsion technologies for the medium-range aircraft. Also shown is an example where all technologies are included.

9.5.1 Aerodynamic Technology

Table 9.9 shows the aerodynamic performance improvements assumed and the corresponding cost increments. Three sets of cost increments (no additional cost, 20 percent additional cost and 40 percent 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.) To validate the aerodynamic performance improvements obtain, the zero-lift drag characteristics are shown on figure 9.17 (copied from ref. 5). The advanced aerodynamics assumed represent a very aggressive set of technologies but are reasonable. The wing planform for the medium-range aircraft when optimized for minimum life cycle cost with the aerodynamic performance improvements and 40% cost increase is shown in figure 9.18. For comparison the baseline minimum LCC planform is also shown. Table 9.10 shows the associated conceptual design variables. The advanced aerodynamic technology allows the wing to use less sweep, span, and area and more thickness to obtain an optimum wing for minimum LCC. The TOGW of the medium-range aircraft when optimized for minimum LCC is shown in figure 9.19. Applying the aerodynamics technology results in a nearly 10 percent decrease in TOGW. This is reasonable according to an estimate made for the expected change using the methods of references 2-5. Appendix G contains the details of this validation. When there is no associated cost
Figure 9.17 - Validation of advanced aerodynamics for study aircraft as predicted by FLOPS (copied from ref. 5).
Figure 9.18 - Effect of advanced aerodynamics technology on the medium-range minimum life cycle cost airplane wing planform.

TABLE 9.10 - DESIGN VARIABLES FOR ADVANCED AERODYNAMIC TECHNOLOGY MINIMUM LIFE CYCLE COST CONCEPTS.

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>BASELINE</th>
<th>ADV AERO TECH</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR</td>
<td>8.412</td>
<td>8.145</td>
</tr>
<tr>
<td>$S_{\text{ref}}$, ft$^2$</td>
<td>2254.4</td>
<td>2060.6</td>
</tr>
<tr>
<td>$\Lambda_c/4\pi$</td>
<td>28.07</td>
<td>15.25</td>
</tr>
<tr>
<td>t/c, %</td>
<td>0.0799</td>
<td>0.1038</td>
</tr>
<tr>
<td>T, lbs</td>
<td>34542</td>
<td>30766</td>
</tr>
</tbody>
</table>
Figure 9.19 - Effect of advanced aerodynamics technology on the medium-range minimum life cycle cost airplane takeoff gross weight.

increase, the LCC is also dramatically reduced as seen in figure 9.20. With a 20 percent cost increase the LCC is still less than the baseline. If the cost increase is as much as 40 percent, the resulting LCC is greater than the baseline. For this set of economic conditions, a cost increase of up to approximately 30 percent appears to be tolerable for this technology set. The acquisition cost and direct operating cost for this configuration are shown in figures 9.21 and 9.22, 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 percent increase in cost, the acquisition cost is somewhat greater than the baseline and the direct operating cost is still significantly less. A 40 percent
Figure 9.20 - Effect of advanced aerodynamics technology on the medium-range minimum life cycle cost airplane life cycle cost.

Figure 9.21 - Effect of advanced aerodynamics technology on the medium-range minimum life cycle cost airplane acquisition cost.
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 where advanced aerodynamic technology is affordable is highly dependent on the assumed economic conditions.

9.5.2 Weights Technology

The wing planform for the medium-range aircraft when optimized for minimum life cycle cost with the weight technology improvements and 40 percent cost increment assumed (Table 9.11) is shown in figure 9.23. Table 9.12 presents the associated conceptual design variables. There is very little difference in wing planform between the advanced weights technology and the baseline. Figure 9.24 shows that there is a significant difference in TOGW
between the baseline and the advanced technology configurations. Again this weight decrement is shown to be reasonable in Appendix G. The life cycle cost for the baseline and cost increment cases is shown in figure 9.25. For this case, the

**TABLE 9.11 - WEIGHT TECHNOLOGY EFFECT ASSUMPTIONS.**

**WEIGHT IMPROVEMENT:**
20% REDUCTION IN WING WEIGHT DUE TO ADVANCED MATERIALS

0%, 20%, AND 40% COST INCREASES ASSUMED IN:
- AIRFRAME RDT&E
- MANUFACTURING OF WING
- OPERATING OF WING

Figure 9.23 - Effect of advanced weights technology on the medium-range minimum life cycle cost airplane wing planform.
TABLE 9.12 - DESIGN VARIABLES FOR ADVANCED WEIGHT TECHNOLOGY
MINIMUM LIFE CYCLE COST CONCEPTS.

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>BASELINE</th>
<th>ADV WTS TECH</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR</td>
<td>8.412</td>
<td>8.776</td>
</tr>
<tr>
<td>$S_{\text{ref}', \text{ft}^2}$</td>
<td>2254.4</td>
<td>2146.9</td>
</tr>
<tr>
<td>$\lambda_{0\text{C/4}'}$</td>
<td>28.07</td>
<td>28.22</td>
</tr>
<tr>
<td>t/c, %</td>
<td>0.0799</td>
<td>0.0772</td>
</tr>
<tr>
<td>T, lbs</td>
<td>34542</td>
<td>33423</td>
</tr>
</tbody>
</table>

Figure 9.24 - Effect of advanced weights technology on the medium-range minimum life cycle cost airplane takeoff gross weight.

* COST FOR ADV WTS TECH
advanced technology will only be worthwhile if the cost increment is no more than 20 percent. Once again the acquisition cost (fig. 9.26) is greater for a 20 percent cost increase than the baseline but the direct operating cost (fig. 9.27) is less. Examining LCC gives a different and much more balanced configuration than using DOC or acquisition cost. Using weight makes it impossible to gain any insight at all into the cost tradeoff of technology.
Figure 9.26 - Effect of advanced weights technology on the medium-range minimum life cycle cost airplane acquisition cost.

Figure 9.27 - Effect of advanced weights technology on the medium-range minimum life cycle cost airplane direct operating cost.
Table 9.13 shows the systems technology improvements assumed and the corresponding cost increments. (A systems technology improvement in FLOPS translates into a weight saving.) The resulting wing planform when the medium-range aircraft is optimized for minimum life cycle cost is shown in figure 9.28 along with the baseline planform and the conceptual design variables are shown in Table 9.14. The technology improvement yields greater aspect ratio and more wing area. The effect on takeoff gross weight is not that great as seen in figure 9.29. A change in systems weight (which is a small part of the total weight) does not have a great effect as might be expected. (Appendix G demonstrates that this change in TOGW is reasonable.) However, the effect on LCC is very large as seen in figure 9.30. The improvement in LCC for no cost

Table 9.13 - Systems Technology Effect Assumptions.

<table>
<thead>
<tr>
<th>Systems Weight Improvement:</th>
<th>10% Reduction in weight of Miscellaneous Propulsion System, Fuel System, Instrument Group, Hydraulics Group, Electrical Group, and Avionics Group</th>
</tr>
</thead>
</table>
Figure 9.28 - Effect of advanced systems technology on the medium-range minimum life cycle cost airplane wing planform.

TABLE 9.14 - DESIGN VARIABLES FOR ADVANCED SYSTEMS TECHNOLOGY MINIMUM LIFE CYCLE COST CONCEPTS.

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>BASELINE</th>
<th>ADV SYS TECH</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR</td>
<td>8.412</td>
<td>7.112</td>
</tr>
<tr>
<td>$S_{ref}, \text{ ft}^2$</td>
<td>2254.4</td>
<td>2162.9</td>
</tr>
<tr>
<td>$\Lambda_{c/4}$°</td>
<td>28.07</td>
<td>26.36</td>
</tr>
<tr>
<td>t/c, %</td>
<td>0.0799</td>
<td>0.0783</td>
</tr>
<tr>
<td>T, lbs</td>
<td>34542</td>
<td>34736</td>
</tr>
</tbody>
</table>
Figure 9.29 - Effect of advanced systems technology on the medium-range minimum life cycle cost airplane takeoff gross weight.

Figure 9.30 - Effect of advanced systems technology on the medium-range minimum life cycle cost airplane life cycle cost.
increment is very small. The acquisition cost is reduced for cost increments less than 20 percent (fig. 9.31) but the direct operating cost (fig. 9.32) is greater for all cost increments. This illustration makes it clear that improvements in systems are going to have to do more than reduce weight to pay for themselves. The combined effect of this and all other technologies will be examined in the final example.

9.5.4 Propulsion Technology

The propulsion performance improvements and associated cost increments are shown in Table 9.15. The wing planform for the medium-range aircraft when optimized for minimum life cycle cost with the advanced propulsion technology and 40 percent cost increment is shown in figure 9.33 and Table 9.16 presents the

Figure 9.31 - Effect of advanced systems technology on the medium-range minimum life cycle cost acquisition cost.
Figure 9.32 - Effect of advanced systems technology on the medium-range minimum life cycle cost direct operating cost.

TABLE 9.15 - PROPULSION TECHNOLOGY EFFECT ASSUMPTIONS.

PERFORMANCE IMPROVEMENT IN PROPULSION:
10% REDUCTION IN SPECIFIC FUEL CONSUMPTION OF ENGINE

0%, 20%, AND 40% COST INCREASES ASSUMED IN:
ENGINE RDT&E
MANUFACTURING OF ENGINE AND ENGINE SYSTEMS
OPERATING OF PROPULSION SYSTEM
MAINTENANCE MAN HOURS
Figure 9.33 - Effect of advanced propulsion technology on the medium-range minimum life cycle cost airplane wing planform.

TABLE 9.16 - DESIGN VARIABLES FOR ADVANCED PROPULSION TECHNOLOGY MINIMUM LIFE CYCLE COST CONCEPTS.

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>BASELINE</th>
<th>ADV PROP TECH</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR</td>
<td>8.412</td>
<td>7.352</td>
</tr>
<tr>
<td>$S_{\text{ref}}$ ft$^2$</td>
<td>2254.4</td>
<td>2132.2</td>
</tr>
<tr>
<td>$\Lambda_{c/4}$ °</td>
<td>28.07</td>
<td>29.53</td>
</tr>
<tr>
<td>t/c, %</td>
<td>0.0799</td>
<td>0.0800</td>
</tr>
<tr>
<td>T, lbs</td>
<td>34542</td>
<td>33839</td>
</tr>
</tbody>
</table>

associated conceptual design variables. The advanced technology results in a smaller aspect ratio, less wing area and slightly more sweep than the baseline. As would be expected (and is validated in Appendix G), figure 9.34 shows that the TOGW for the performance
Figure 9.34 - Effect of advanced propulsion technology on the medium-range minimum life cycle cost airplane takeoff gross weight.

Figure 9.35 - Effect of advanced propulsion technology on the medium-range minimum life cycle cost airplane life cycle cost.
improvement is reduced. Figure 9.35 shows LCC for these cases. A cost increment of less than 10 percent would result in a reduction of LCC compared to the baseline. As seen in figure 9.36 a cost increment of approximately 20 percent yields an acquisition cost equivalent to the baseline while figure 9.37 shows that the DOC cross-over point is at about a 10 percent cost increment.

9.5.5 All Advanced Technologies

The final case considered is for all of the above technologies combined. The resulting wing planform for the medium-range aircraft when optimized for minimum LCC is shown in figure 9.38 and the associated conceptual design variables are shown in Table 9.17. The planform very closely resembles that of the

![Chart](image)

* COST FOR ADV PROP TECH

Figure 9.36 - Effect of advanced propulsion technology on the medium-range minimum life cycle cost acquisition cost.
Figure 9.37 - Effect of advanced propulsion technology on the medium-range minimum life cycle cost airplane direct operating cost.

Figure 9.38 - Effect of all advanced technologies on the medium-range minimum life cycle cost airplane wing planform.
TABLE 9.17 - DESIGN VARIABLES FOR ALL ADVANCED TECHNOLOGIES MINIMUM LIFE CYCLE COST CONCEPTS.

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>BASELINE</th>
<th>ALL ADV TECH</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR</td>
<td>8.412</td>
<td>8.601</td>
</tr>
<tr>
<td>$\frac{S_{\text{ref}}}{\text{ft}^2}$</td>
<td>2254.4</td>
<td>1968.6</td>
</tr>
<tr>
<td>$\Lambda_{\text{C/4}}$</td>
<td>28.07</td>
<td>14.75</td>
</tr>
<tr>
<td>t/c, %</td>
<td>0.0799</td>
<td>0.1103</td>
</tr>
<tr>
<td>T, lbs</td>
<td>34542</td>
<td>27349</td>
</tr>
</tbody>
</table>

Figure 9.39 - Effect of all advanced technologies on the medium-range minimum life cycle cost airplane takeoff gross weight.
advanced aerodynamics technology. Figure 9.39 shows that there is a dramatic decrease in takeoff gross weight relative to the baseline minimum LCC airplane. Examination of LCC in figure 9.40 shows that anything more than a cost increment of about 15 percent yields an increase in life cycle cost relative to the baseline. For this case a cost increment of between 10 and 15 percent yields an acquisition cost (fig. 9.41) and direct operating cost (fig. 9.42) equal to the baseline.

9.6 OPTIMIZATION CONSIDERATIONS

For the airplanes used in this study the optimizations for minimum TOGW and fuel generally converged without any difficulty. The acquisition cost optimization also succeeded in finding the

Figure 9.40 - Effect of all advanced technologies on the medium-range minimum life cycle cost airplane life cycle cost.
Figure 9.41 - Effect of all advanced technologies on the medium-range minimum life cycle cost airplane acquisition cost.

Figure 9.42 - Effect of all advanced technologies on the medium-range minimum life cycle cost airplane direct operating cost.
global minimum during the first run. The LCC and DOC optimizations generally converged but not to the global minimum the first time. It was usually necessary to restart the runs at least once. During all of the optimization runs there was a lot of movement of the design variables. However, runs did tend to encounter problems and abort if the starting point was too far from the optimum. It was interesting to note that this study did uncover two problems with the FLOPS analysis. In trying to optimize the medium-range aircraft for minimum fuel burned, the aspect ratio went to 26, the wing sweep to 88 degrees, and the wing span to 225 feet. The problem was an error in the sweep portion of the wing weight equation. When that was corrected everything worked fine. Another problem uncovered was a weakness between the aerodynamics and weights for taper ratio. For all aircraft the taper ratio optimized to near zero. The final solution to this problem was to recognize that taper ratio is not a critical parameter for conventional aircraft and to leave it fixed for all configurations.
A conceptual aircraft design system has been developed to include life cycle cost in the design of subsonic commercial transports. Using this system, a configuration can be optimized for minimum life cycle cost, direct operating cost, or acquisition cost, in addition to minimum takeoff gross weight, fuel burned, or maximum range. Extensive use of the methodology on short-, medium-, and medium-to-long range conventional subsonic 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. Results show that advanced technology can be worthwhile, even if it results in higher manufacturing and operating costs. Considering the amount of technology that can be afforded based on acquisition cost, direct operating cost or life cycle cost illustrates a major benefit of including life cycle cost in the conceptual design process. The configurations are all different with the life cycle cost configuration providing the most balance. Examining the number of engines a configuration should have demonstrated another real payoff of including life cycle cost in the conceptual design
process: the minimum TOGW or fuel aircraft did not always have the lowest life cycle cost when considering the number of engines.
REFERENCES


A total of 15 computer codes that calculate some portion of aircraft cost were found during the literature search for this research effort. A brief description of each code is presented here. None of these codes are used in the LCC Module developed here.

A.1 ABC-ART CODE

The ABC-ART code (ref. 46) consists of models developed by NASA for use in analyzing the economic feasibility of applying advanced aeronautical technology to future civil aircraft. The three major modules are:

Fleet Accounting - projects fleet composition and associated fuel consumption for each of the 31 years from 1975 through 2005. The fleet projections are based on the number of aircraft required to meet passenger traffic demand. Provisions are made in the model to account for modifications of aircraft in the fleet. New aircraft are assumed to be purchased as necessary to replace aircraft that have reached retirement age or to meet increased traffic demand.

Airframe Manufacturer - estimates the aircraft manufacturing rates of return on investment. These estimates are based on the estimated numbers of aircraft required over time (as predicted by the Fleet Accounting Module) and assumed aircraft prices. The module accounts for production, order and
delivery schedules, RDT&E costs and individual and total component manufacturing costs over the life of the production program, and the net cash flow that the manufacturer can expect to receive from manufacturing the new aircraft. Air Carrier - analyzes the financial feasibility of an airline purchasing and operating an aircraft. The module provides a methodology for computing the air carrier costs and revenues over the economic life of the aircraft, performing a cash flow analysis, and computing an internal rate of return on investment. The module includes models for estimating direct and indirect operating expenses and techniques for accounting for initial investment, purchase loan repayments, depreciation, and tax expenses. Unfortunately, the code has many built-in restrictions and has not been debugged, making it's usefulness limited.

A.2 ALICE

The Aircraft Life Cycle Cost Evaluation (ALICE) model was created to provide detailed cost at the preliminary design level for both civil and military configurations (ref. 54). Both civil acquisition and military production costs, including RDT&E, can be computed using similar bookkeeping. ALICE may be run independently or coupled with an aircraft sizing program to automatically develop the costs with the appropriate inputs.

A.3 DAPCA-III

DAPCA-III (Development and Procurement Costs of Aircraft) described in reference 60 applies parametric estimating
relationships to calculate development and procurement costs of two major flyaway subsystems of the aircraft: airframe and engines. All data used to derive the CERs for DAPCA-III were taken from both Government and industry sources. The sample consisted of 25 military aircraft.

The major explanatory variables for airframe cost are AMPR and maximum speed at best altitude. Many other variables relating to aircraft characteristics were tried and evaluated but generally were found not to be significant. However, for manufacturing labor and materials, the time of first flight in calendar quarters after 1942 was found to be significant. Also, a dummy variable distinguishing between cargo and noncargo aircraft was found to be significant for flight-test cost. The airframe CERs include prototype aircraft costs. Efforts to develop separate CERs for prototype aircraft were not successful. DAPCA-III can be used to estimate costs of very small programs, but such costs should be considered carefully. The engine CERs make use of a quantitative measure of an engine's technology content, based on the time when the engine is calculated to pass its 150-hour Model Qualification Test (MQT).

There are no CERs for avionics in DAPCA-III. Avionics development cost is entered as a throughput and added to the other development costs. For avionics production, the cost is assumed to follow a cumulative average curve for which the user is required to enter the cost of the first production unit. Determining a reasonable learning curve slope for avionics is troublesome because
the total avionics package is usually a mix of old and new equipment. Some items will have been in production for several years, and little additional cost reduction because of quantity production can be expected. Although a slope of 90 percent is generally used for the avionics learning curve, DAPCA-III uses 95 percent as a way of compensating for the older equipment in the avionics package.

DAPCA-III is designed for use as a long-range planning tool for normal, full-scale production programs and not for short-run financial or budget operations. Any attempts to use it for purposes other than for which it is designed may lead to serious errors in the interpretation of the results.

A.4 GASP

The General Aviation Synthesis Program (GASP) performs tasks generally associated with aircraft preliminary design and allows an analyst the capability of performing parametric studies in a rapid manner (refs. 42 and 43). GASP emphasizes small fixed-wing aircraft employing propulsion systems varying from a single piston engine with fixed pitch propeller through twin turboprop/turbofan powered business or transport type aircraft.

Input quantities to GASP are general indicators of aircraft type, size, and performance, and the synthesis is extended to the point at which all of the important aircraft characteristics have been analyzed quantitatively. By utilizing the computer model, the impact of various aircraft design factors and requirements may
be studied in a systematic manner with benefits measured in terms of overall aircraft performance and economics.

The cost subroutines estimate a number of economic parameters using about 30 descriptive aircraft input quantities. Many of the computations take the form of regression equations, in which the component cost is expressed as a nonlinear function of one or more known parameters. The subroutines deal with basic performance characteristics of several types of aircraft, and these gross descriptors of the aircraft are such as to predict conceptual initial design and operating costs with reasonable accuracy from minimum design and performance inputs. In addition, the procedure can be used to evaluate the effects of basic technology tradeoffs, performance, and production rates on cost.

A.5 MLCCM

The Modular Life Cycle Cost Model (MLCCM) is a design-oriented methodology for calculating the life cycle costs of advanced aircraft during the conceptual and preliminary design phase of a system development program (refs. 48-53). The code is a tool for determining design alternatives, resulting in the most effective tradeoffs between cost and performance. Reference 14 describes using the output from a vehicle sizing program as the input to MLCCM.

The MLCCM predicts total costs for the RDT&E, production, support investment, and the operations and support phases, at the subsystems level of an aircraft. Whereas most cost models to date have leaned heavily on product weight as the major cost driving
element, the MILCOM represents an important improvement in assisting the designer to better understand the sensitivity of cost to other design parameters such as wetted area, volume, density, length plus span, sink speed, etc., which logically influence cost to a greater degree.

A.6 OART COST MODEL

The OART cost model (ref. 44) was designed to use a vehicle synthesis computer program to generate the independent variables in the CERs. Typically, such programs in the conceptual design stage give general descriptions of the vehicle geometry, a group weight statement, required thrust, structural material requirements, and maximum speed. The complete life cycle costs can be calculated. Operating costs for commercial aircraft are not computed with the OART model. Instead, the unit cost of the aircraft, including the amortized RDT&E costs, is used with the standard Air Transport Association formulas (refs. 94 and 95) or other airline operating cost model.

A.7 RCA PRICE MODEL

PRICE is an acronym for Programmed Review of Information for Costing and Evaluation. It has by far the widest use and is now employed by the Air Force, Army, Navy, NASA, aerospace companies, and several foreign governments to provide cost estimates (ref. 24). It can be used in all phases of hardware acquisition, from development and production to purchase or modification, estimating the costs associated with design, drafting, project management, documentation, sustaining engineering, tooling, system
testing, labor, materials, and overhead (ref. 58). The PRICE model employs a parametric method of estimating costs that can use a minimal amount of input or be refined with more accurate data. Missing data can be computed by using existing cost-estimating relationships that are available in the model.

A.8 TRANSYN

The TRANsport SYNthesis program (ref. 47) is basically a computerized, integrated form of the preliminary design process. The program consists of a control module and discipline area modules to perform the required geometry, aerodynamic, propulsion, structures, weight and volume, and economics computations. The code can be used to generate sensitivity data for advanced technology transports. The effects on performance and economics of perturbations to parameters in the area of structures, aerodynamics, and propulsion can be determined.

A.9 VDEP

The General Dynamics VDEP model (ref. 59) is the result of a series of Air Force and NASA contracts to develop a computer model that would perform preliminary design analysis and tradeoff studies on commercial transport aircraft. The model consists of an aircraft vehicle sizing routine and a cost-analysis routine, and it determines first-unit manufacturing costs, total program costs, and return on investment.

The model was developed originally from statistical data on several aircraft, with a statistical bases being used to determine vehicle sizes and weights. Detailed cost data were available to establish
the necessary relationships between aircraft design characteristics and development and production costs. In addition, a total program cost model was developed that uses CERs and learning curves as well as internally generated cost elements.

Input data consist primarily of key system design parameters that affect overall mission performance. Depending on the level of detail, specific inputs include gross takeoff weight, payload, speed, range, landing-field length requirements, wing loading, span, sweep, taper, aspect ratio, takeoff field length requirements, climb requirements, slenderness ratio, and fuel requirements. Where nonmandatory inputs are desired but are not available, they are calculated internally by model subroutines. The model output consists of aircraft design and performance characteristics and development and production costs.

A.10 VSAC

The Vehicle Sizing and Cost (VSAC) program consists of a vehicle sizing subprogram and a cost analysis subprogram (ref. 57). The vehicle sizing subprogram provides geometry, weight, and balance analysis for aircraft using JP, hydrogen or methane fuels. It has an option of providing first pass performance data or conducting a detailed mission and performance analysis. A mass distribution and moment of inertia analysis is also provided. The cost analysis integrates first unit manufacturing costs based on CERs, total program costs that include tooling and engineering and a ROI analysis based on route structures. One advantage provided by the method is the capability
to make trade studies from several levels of consideration. For example, weight and cost data can be directly related to key system parameters at the vehicle mission level such as payload, speed, range and landing field length requirements. At the vehicle configuration level, data can be related directly to surface areas, span, sweep, taper, etc., and fuselage length, slenderness, etc. Thus, insight can be gained into the cost effectiveness of alternate aircraft systems, design trade studies can be performed, and studies to determine the impact of more detailed engineering alternatives with respect to particular aspects of design can be conducted. The program is designed to provide trade study data for fuel conservative aircraft, multi-bodied aircraft, and large cargo aircraft using both JP and cryogenic fuels.

A.11 INTRASIM II

Intercity and Intraurban V/STOL System Simulation Model

(INTRASIM II) evaluates intercity and interurban V/STOL systems for a typical weekday of operation (ref. 61). V/STOL demands, schedules, fleet requirements, costs, revenues, and profit are all generated for this typical day. Vehicle procurement costs, daily operating costs, and revenues are calculated. INTRASIM II uses the PLACE (Parametric Life-Cycle Army Cost Estimation) model to calculate initial cost and an extension of the ATA direct operating cost model (ref. 95) for turbine powered VTOL transport aircraft for DOC. An IOC model applicable for V/STOL aircraft was developed for INTRASMIM II.
A.12  REFERENCE 62

Reference 62 describes a computer code to calculate DOC and ROI. The DOC model is based on the standard ATA-67 model (ref. 95), using the 1976 coefficients from Boeing. The ROI program includes the Lockheed IOC model (ref. 96) using 1976 cost data. A discounted cash flow method is used to determine the return on investment.

A.13  REFERENCE 45

Reference 45 describes a computer program that computes the economics of making changes to existing aircraft. It figures the total cumulative cost is the change isn't made and if it is. The code is used by the Army to determine whether or not the modification is worthwhile.

A.14  REFERENCE 55

Reference 55 reports on a computer program to predict the effect of various JP-type fuels on performance, operability and LCC of the Air Force aviation fleet. It will analyze the changes on the F16/F100(3), B-52/TF33, and KC-135A/J57 systems. The program outputs any change in operability and performance associated with an input fuel change; then it specifies the concurrent changes in LCC (over the current levels with JP-4). The model has been formulated to rank the components most sensitive to fuel variations and thus point out the drivers to increased LCC.

A.15  REFERENCE 56

Reference 56 presents the development of a procedure for military aircraft to evaluate and select from existing
survivability methodologies the one that will best satisfy the needs of an analyst. A procedure is presented which will allow an analyst to select a desired level of performance for a methodology with respect to vulnerability, susceptibility, reliability, maintainability, mission effectiveness, and life cycle cost analyses.
A total of five computer codes that optimize some portion of aircraft cost were found during the literature search for this research effort. A brief description of each code is presented here. None of these codes are used in the LCC Module developed here.

B.1 REFERENCE 67

Reference 67 presents a code to optimize fuel economy along with subjective passenger preference. The passenger preference is primarily related to interior cabin layout (e.g., seats abreast, number of aisles, seat pitch, cabin headroom, etc.)

B.2 REFERENCE 63

Reference 63 presents a gradient optimizing computer program to minimize DOC as a function of airplane geometry. In this way, the best airplane operating under one set of conditions can be compared with the best operating under another set. Best, in this case, means having the minimum DOC.

B.3 OPDOT

The Optimal Preliminary Design of Transport Aircraft (OPDOT) program uses constrained parameter optimization to minimize a performance index (e.g., direct operating cost per block hour) while satisfying operating constraints (ref. 64). The approach in OPDOT uses geometric descriptions as independent design variables. A set of starting values for the selected independent design
variables and design constants is input and used to initialize the optimizer and the data base. Initially, the program was written with seven independent variables (wing area, wing aspect ratio, fuselage length, horizontal tail area, horizontal tail aspect ratio, aft-most center of gravity position, and installed thrust), but it has the inherent capability to handle more and has successfully converged with 13. Typical design constants include nonvarying geometries, mission parameters, economic constants, nonlinear aerodynamic data and some levels of technology.

The inputs (current value of independent design variables and the design constants) are utilized by a sequence of subroutines that calculate a performance index which is selected by the user. Typically, minimum DOC/block hour is chosen, but minimum DOC/flight, maximum ROI, minimum income required for a 15 percent ROI, maximum I/D, and minimum takeoff gross weight are also available as criteria to be optimized.

OPDOT allows the evolution of new technologies incorporated into an aircraft design in an optimal fashion. The degree of detail in the analyses when the performance function and the constraint functions are evaluated is at the preliminary design or classical aeronautics level. That is, the precision in some phases of the calculations is expected to be as poor as five to ten percent. Hence, whereas the predictive capabilities are expected to be marginal, the accuracy of the relative comparisons of designs is expected to be good.
In a study where the FARE (income required for a 15 percent ROI) was optimized (ref. 65), the optimal design in terms of aircraft geometry was shown to be relatively insensitive to certain design assumptions which had significant impact on the absolute magnitude of the optimized FARE. They included the following parameters: annual utilization, aircraft purchase price and airframe maintenance costs. In comparison, choosing landing field length, Mach number, design range, number of passengers and fuel price were economic choices that had significant impacts upon the optimal configuration, as well as the value of optimal FARE.

**B.4 RAE OPTIMIZATION CODE**

A computer program which can optimize the preliminary design of a subsonic swept-wing aircraft has been developed at the Royal Aircraft Establishment, Farnborough (ref. 13). This program can be used to assess rapidly the effects on the optimum design of changes in the specified performance or of advances in aerodynamic, structural, or engine technology. Compound optimization functions including several of the aircraft operating characteristics, e.g., operating cost, noise, ride comfort, etc., with different weighting factors can be used to produce designs with large improvements in some characteristics which have been obtained at the cost of small penalties in others.

At present the minimum DOC is generally used as the optimization function; i.e., the aircraft design variables are optimized to achieve the minimum possible value of DOC. For commercial transport aircraft with specified mission requirements,
the alternative optimization functions include: minimum first cost, minimum (fare + value of journey time), minimum noise footprint area, minimum fuel consumed, maximum passenger comfort, and maximum airline profit.

B.5 V/STOL CODE

The V/STOL code (ref. 68) uses performance and cost together to define a minimization problem for a Vertical/Short Takeoff and Landing (V/STOL) military transport aircraft. The costs included are those of research and development, production, maintenance, and operation. The minimum LCC is found by the minimization of a function of three variables: maximum speed at best altitude, takeoff gross weight, and maximum thrust per engine.
APPENDIX C

ACQUISITION COST MODELS

Many different models to calculate either the total, or some part of, acquisition cost were found during the literature search. Acquisition cost is composed of RDT&E and production for the airframe, engines, and avionics. A brief description of each of the various models found is presented here.

C.1 AIRFRAME COST MODEL

The method of cost estimation outlined in reference 80 uses a unique method of predicting the weight and physical design of each detail part of a vehicle starting at a time when only configuration concept drawings are available. In addition, the technique relies on methods developed to predict the precise manufacturing processes and the associated materials required to produce each detail part. These items are, in turn, used to derive the manufacturing, labor, and materials required to produce a complete component, and hence to derive the associated costs.

The goals of this model are: flexible from user's point of view, easily modified and updated, data difficult to obtain during aircraft preliminary design should be generated within the program, and analysis may be used at any preliminary design stage. To achieve these goals, the program is: modularized; much of the driving data may either be input or generated, depending on the definition of the vehicle; and output may be selected anywhere from the complete and fully detailed version to summary sheets.
C.2 R&D COST ESTIMATION

Reference 99 summarizes the results of the study of cost estimation of research and development programs. In this study, a cost data base was developed consisting of the development costs associated with a number of North American Rockwell Aircraft. These costs were put into a work breakdown structure (WBS) format. Special analyses were then conducted to develop cost factors associated with the effect of specifications, with various levels of risk, with business environment considerations, and methods of reducing R&D costs were evaluated. Using the cost data base and the results from the special analyses, CERs were developed for the various WBS cost elements. These CERs were then programmed. The results of a run of the program give a prediction of the development costs of a new aircraft program, based on the design, material, and business environment characteristics associated with the particular aircraft development program.

The cost model is built on a data base derived primarily from a sample of relatively high-performance small, fixed wing aircraft developed during the past several decades. The most appropriate and confident use of the estimating tool therefore, is for new aircraft of this general variety. The user is cautioned in applying the total estimating model to extrapolations to other technologies (e.g., spacecraft, rotary wing aircraft, etc.). Many of the individual CERs, however, could be judiciously utilized for various elements of RDT&E cost for other program types.
C.3 EXPERIMENTAL AIRCRAFT PROGRAMS COST

Reference 79 describes a parametric model to obtain the cost for research aircraft programs. One of the most frequently used techniques for developing budgetary cost estimates is based on parametric analysis of historical cost data. Most existing models were developed for use in estimating development and acquisition costs of military aircraft or space vehicles. None of these is applicable to experimental aircraft programs, which have much lower costs by virtue of production quantity, documentation requirements, design and tooling approach, test requirements, and other factors.

The model developed for estimating the cost of NASA's research aircraft is based on parametric estimating relationships for man-hours and materials, using weight as the primary cost driver. Data from previous experimental and prototype programs were used to develop the estimating relationships. Both company-funded and government-sponsored aircraft programs are included in the data. The data are primarily for subsonic fixed-wing aircraft of aluminum construction. Some aircraft were all new and some were modifications.

C.4 GENERAL DYNAMICS MODEL

The General Dynamics model described in reference 100 estimates cost at the major system level based on estimated costs for some study aircraft and some actual aircraft costs. All types of aircraft are represented in the General Dynamics data base. The applicability of much of that data to transport aircraft is not clear because fighters and bombers are characterized by more costly
high performance and low weight components. Furthermore, the
reliability and consistency of the data used in developing the
model could not be determined because the data were not documented
(ref. 77).

C.5 REFERENCE 76

Reference 76 presents a statistical approach to aircraft cost
estimating for various types of military aircraft. The approach
relates cost to various aircraft physical and performance
characteristics so that the preferred combinations of variables for
specific effectiveness levels can be identified. It also enables
cost estimates to be made with fair accuracy based solely on the
major aircraft characteristics before the detailed design is
actually completed.

C.6 REFERENCE 91

Cumulative cost data from 25 separate aircraft programs is
used in reference 91 to derive cost estimating relationships for
the development and production of aircraft airframe programs. CERs
are derived for engineering, tooling, production, and materials for
each phase and for development support and flight-test operations
during the development phase. This model is used in the LCC Module
to predict airframe RDT&E cost.

C.7 JWN-I MODEL

The JWN-I model (ref. 101) estimates recurring and
nonrecurring costs in 1970 dollars. The costs are per pound of
AMPR. The recurring cost is the cumulative average cost at unit
100. These costs are functions of maximum speed at altitude,
takeoff gross weight/AMPR, AMPR, a complexity dummy, and a technology index which is the number of changes made in aircraft since World War II. The F-14 has a technical index of 198. This model is primarily for fighter aircraft and has little value for heavy bombers or cargo aircraft.

C.8 JWN-II MODEL

The JWN-II model is an updated version of the JWN-I model (ref. 102). Instead of recurring and nonrecurring costs, it estimates design and production costs in 1975 dollars. The design costs are a function of AMPR, maximum speed at best altitude, gross weight, maximum thrust, and the same technology index as described above. There is a factor which can be applied to account for bomber aircraft and another factor which can be applied for a major technology advance. The production costs are the cumulative average for quantity 100 and are a function of AMPR, maximum speed at best altitude, and maximum thrust. Factors can be applied for cargo aircraft, bomber aircraft, and for a major technology advance.

The JWN-II model provides usable total-cost estimates very consistently. The estimates are, of course, contingent upon the ability to choose the proper complexity factor ahead of time. This is a subjective decision by the model user. It is obvious, however, that some independent variable, other than weight and speed, is required to distinguish between simple and complex aircraft. Extrapolation outside the limits of the data is dangerous with any model, but is particularly risky with this model.
because of the interdependence of the variables. The model does lend credence, however, to what many cost analysts believe - that total-cost models are more reliable than more detailed models.

C.9 PRC MODEL

The Planning Research Corporation cost model (ref. 103) estimates engineering, tooling, manufacturing labor and material costs for the total airframe as a function of a few aircraft characteristics - most importantly weight, speed, and quantity. This model is very similar to the Rand models.

C.10 RAND MODELS

The Rand Corporation has been involved in the development and improvement of aircraft cost models over a long period of time. The data base consists only of military aircraft and care should be used in estimates of the cost of a normal transport aircraft. The early models were originally developed in 1966 (ref. 104) and revised in 1971 (ref. 105) to provide consistent, accurate cost estimates of airframe costs. The model that was developed considered several variables, such as weight, speed, wing loading, wetted area, and aspect ratio, but found that only weight and speed were significantly correlated to warrant consideration. The aircraft included in the model are all military.

Inputs to the model consist of takeoff gross weight, airspeed, maximum production rate, number of engines, engine thrust, engine and avionics RDT&E costs, avionics costs for first unit, and desired airframe profit. The model output consists of airframe R&D costs, airframe production costs (both unit and
cumulative), engine production costs (both unit and cumulative), and total aircraft production costs, with or without RDT&E costs.

An updated Rand model (ref. 106) examined other variables that might better explain airframe development and production costs, or that could be combined with several variables to describe program costs accurately. The impact of advances in manufacturing technologies and materials on cost-estimating methodologies was also examined. The resulting parametric model concluded that weight and speed are still the two items of major significance, although other variables could produce minor impacts.

Inputs to the parametric equations consist of airframe unit weight, maximum speed, and the number of test aircraft. The parametric equations used can be categorized according to aircraft grouping or total sample: Group 1 is small, slow aircraft; Group 2 is small, fast aircraft; and Group 3 is large, slow aircraft. The output of the parametric equations is the number of hours needed to design and manufacture an airframe (engineering hours, tooling hours, manufacturing hours, and quality-control hours), the cost of materials, flight-test costs, and the total program costs. Generally the last model is the best.

Rand also developed a model for estimating the development and production costs of engines (ref. 93). The refined aircraft turbine engine TOA (Time of Arrival) model is based on 26 U.S. military turbojet and turbofan engines developed and produced during the past 30 years. The model predicts the man-rated 150-hour MQT date as a function of maximum thrust of the engine at sea
level static conditions, weight, specific fuel consumption at military thrust at sea-level static, turbine inlet temperature, and a pressure term (the product of the flight envelope maximum dynamic pressure and the overall pressure ratio of the engine).

The equations apply to military development and pricing practices similar to those of the 1950's and 1960's. They do not apply to engines that can be expected to fall outside the historical distribution because of special features, such as "quiethotechnology" or commercial pricing. It is also important to remember that the equations cannot be used for marginal analysis of existing engines, whether they fit the assumptions or not, and they cannot be used to make fine distinctions among various engines. They are intended for planning estimates for new engine programs.

C.11 SAI MODEL

In assessing and prioritizing its aeronautical research programs, the NASA found that the RAND models were not wholly satisfactory because it was necessary to make many detailed calculations and perform much analysis outside of the model to account for the incorporation of any new technologies. A method was, therefore, required by the NASA wherein a new aircraft could be divided into its major systems and the cost for each system could be determined as a separate entity, in order to assess the cost impact of new or different technologies on each system and, in turn, the entire aircraft.

Science Applications, Incorporated (SAI) developed a model (ref. 92) comprised of system level weight and cost estimating
relationships (WERs and CERs) for transport aircraft. This model provides a rapid means for estimating the approximate weight and cost of transport aircraft at the system level, exclusive of engines. The estimating relationships were developed so that production cost estimates could be made with relatively little effort, based on performance parameters which are available during the preliminary design phase. This is accomplished by a two step process as weight is estimated based on performance parameters and cost is then estimated as a function of weight. Further, because these estimates are at the system level, the planner may revise selected equations as required to reflect more accurately the effect of new technologies.

A guiding philosophy related to the development of the SAI model was that it is unlikely that an aircraft which utilizes new technologies for every system will be designed or produced in the foreseeable future. Rather, future aircraft will probably be derivatives of current aircraft. Therefore, many of the CERs provided (which are based on current technology) will be appropriate for estimating the costs of future aircraft designs. This philosophy has indeed been upheld by the next generation of aircraft.

It is cautioned that it was impossible to evaluate the accuracy of the individual system estimates and, although the aggregate estimates were reasonably accurate, there could conceivably be significant off-setting errors at the system level. Estimates made for the DC-10-10, C-141A, and F-28 showed that the
weight estimates were also very good. When the total estimated weights were compared with the total actual weights, it was found that the DC-10-10 and the C-141A were underestimated by 2.9 and 4.7 percent, respectively. The F-28 was overestimated by 5.5 percent. All in all, the SAI model appears to do a good job for contemporary transport aircraft with speeds not exceeding Mach 0.85 (ref. 106).
Operating and support costs for commercial aircraft are broken down into direct operating costs and indirect operating costs. DOC is broadly defined as the costs that are associated with flying operations, and the maintenance and depreciation of the flying material. IOC include the operator's other costs. Two models were found during the literature search for estimating DOC and one for IOC. These models are described here.

D.1 AIR TRANSPORT ASSOCIATION MODELS

The Air Transport Association developed a standard model for estimating airline direct operating costs in 1960 (ref. 108) and in 1967 that model was updated to reflect more recent conditions (ref. 95). The ATA-67 model (as ref. 95 is known) has been used extensively to estimate DOC. The model consists of Flying Operations (flight crew costs, fuel and oil, and hull insurance costs), Direct Maintenance - Flight Equipment (labor - airplane, labor - engine, material - airplane, material - engine, and maintenance burden), and Depreciation - Flight Equipment.

Reference 109 addresses some of the assumptions and limitations of the ATA-67 model. Maintenance costs have been based traditionally on such parameters as airplane empty weight, engine thrust, and airframe or engine initial cost. It should be noted that the correlations in the ATA method are purely statistical. There is no direct relationship, for example, between the aircraft
weight and ease and cost of maintenance. On the contrary, provisions intended to simplify maintenance by means of improved accessibility will tend to increase the empty weight, but this will result, wrongly, in increased maintenance costs if the ATA method is used incorrectly. Ideally the maintenance cost item should be broken down into various components, as systems vary widely in their maintenance costs, partly due to their difference in complexity and sensitivity to hourly and cyclical effects.

Depreciation, like insurance, is in reality an annual cost. In the ATA-67 method, the depreciation period is taken as twelve years. The lifetime of the aircraft, in terms of both flying hours and flight cycles, must obviously exceed this period.

Utilization is principally affected by the elapsed time during which the airplane is on the ground due to traffic requirements, loading, unloading and refueling, and regular maintenance, and due to delays caused by the weather and unscheduled maintenance. The general trend given in the ATA method is a curve of annual utilization versus block time, showing a variation between 3,000 hours/year for a block time of one hour, to 4,500 hour/year for a block time of eight hours. If the number of flights per day is fixed, however, the utilization is proportional to the block time. It should be noted that measures to improve the utilization, e.g., by reducing the air maneuver time, transition time between two flights, etc., are not reflected in the statistical correlation. To appreciate potential improvements in utilization, a detailed assessment of the effects involved must be made.
D.2 AMERICAN AIRLINES MODEL

A methodology has been developed by which the operating cost associated with variations in aircraft design and technology characteristics can be assessed (ref. 94). The model consists of a set of parametric equations to determine commercial air transport aircraft as a function of aircraft design characteristics. It can be used to assess the effect of different designs and the effect of advanced technology on existing and future aircraft. This model includes more cost categories than the standard ATA 1967 model, permitting more accurate descriptions of aircraft-related operating costs. The cost categories added to the ATA model account for nearly 25 percent of aircraft-related operating costs.

The American Airlines model is particularly useful in determining operating costs and benefits because the extensive data base used in developing the model provides a significant number of data points as references. American Airlines used the operating-cost data base accumulated on jet aircraft since 1958. In addition, the company used the Boeing Service Experience Retention Files, which include data on all Boeing aircraft in airlines service. This data base permitted and facilitated an extensive regression analysis.

Input data for the parametric equations consist of aircraft purchase price, seating capacity, maximum gross weight, average flight time, airframe weight, number of engines, number of electrical generators and their rating in kilovolt amperes (kVA), the number of inertial navigation systems, the air-flow capacity of
the air conditioning package, and the flow capacity of hydraulic pumps. The output consists of the aircraft-related operating costs, in 1976 dollars, per trip for the different cost categories. The maintenance costs are further divided into labor costs and material costs for each of the ATA Specification 100 Codes. Dividing by the average flight time will yield the aircraft-related operating costs as cost per flight hour.

D.3 LOCKHEED-GEORGIA IOC MODEL

The Lockheed-Georgia IOC model was originally published as a proposed standard method to estimate indirect operating costs (ref. 96). No other models for IOC have surfaced since then and it appears that this model has become the standard. It includes Maintenance - Ground Property and Equipment (direct maintenance and maintenance burden), Servicing - Flying Operations (passenger service, aircraft servicing, and traffic servicing), Administration and Sales (servicing administration, reservation and sales, advertising and publicity, and general administration), and Depreciation - Ground Property and Equipment.

The maintenance function includes expense related to repair and maintenance of ground property and equipment. Passenger Service encompasses all activities related to passenger comfort, safety, and convenience while in flight and when flights are interrupted. It is broken into cabin attendant activity, passenger food expense, and passenger service support items. Aircraft Servicing covers all expense incurred on the ground incidental to the protection and control of the in-flight movement of aircraft;
scheduling flight and cabin crews; landing and parking aircraft; visual inspection, routine checking, servicing and fueling of aircraft; and other expenses incurred on the ground pertinent to readying for the arrival and takeoff of aircraft at airport terminals. Traffic Servicing encompasses the processing of revenue payloads at airport terminals. It is divided into passenger handling and cargo handling.

Servicing Administration includes expenses of a general nature incurred in performing supervisory or administrative activities solely and in common to function Aircraft Servicing and Traffic Servicing. It is broken into general aircraft handling and traffic handling personnel, communications personnel, record keeping and statistical personnel, other personnel, and rentals. Reservations and Sales include expenses incident to direct sales solicitations, ticket sales, controlling and arranging or confirming passenger and cargo space sold on aircraft, development of tariffs and operating schedules, the expense attributable to the operation of city ticket offices, and agency commissions on sales of passenger and freight transportation. Most of the expense is related to reservation-office and ticket-office activity. Advertising and Publicity expense encompasses all costs associated with creating public preference for the air carrier and stimulation of air travel. General and Administrative includes all expense items of a corporate nature, plus expense incurred in performing activities which contribute to more than a single operating function, such as general financial accounting activities, purchasing, legal, and
general operational administration not directly applicable to a particular function.

Depreciation of Ground Property and Equipment includes all charges to expense which record losses attributable to the current exhaustion of the serviceability of ground property and equipment. It includes losses from obsolescence as well as wear and tear activity. Amortization of capitalized developmental and preoperating costs are found in this function also. All depreciation expense associated with ground property and equipment is assigned on a yearly basis.
APPENDIX E
LIFE CYCLE COST MODELS

A total of 6 LCC models were found during the literature search. They are described below.

E.1 EAGLE

The EAGLE model (ref. 109) data base currently includes a typical fighter which is capable of supersonic cruise, employs a cranked wing, and is powered by one or two afterburning engines. The baseline engines included are members of the Pratt & Whitney JT69 family of engines. The technology level assumed for this family is representative of engines to be operational in the 1990's time period. Component engine costs are determined based on internal engine performance parameters and geometries which are an automatic output of Pratt & Whitney's advanced engine parametric performance decks. The EAGLE model uses the Modular Life Cycle Cost Model (described in Appendix B) to predict airframe/avionics and base operating support costs. MLCCM is becoming the industry standard airframe LCC model.

E.2 MACO LCC MODEL

The Model for Estimating Aircraft Cost of Ownership (MACO) is described in reference 40. Its purpose is to address the ownership portion of LCC. It is widely believed that ownership costs can be significantly influenced by systems design, performance, operational, and logistics choices made during the system acquisition process. LCC analysis offers a means for explicitly weighing the consequences of those choice and for making tradeoffs
among system performance objectives and the temporally and fiscally
different components of LCC - development, procurement, and
operations and support (ownership).

E.3 MLCCM

The Modular Life Cycle Cost Model (refs. 48-53) is described in Appendix B.

E.4 PMLCC MODEL

The PMLCC model (ref. 110) estimates the cost breakdown structure and work breakdown structure elements that compromise the LCC of a missile. Cost-estimating algorithms, cost factors, and cost relationships in the PMLCC model are based on development and production costs of ten missile programs: SUBROC, HARPOON, SPARROW, SIDEWINDER, HARM, PHOENIX, STANDARD, STANDARD ARM, MAVERICK, and CONDOR.

E.5 SCOUT HELICOPTER MODEL

A computerized Scout helicopter LCC model is described in reference 111. It includes research and development, investment (non-recurring and recurring), and operating costs. Each one of these categories is broken down into lower level cost elements and describes them. The reference presents the equations contained in the model and a data base for helicopters.

E.6 REFERENCE 112

Reference 112 presents a model developed where the basic objective was the definition of future strategic airlift concepts and the technologies required for their successful implementation. Emphasis was placed on the cost of a new strategic airlift system, because it was considered to be a primary deterrent to the
acquisition of expanded airlift capability. Specific categories of cost were identified, quantified and evaluated. In the process, it was determined that flexibility in estimating was essential, and that adherence to a conventional cost model was inappropriate. Since with a conventional model, the estimating process would be driven toward the procedure extrapolating from a historical base to achieve the estimates of the advanced systems, specific attention was given to the unique characteristics of each design concept in order to maximize the discrete estimating aspects.

A life cycle cost structure was formulated for the purpose of identifying the significant functional elements that would have to be quantified and thus provide a contribution to the concept evaluation process. Emphasis was placed on the development of reasonable and relative costs among the various concepts instead of absolute values. Some imprecision and uncertainty are to be expected when dealing with concepts and technologies two decades downstream. The technical depth of this study is essentially limited to top level configuration and system characteristics. Therefore, cost data were generated consistent with these technical definitions and characteristics. Cost generation was accomplished by using a combination of techniques (i.e., analogous, trend analyses, discrete, and historical data).
In order to insure that the LCC Module was operating correctly before connecting it to FLOPS and in order to understand the calibrate the results generated by the model, the LCC Module was run by itself for the Boeing 737, Boeing 767, and Boeing 747. Information that would come from FLOPS was input directly into the model.

Table F.1 shows the results calculated and pieces of information obtained from various sources for calibration. The GASP numbers were calculated in the General Aviation Synthesis Program (refs. 42 and 43) using models developed and calibrated at NASA-Ames. The propulsion system in the Boeing 767 model was a projected advanced engine and not a model of the actual engine. The Anderson (ref. 81) and Aviation Daily (ref. 114) numbers are "real" data. Unfortunately, the Boeing 767 is too recent to be included in the Anderson paper.

Comparison of the results show that agreement between most of the LCC values and the other data is reasonable. The only comparisons that are noticeably bad are the engine costs. Unfortunately the engine cost module has been questionable from the start. Research could not uncover another engine cost model more appropriate for this effort. In an attempt to correct the engine cost results to more closely match reality, a correlation was done for several different existing engines between the cost predicted
### TABLE F.1 - SUMMARY OF RESULTS COMPARISON

<table>
<thead>
<tr>
<th>CONDITION</th>
<th>LCC</th>
<th>GASP</th>
<th>ANDERSON</th>
<th>AVIATION DAILY</th>
<th>PERCENT ERROR</th>
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LCC = Life Cycle Cost Module  
GASP = General Aviation Synthesis Program (calibrated models)  
Anderson = SAWE Paper 1224, May 1978  
Aviation Daily = reports on operating costs for specific aircraft types
by the engine cost model and the actual cost. The spread, even for similar types of engines, was very wide. Two correction factors were developed, one for engines on widebody aircraft and one for all other engines, in an attempt to normalize the error. Unfortunately, the aircraft chosen here have engines that did not fall near the average correction factors. Part of the problem with these types of comparisons is that what something should cost and what it actually costs are often two different things.

The airframe cost comparisons are not as good as would be hoped but at least appear to be reasonable. The GASP numbers are underpredicted slightly (less than 10 percent) by the LCC Module; it is really not possible to draw any conclusion about comparison with the Anderson numbers.

The DOC comparisons are reassuringly consistent. The LCC module underestimates slightly compared to the GASP results and very consistently overestimates the Aviation Daily numbers (between 25 and 29 percent). This leads to confidence that the model is behaving correctly and is properly accounting for differences in the aircraft due to size. Hoping to predict current operating costs accurately is hopeless the cost models were all developed prior to deregulation.

The overall conclusion drawn from these comparisons is that the individual components of the LCC Module are functioning as intended and will provide reasonable results that should properly account for differences in conceptual design variables and conditions.
The sensitivity studies method of reference 2 was used to estimate the reasonable changes in takeoff gross weight when incorporating advanced technologies in the LCC Conceptual Design System. Sensitivities of takeoff gross weight to changes in L/D, sfc, and $W_E$ were estimated. This is using a Class One method to check a much more detailed procedure so great accuracy cannot be expected, but it is worthwhile to be sure that the computer code is reasonable.

The first step in estimating the sensitivities was to estimate a mission fuel fraction. The mission segments included:

<table>
<thead>
<tr>
<th>SEGMENT</th>
<th>FUEL FRACTION</th>
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<td>Start, warmup</td>
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<tr>
<td>Taxi</td>
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<tr>
<td>Takeoff</td>
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<tr>
<td>Climb</td>
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<tr>
<td>Descent</td>
<td>0.990</td>
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<tr>
<td>Landing</td>
<td>0.995</td>
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</table>

and

Cruise \( \left( \frac{W_4}{W_5} \right) \)

where

\[
\ln\left(\frac{W_4}{W_5}\right) = \frac{R}{(V/SFC)(L/D)}
\]

With \( R = 2210 \) nmi, \( V = 459 \) kts, \( sfc = 0.564 \), and \( (L/D) = 16.5 \),
\( \left(\frac{W_5}{W_4}\right) = 0.848 \).
Then:

\[ M_{ff} = (0.990)(0.990)(0.995)(0.980)(0.848)(0.990)(0.995) \]

\[ M_{ff} = 0.798 \]

The reserves are estimated with a missed approach (fuel fraction = 0.995) and a 30-minute hold where:

\[ \ln(W_{r2}/W_{r3}) = (E_{ltr}/((1/sfc)(L/D))) \]

where \( E_{ltr} = 0.5 \), sfc = 0.55, and \( L/D = 15 \)

giving \( W_{r3}/W_{r2} = 0.981 \). This makes the complete mission fuel fraction:

\[ M_{ff} = 0.798 \times 0.995 \times 0.981 = 0.779 \]

Next the takeoff gross weight and empty weight are estimated using the equations:

\[ W_E = \text{inv} \cdot \log_{10}( \text{log}_{10} W_{TO} - A)/B \]  \hspace{1cm} \text{(G.1)} \]

and

\[ W_{Etent} = W_{TOguess} - W_F - W_{PL} - W_{tfo} - W_{crew} \]  \hspace{1cm} \text{(G.2)} \]

where the subscript \( E \) = empty, \( T_{Oguess} \) = guess takeoff, \( F \) = fuel, \( PL \) = payload, and \( tfo \) = trapped fuel and oil. For a subsonic commercial transport, reference 2 gives \( A = 0.833 \) and \( B = 1.0383 \).

Using these equations and constants, \( W_{TO} = 175000 \) and \( W_E = 93198 \).

The mission fuel fraction calculated here compares very favorably with that arrived in FLOPS, but the takeoff gross weight and empty weight calculated here are both much less than that determined in FLOPS, indicating that FLOPS is somewhat conservative in its weights estimation.
The following equations are necessary to evaluate sensitivities:

\[ C = \frac{(W_E + D)}{W_{TO}} \]  \hspace{1cm} (G.3)

\[ D = W_{PL} + W_{crew} \]  \hspace{1cm} (G.4)

\[ F = -BW_{TO}^2(CW_{TO}(1-B) - D)^{-1}M_{FF} \]  \hspace{1cm} (G.5)

For this configuration, \( C = 0.775, D = 42450 \), and \( F = 519905 \).

Then:

\[ \frac{\partial W_{TO}}{\partial (L/D)} = -FRsfc(V(L/D)^2)^{-1} \]  \hspace{1cm} (G.6)

= -6136

From FLOPS, \( L/D = 3.6 \) (from 16.5 to 20.1), giving

\( \Delta W_{TO} = -22090 \) lbs or a change of 12.6 percent relative to \( W_{TO} \).

The actual \( \Delta W_{TO} \) in FLOPS was 21,250 lbs or a change of 9.7 percent relative to the takeoff gross weight in FLOPS. Therefore, the change appears to be reasonable.

The sensitivity of takeoff gross weight to fuel burned was calculated using the same constants and equations. This time the sensitivity is given by:

\[ \frac{\partial W_{TO}}{\partial (sfc)} = FR(VL/D)^{-1} \]  \hspace{1cm} (G.6)

= 179514.

The \( sfc \) is -0.0564 (10 percent) giving \( \Delta W_{TO} = 10124.6 \) lbs or 5.8 percent relative to \( W_{TO} \). The actual \( \Delta W_{TO} \) in FLOPS was 7871 lbs or 3.6 percent relative to the takeoff gross weight in FLOPS. Again this seems very reasonable.
The sensitivity of takeoff gross weight to changes in empty weight (advanced structures and systems) was calculated using the equation:

$$\frac{\delta W_{\text{TO}}}{\delta W_E} = B W_{\text{TO}} \left[ \text{inv} \log_{10} \left( \log_{10} W_{\text{TO}} - A \right) / B \right]^{-1} \quad (G.7)$$

First the constant $A$ was modified using:

$$A' = A - B \log \eta$$

Using weights data from reference 4, a new value of $A$ was found to be 0.10171 for a 20 percent reduction in wing weight due to composite materials. Going through this process again and using equation G.7 gave $\frac{\delta W_{\text{TO}}}{\delta W_E} = 2.025$. The actual change in $W_E$ is 5907 lbs, giving a potential $\Delta W_{\text{TO}}$ of 11962 or 6.8 percent. The actual change in takeoff gross weight is 13175 lbs or 6.0 percent of the actual takeoff gross weight in FLOPS. Based on this, it would appear that FLOPS is not as conservative in estimating changes in weights as it is changes in aerodynamics or propulsion, but it is still in the ballpark.

The final sensitivity of takeoff gross weight was calculated for changes in systems weight (these changes were very small). Again the data from reference 4 was used to generate a new value of $A$ ($A = 0.0869$). Using this, $\frac{\delta W_{\text{TO}}}{\delta W_E} = 1.964$ and the potential change in $W_{\text{TO}}$ is 1489 lbs or 0.9 percent of $W_{\text{TO}}$. The actual change in takeoff gross weight was 3302 lbs or 1.5 percent of the actual takeoff gross weight in FLOPS. This is still fairly close to reasonable. These numbers are so small that small errors can have a big impact.

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APPENDIX H

BIBLIOGRAPHY


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269. Wrigley, B.: Engine Performance Considerations for the Large Subsonic Transport. Lecture given at the Von Karman Institute, Brussels, 23 April, 1969.


