Optimization of the Conceptual Design and Mission Profiles of Short-Haul Aircraft

Dimitri Simos* and Lloyd R. Jenkinson†
Loughborough University of Technology, Leicestershire, England, United Kingdom

This paper outlines a method of sizing new short-haul commuter aircraft by conducting a flight profile optimization procedure in parallel with the optimization of the major design parameters. Minimum-fuel, minimum-cost, or minimum-mass aircraft can be designed for a given mission, which would be optimally flown. The method is capable of handling both equality and inequality constraints which may relate to either design boundaries or operational flight restrictions. Results of some case studies are presented. It is found that the impact of operational limitations, particularly restrictions in the rate of descent, can have a significant effect on the value of the objective function. The penalty may be as large as that caused by design requirements such as minimum field performance.

Introduction

OVER the past decade there has been an upsurge of interest in twin-engined, propeller-driven aircraft designed to satisfy the commuter market. These types now cover a large portion of the general aviation spectrum, ranging from six- to over fifty-seat designs. Much engineering effort is being expended by the aerospace industry in the development of such aircraft, spurred on by a strong growth in regional airlines worldwide, plus the "deregulation" policy adopted in the United States. In the United Kingdom, there has been evidence of an increase in small scheduled commuter operations, despite the traditionally fragile nature of general aviation in this country.

Twin-engined, propeller-driven commuter liners pose particularly interesting challenges both in their design and operation. The possibility of engine failure dictates a critical examination of take-off capabilities and climb performance with one engine inoperative. The short-haul nature of the commuter business means that the aircraft flight profile is dominated by the climb and descent phases, and the cruise segment is often insignificant. Over 95% of U.S. commuter airline passengers travel less than 250 n. mi. (460 km), therefore the flight profile optimization of short-haul operations is vital to economic success.

The optimization of the vertical flight profile of an aircraft under particular operating conditions has always been an important problem in aeronautics. In the early 1960's, complex dynamic programming techniques were developed, stimulated by the need to optimize the trajectories of spacecraft. These methods were applied to aircraft, but, because of the complication of atmospheric drag, they were involved and restricted in application. Rutowski[6] made a significant simplifying contribution by applying the energy state approximation to the performance of aircraft. Although continuous development has resulted in improved realism, most work has been conducted in relation to long-range, marginally subsonic or supersonic aircraft, and the problem of optimizing the flight profiles associated with short-haul routes has received little attention. The few efforts in this area have concentrated exclusively on jet aircraft.[7] In addition, it has always been assumed that an autopilot would be available for following the optimal trajectory. For propeller-driven commuter aircraft this is rarely the case. It was recently demonstrated[1] that, for this type of aircraft, it is possible to provide a realistic flight profile optimization procedure using simple, discrete, time-independent variables. Such a procedure can be coupled to a standard mathematical multivariate optimization program and eliminates the need to use the calculus of variations and the associated complex, time-dependent control variables. A logical extension to this method involves the inclusion of aircraft design parameters in the algorithm to enable a combination of flight and aircraft geometry parameters to be optimized together. Through this approach, the aircraft designer can identify the optimum aircraft to fly a particular operational pattern. Such a combined design/flight profile optimization method is discussed in this paper.

The hitherto separate aspects of preliminary design optimization and flight-profile optimization have now been integrated in a program called CASTOR (Commuter Aircraft Synthesis and Trajectory Optimization Routine). The program is currently limited to the analysis of twin-turboprop aircraft of conventional layout (aft tail, wing-mounted engines) and utilizes 22 optimizable variables, of which 10 are design, or "sizing" variables, and 12 are flight-profile variables. Twelve constraints are used to control the optimization in terms of design/operational limitations and to satisfy aspects of the analysis methodology used. A multivariate optimization (MVO) routine developed at the Royal Aircraft Establishment is used as the mathematical optimizer. This is designed to minimize a nonanalytical, user-specified objective function subject to equality constraints, inequality constraints, and variable bounds.[8] It is currently possible to use a maximum of 50 variables and 75 constraints.

For preliminary aircraft design, computer techniques are well established[2-5] although, to date, most optimization studies have been concerned with civilian and military jet aircraft. In this study, the aircraft geometry is used for the calculation of basic aerodynamic and mass characteristics of the aircraft, for each point during the search. Various fundamental data can be provided by the user as fixed input values (e.g., aerofoil maximum lift coefficient, or $C_{L\max}$). Some static stability considerations are included in the methodology, thereby producing a balanced aircraft and allowing for the effects of trim drag. Powerplant characteristics are modeled within the program using data provided by manufacturers of existing engines. A

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*Research Fellow, Department of Transport Technology; currently Aircraft Design Specialist, Rolls Royce. Member AIAA.

†Senior Lecturer, Dept. of Transport Technology.

facility is available for scaling ("rubberizing") these engines and for factoring fuel characteristics to account for expected design improvements.

The aircraft is "flown" through a specified number of stages which constitute the main mission, plus a diversion and hold segment. In light of the experience gained with the Short-haul Computer Optimum Profile Evaluation program (SCOPE),[1] the flight profile analysis has been simplified with no significant loss in accuracy. Multistage missions are assumed to consist of equal-length main stages, although the diversion stage length may be different. From the point of view of aircraft design, this is regarded as a realistic assumption.

Output from the program includes the final geometry, component mass breakdown, maneuver and gust load factors, center-of-gravity positions, trimmed drag polar, optimum flight profiles and field performance. Currently a choice of three objective functions is available: minimum fuel, minimum takeoff mass, and minimum direct operating cost (DOC).

Aerodynamics

Most of the aerodynamic calculations are carried out by the main design program routine. This routine is called by the mathematical optimizer whenever a value of the objective function is required. The calculated aerodynamic data are then fed to a trim subroutine which will, in turn, determine the total trimmed aircraft drag at any point during the flight profile analysis.

At a given aircraft lift coefficient, the classical linearized trim equations are used to calculate the lift split between the tailplane and the aircraft-minus-tail. The lift of the aircraft-minus-tail is then further apportioned to the wing, fuselage, and nacelles. Simplifications made in the formulation of the aerodynamic model include the use of linear lift slopes for the wing/fuselage/nacelles (justified for angles of attack used in normal operations), and the assumption of shallow climb angles (justified for propeller-driven commuters). Vertical offsets between the center of gravity (c.g.), the aerodynamic center, and the thrustline are assumed to have negligible effects.

The static margin is constrained to be no less than an input value (typically 5%) in order to ensure adequate static stability. This constraint must be satisfied under a "worst-case" condition, which is assumed to be aftmost c.g., and full power at takeoff safety speed. The high thrust coefficient associated with this condition will be destabilizing and is modeled according to empirical data giving a reduction in static margin as a function of thrust coefficient and the location of the tailplane in relation to the wing wake.

The location of the wing along the fuselage is a variable. This provides a good illustration of the flexibility of the MVO routine. Normally, wing position would be found by iteration but, by assigning it to the role of a variable, it is possible to find its optimum value subject to any trim and balance constraints.

The total lift-dependent drag of the aircraft is calculated as the sum of the induced drag, incremental wing profile drag, trim drag, and the induced interference drag between the wing and tailplane (Munk's term).

Zero-lift drag of the various components is calculated on the basis of the flat-plate and axisymmetric-body analogies. Correction factors representing typical modern commuter surface finishes and shapes are included.

Lift due to flap deflection is modeled according to thin aerofoil theory. Lift effectiveness and drag correction factors, which are functions of flap deflection and type, are included. The user can choose from four types of flap, namely single- or double-slotted, with or without Fowler movement. Take-off flap deflection is an optimizable variable. Landing deflection is a fixed user-input, assumed to be the maximum allowable value since drag is not a design consideration in this phase. It is possible for the user to specify a value for the aerofoil maximum lift coefficient in the landing configuration, overriding the program calculations. In either case, corrections are applied to account for the reduction in aircraft $C_{L\max}$ due to tail-plane download.

Prior to their incorporation into the main program, the aerodynamic subroutines were tested separately. Their estimates compared favorably with known lift-drag polars for the Shorts SD-360 and Fokker F27, in both flaps-up and flaps-down conditions.

Mass and Balance

Wing mass is calculated according to an equation used in the General Aviation Twin-Engine Program (GATEP)[9] which was tailored around the actual masses of some 14 existing twin-engined propeller aircraft. The fuselage mass is taken as the average of three empirical equations again adjusted to fit known aircraft. Other component masses are evaluated using a mixture of equations from past Loughborough and Shorts aircraft project work.

Iteration is usually necessary to evaluate the aircraft takeoff mass (M_{TO}). This is avoided by using the flexibility of the optimization program and introducing M_{TO} as a variable, with a constraint to ensure that calculated M_{TO} equals variable M_{TO}. It is not possible to say whether the use of such optimizer constraints is more or less efficient than the traditional use of iteration. However, it can be recommended insofar as it allows a substantially simpler program architecture.

The calculated component masses are used to estimate the empty c.g. of the aircraft. Certain assumptions have to be made (e.g., the fuselage mass is assumed to be distributed between the nosecone, cabin, and tailcone in proportion to the shell or "wetted" areas). In order to determine the forward and aft c.g. limits, a number of different loading cases are examined. These include the empty case, full payload evenly distributed, and partial payload distributed according to a simplified "window seating" rule. The passenger luggage, accounting for 20% of the total payload, may also be concentrated in a rear hold. All cases are examined in both the zero-fuel and full-fuel configurations. These considerations are representative of current designs and have been found to provide realistic c.g. limits. Different rules may be introduced or the existing ones modified (e.g., to account for a forward luggage hold), if necessary. The c.g. positions are stored for use in conjunction with subsequent calculations (e.g., field performance evaluation is conducted at forward c.g. and stability calculations are made at aft c.g. conditions).

Airfield Performance

Three constraints are available which will allow the user to specify the minimum acceptable performance in terms of balanced field length (BFL), landing field length (LFL), and second segment climb gradient. This last constraint is commonly referred to as the WAT constraint (Weight/Altitude/Temperature) and ensures that the aircraft can achieve a gradient of at least 0.024 with one engine failed at take-off safety speed (V_2) and at given values of airport elevation, temperature, and aircraft take-off mass.

It is not practical to use a stepwise-integration approach to evaluate field distances through integration of the equations of motion because of the large computational-time requirements of optimization compared to single-pass programs. Therefore closed-loop equations are used. Torenbeek's formula[10] is used for the estimation of the BFL, and the LFL equation was developed from expressions used by Chacksfield,[2] Loftin[11] and adjusted with known data for existing commuters. BFL is evaluated at SL-ISA conditions (Sea Level, International Standard Atmosphere) and maximum takeoff mass. The LFL is evaluated at SL-ISA and maximum landing mass (specified as the mass at the end of the first stage, or at the end of the mission, or a percentage of the takeoff mass).

Powerplant Characteristics

To conduct accurate flight profile analysis, it is necessary to have an adequate mathematical model of the engine performance. Manufacturers' computer models that simulate existing turboprop engines (used on many of the "new generation" commuters) were used to generate a database of characteristics. These characteristics were analyzed and surface-or-curve fitted. Available takeoff, continuous and cruise powers (including gearbox torque limitations) are given as functions of altitude and true airspeed. Fuel flow is a function of altitude, airspeed, and power setting. Fuel flow is modeled at idle as well as at design conditions because descent is usually conducted at idle or low-power settings.

Flight Profile Analysis

Flight profile analysis is conducted using methods similar to the SCOPE[1] program. A quasistatic approach is utilized, in which the climb, cruise, and descent phases are split into a number of segments and average performance is then calculated for each segment. Control variables which will dictate the shape of the flight profile are chosen in such a way as to model the behavior of a human pilot rather than an autopilot. For example, each phase is flown at constant indicated airspeed (IAS). This implies that the true airspeed is increasing with altitude, and, therefore, corrections are applied to the climb rate to account for acceleration effects.

The following optimizable variables are used to control the flight profile: 1) indicated airspeed, throttle setting, propeller rpm (climb); 2) indicated airspeed, distance, height, propeller rpm (cruise); 3) indicated airspeed, propeller rpm, initial throttle, final throttle (linear variation of throttle with assumed altitude; descent).

The problem created by this choice of control variables is that the distance flown becomes an output quantity. For example, the aircraft will climb at the specified IAS and throttle until the cruise altitude is reached, without any control over the distance covered during the climb. This problem is overcome by introducing an equality constraint which stipulates that the sum of the calculated climb distance, optimized cruise distance and calculated descent distance, must equal the total stage distance specified by the user. This is another good illustration of the versatility of the mathematical optimizer and shows that constraints may themselves be functions of optimizable variables and calculated data.

Climb and descent are divided into a number of equal-height (as opposed to equal-distance) segments. This rearrangement of the method was found to reduce the number of necessary equality constraints.

In previous work, two versions of SCOPE were developed. One utilized a constant-throttle descent, for use with pressurized aircraft. The other utilized a constant rate-of-descent (ROD), to model unpressurized aircraft. It was desirable to avoid this situation in the new program, because different variables and constraints would need to be defined in each version and the analyses would differ. Specifically, a constant ROD profile requires the use of "inverse" propeller characteristic equations to give power as a function of input thrust instead of vice versa. Examination of flight profiles output by SCOPE revealed that a constant ROD was associated with an approximately linear variation of throttle with altitude. It was therefore decided to use this result in the development of CASTOR by stipulating a linearly variable descent throttle to approximate a constant-ROD profile. Initial and final descent throttles are optimized. In general, the program will set both values to idle power, which implies a constant zero-throttle descent. The user may activate an additional constraint to specify a maximum ROD at the start and end of the descent. In this case, the initial and final throttles required to satisfy the constraint are calculated and linear interpolation applied. As a check, a history of the calculated intermediate values of ROD is output. It has been found that these are constant, to within a few percent.

In theory it is possible to conduct a full flight-profile optimization for every single stage of a multistage flight. In practice, however, this would entail the specification of six extra variables and two extra constraints for every additional stage. This would become prohibitive in terms of computer time. The approach adopted has been to analyze two stages in full, namely the first stage and a "notional" stage similar to the last one. This notional stage is flown at a reduced take-off mass, and linear interpolation is then used to calculate the fuel burn of the intermediate stages. The assumption of a linear variation of fuel-burn with take-off mass (for equal-length stages) was checked against results from SCOPE and also against flight manual data for a number of aircraft and was found to be accurate for stage lengths less than 600 n.mi. (well above common commuter stage lengths).

The difference in fuel burn between the first and last "main mission" stages is found to be small. It is assumed that the first and notional stages can utilize the same values of airspeeds and throttle settings. Originally, the diversion stage was allocated a separate set of these control variables. This was felt to be necessary because of the possible difference in stage length between main mission and diversion. However, examination of the program output showed that the diversion tended to assume optimum settings of the climb/descent control variables that were very similar to the main mission values. It was therefore decided that only the cruise phase of the diversion need utilize separate control variables (airspeed, height, distance). Climb and descent use the same values as the main mission. These simplifications result in a diversion fuel-burn which is slightly higher than the achievable optimum. This is acceptable since diversion fuel is not included in the objective function (e.g., minimum main mission fuel); it is only a "dead mass" which must be carried by the aircraft. The small inaccuracy in diversion fuel mass is well within the overall mass estimation tolerances.

Case Studies

In order to test the capabilities of the program, a series of studies was conducted around an arbitrarily defined mission. The mission requirement was to transport a payload of 5100 kg over 5 stages, each of 100 n.mi. length, with reserves for a 100 n.mi. diversion and a 45 min hold. This is representative of a 50-seat short-haul commuter aircraft. Performance constraints included BFL less than 1100 m (SL-ISA), LFL less than 1200 m (SL-ISA), and WAT climb gradient not less than 2.4% (from an ISA + 20 deg and 5000 ft elevation field). These are considered to be fairly "relaxed" performance requirements which can be met by many modern aircraft in this class. Power is provided by 2000 shp engines. CASTOR was used to pro-

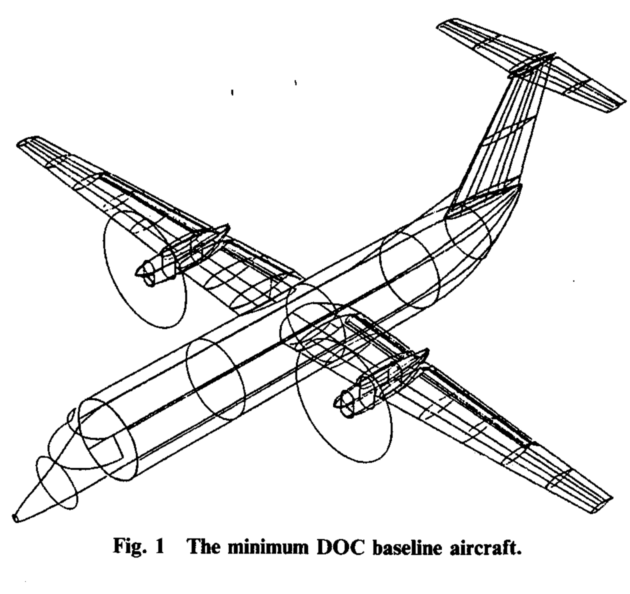

Fig. 1 The minimum DOC baseline aircraft.

duce minimum-fuel (min-fuel), minimum-DOC (min-DOC), and minimum-mass (min-mass) aircraft around this mission. Basic characteristics of the resulting aircraft are shown in Table 1. The min-DOC design is depicted in Fig. 1. Optimizing for a particular objective function yields nonoptimum values of the alternative objectives. The associated penalties to the nonminimized objectives are shown in Fig. 2. For example, the min-DOC baseline is 7% less efficient in fuel than the min-fuel baseline, indicating that time is a substantial factor in the cost estimation.

The impact of changes on the field performance constraints was examined next. A series of fuel-optimal and DOC-optimal designs were produced with different values of BFL constraints. Changes in objective function relative to the baseline values are plotted in Figs. 3 and 4. It is stressed that every point on these curves corresponds to a different, optimally resized aircraft. Tightening the BFL constraint is seen to result in significant penalties, but relaxing it yields relatively little benefit. In the min-fuel case, BFL greater than 1120 m can, in any case, be met automatically (i.e., the constraint is inactive). Figures 5 and 6 show the effects of specifying different temperature and elevation conditions for the WAT climb gradient constraint. If the conditions are relaxed (e.g., 5000 ft and less than ISA + 18 deg), the constraint becomes inactive in the min-fuel case. Extreme conditions (e.g., 9000 ft and ISA + 25 deg) may result in infeasible aircraft. In this case, the program will warn the user that a satisfactory solution has not been obtained. It would then be necessary to either allow the engine to be scaled up or to relax the mission specification (e.g., reduce payload).

LFL can also have a significant impact on the objective function (Figs. 7 and 8). The baselines were assumed to have single-slotted Fowler flaps. The impact of choosing a more sophisticated double-slotted Fowler system has been shown as a dashed line on these curves. As might be expected, the more complex flaps can help reduce the objective function if the LFL constraint is stringent, but become detrimental (because of the greater weight) when the constraint is relaxed. For the baseline value of LFL, it is seen that the single slotted flap is preferable.

The results of SCOPE and other investigations have shown that optimum flight profiles are frequently of the "saw tooth" type, i.e., a climb/descent without any cruise phase. Under operational conditions this type of profile would rarely be convenient or allowable. In CASTOR, one may specify a minimum allowable cruise distance as a proportion of the total distance. A typical value used for the baseline cases is 30% of the stage distance. The impact of choosing other values is shown in Figs. 9 and 10. Min-DOC is seen to be relatively unaffected, and this can be explained by the reduced flight time resulting from a substantial cruise portion (less time to climb), which balances the increased fuel burn. However, specifying a substantial minimum-cruise proportion can have a significant impact on fuel burn (4.6% penalty for a 50% cruise). Note that maximum cruise altitude associated with each cruise distance is also shown in Figs. 9 and 10.

The baseline designs were assumed to be pressurized aircraft, and, therefore, an unconstrained ROD was allowed. When an ROD limit of 500 ft/min was imposed, to simulate unpressurized aircraft, very significant penalties to the objective functions resulted (Fig. 11). In order to make comparison

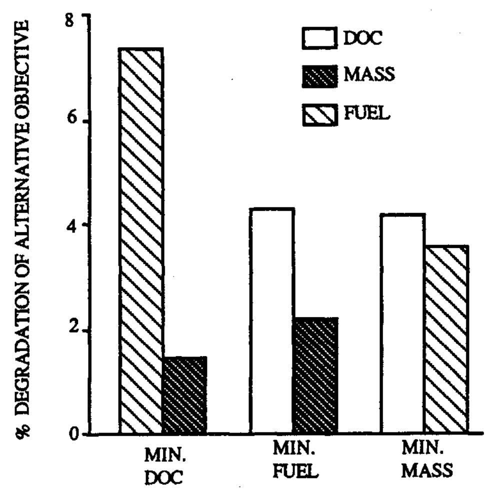

Fig. 2 Degradation of nonminimized objectives.

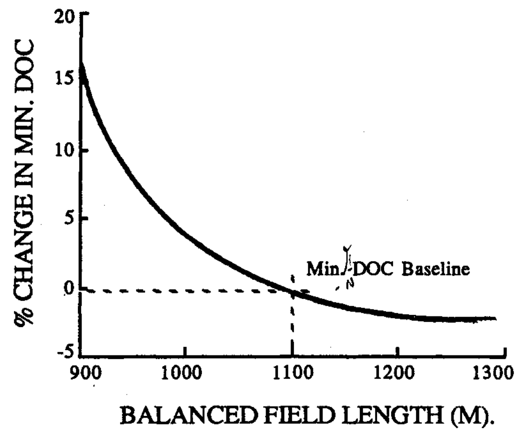

Fig. 3 Effect of BFL constraint on min-DOC.

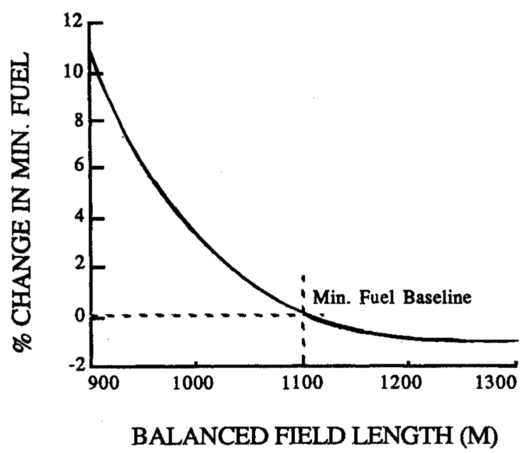

Fig. 4 Effect of BFL constraint on min-fuel.

Table 1 Characteristics of baseline designs (unscaled 2000 shp engines)

Objective function	DOC ($/Stage)	Fuel (main mission) kg	Mass (T.O.) kg	Aspect ratio	Wing area m^2	Taper ratio	T/C ratio
Min-DOC	441.9	1010	16,245	12.62	52.40	0.3	0.21
Min-fuel	460.9	942	16,413	13.00	52.86	0.3	0.18
Min-mass	459.9	974	16,030	12.28	51.84	0.3	0.21

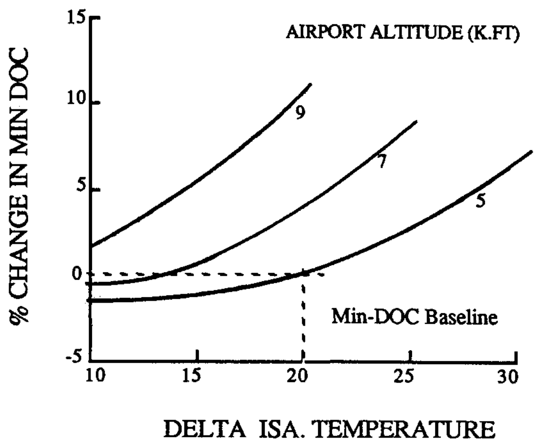

Fig. 5 Effect of WAT constraint on min-DOC.

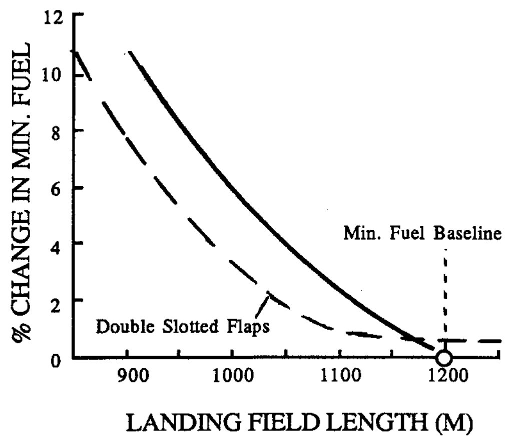

Fig. 8 Effect of LFL constraint on min-fuel.

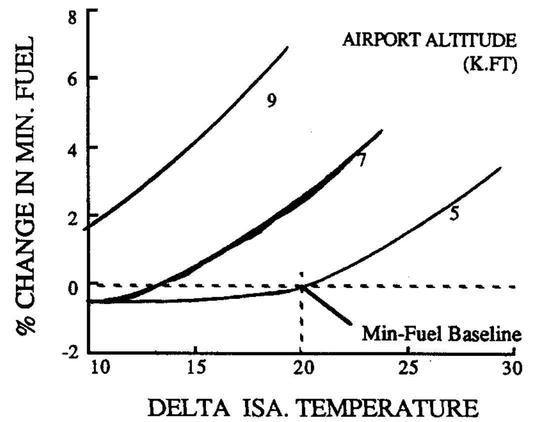

Fig. 6 Effect of WAT constraint on min-fuel.

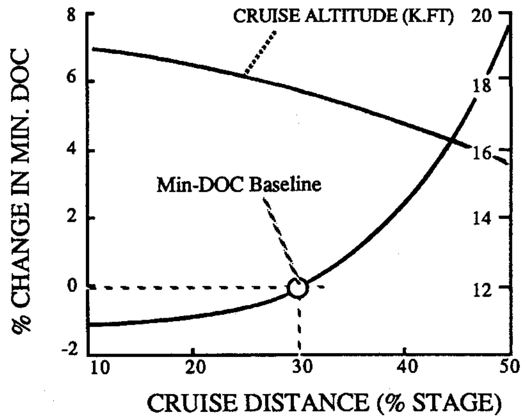

Fig. 9 Effect of cruise distance on min-DOC.

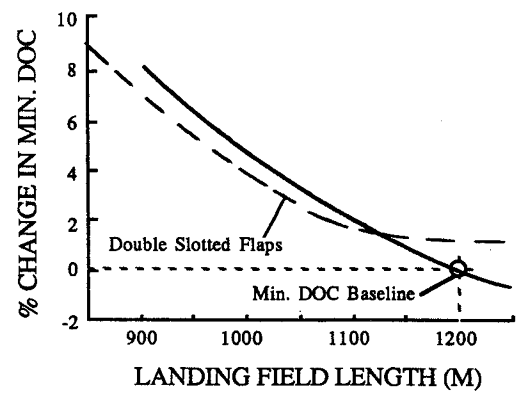

Fig. 7 Effect of LFL constraint on min-DOC.

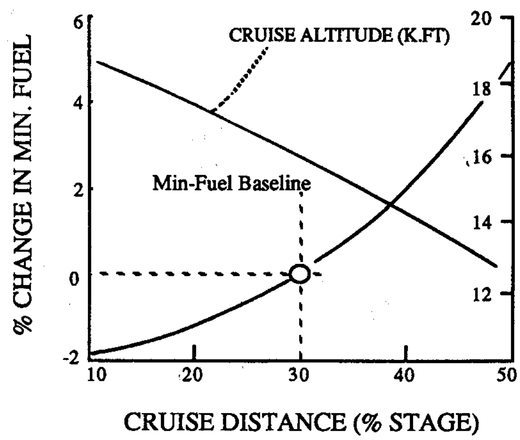

Fig. 10 Effect of cruise distance on min-fuel.

fairer, an 8% reduction in fuselage mass was then incorporated in the unpressurized aircraft to account for the reduced cabin strength requirements and systems. It is seen that this made relatively little difference to the objective-function penalties, especially in the min-fuel case.

Figures 12 and 13 show the impact of changing the main mission stage length, which, as expected, significantly affects the objective functions. Dashed lines are used to show how the baseline designs perform at reduced mission lengths, without being optimally resized. The penalty for not resizing is fairly small which indicates that the designs could be usefully operated over a variety of missions. Nonresized data cannot be shown for increased stage lengths because field-performance constraint violations then occur. Such stage distances could only be achieved by the baseline designs at reduced payload masses, thereby precluding meaningful comparison.

Finally, Figs. 14 and 15 are indications of the effects of "advanced technology," showing the possibilities offered by more efficient (reduced s.f.c.) engines and by improvements in wing zero-lift drag (possible through laminar aerofoils). In these cases there would be an incentive to resize the aircraft, especially if the improvements are large.

Every resized design has its own geometric characteristics and corresponds to a single point on the graphs. It would be

Table 2 Characteristics of designs with optimally scaled engines

Objective function	DOC ($/stage)	Fuel (main mission) kg	Mass (T.O.) kg	Aspect ratio	Wing area m^2	Taper ratio	T/C ratio	Engine scale factor
Min-DOC	438.1	1035	16,164	9.43	52.42	0.3	0.21	1.12
Min-fuel	470.3	937	16,927	13.00	54.27	0.3	0.16	1.13
Min-mass	456.6	987	15,950	9.90	51.83	0.3	0.21	1.09

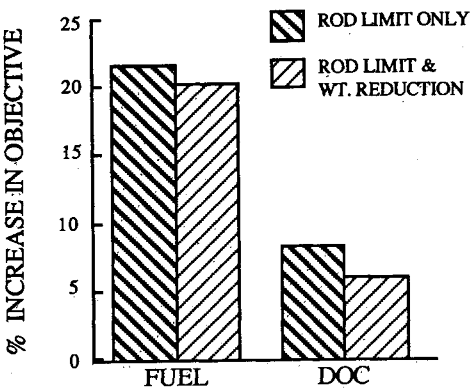

Fig. 11 Penalties of nonpressurization.

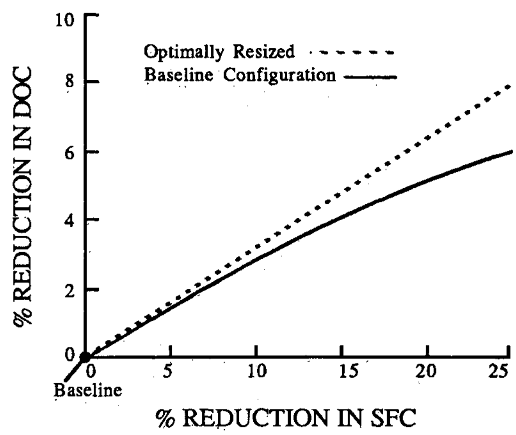

Fig. 14 Effect of improved SFC on DOC.

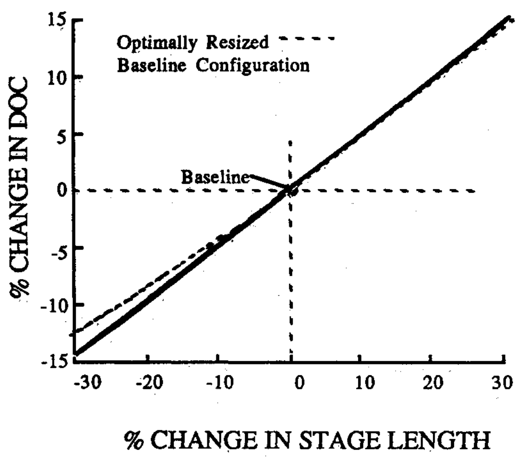

Fig. 12 Effect of stage length on DOC.

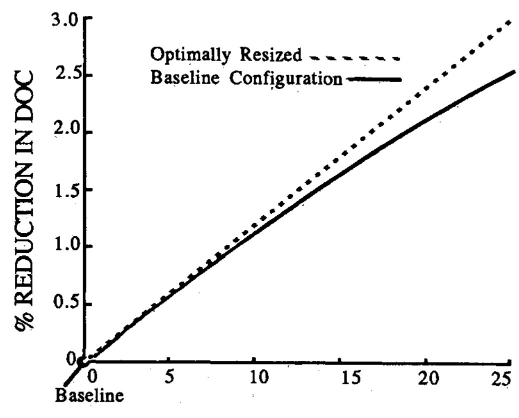

Fig. 15 Effect of drag reduction on DOC.

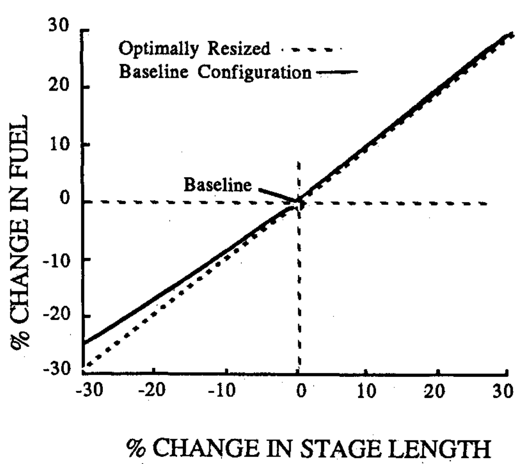

Fig. 13 Effect of stage length on fuel.

confusing to list all the geometric data associated with each design, however, some general observations can be made. Min-fuel designs tended, in general, to opt for the highest allowable aspect ratio (i.e., 13 in this case) but displayed a wide preference in t/c ratio (between 16% and the maximum value of 21%). Min-DOC designs selected slightly lower values of aspect ratio, with occasional excursions to substantially lower values when large wing areas were required (8 to 9, which is unusual for this type of aircraft). Thickness-chord ratio for min-DOC was mostly at the upper limit. In all cases, taper ratio was pegged at its lower limit of 0.3. The only occasion on which slightly higher values were observed was when the upper limits imposed on aspect ratio were reduced. All the aircraft discussed have been based on fixed-size (2000 shp) engines. The effects of allowing this engine to be freely scaled by CASTOR are shown in Table 2. Modest changes in engine size are observed, as might be expected by the fact that this type of engine was designed to power this class of aircraft. Interestingly, the min-DOC and min-mass cases show substantial reductions in aspect ratio when engine size is variable, showing a close interrelationship between engine (thrust) and wing (drag) parameters.

Conclusions

The CASTOR program provides results that are useful to the operator as well as to the manufacturer. It is now common for manufacturers to conduct detail route studies on behalf of their customers, and, conversely, the customer may require detailed engineering analyses of competing aircraft prior to purchase. In addition to designing more efficient, task-oriented commuter liners, CASTOR may be used to give an indication to the operator of how closely any existing or projected competitors approach the "ideal" design tailored to their own needs.

Viewed in the context of the continuous development in computer methods for aircraft design, CASTOR represents a typical evolutionary step. Despite offering the various new features already outlined, a number of limitations are also apparent which are generic to all current computerized design optimization methods. Firstly, the optimization approach is time-consuming and produces a single optimum design. This may be overcome, at the expense of more computer time, by conducting a sequence of parametric studies with various parameters, "nudged" off their optimum values in order to obtain a feel for their sensitivity. Secondly, such programs do require some degree of familiarization from the operator. This tends to discourage their use by nonexpert personnel, among which are usually the decision-making management levels.

The possibility of realizing these objectives is now being explored by the fast-expanding Artificial Intelligence (AI) sector. Generating and understanding sensitivity studies is a process that can be eased through the use of functional languages (e.g., LISP) developed for AI applications. The incorporation of built-in tutorials, thorough help and menu facilities, and even helpful suggestions based on human expert knowledge, are all possibilities offered by new knowledge-based systems.

Preliminary work on the application of AI techniques in the aircraft design field at Loughborough University indicates that the flexible, powerful, yet, friendly, design environment is a near-term possibility.[12]

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