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Regional Fanjet Aircraft Optimization Studies

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This article illustrates the use of optimization methods in the development of a new regional aircraft. These aircraft are more sensitive to changes in operational requirements than other types due, in part, to their high zero-fuel weight ratio. For such aircraft it is essential that the best information possible be available to the designers in the early project definition phases. The identification of optimum aircraft configurations and mission characteristics for various operational and configurational options constitutes a vital part of this knowledge. A series of industrially-related design studies are presented. These include 1) the selection of the baseline configuration; 2) parameter sensitivity investigations; 3) analysis of aircraft and engine stretch potential; and 4) generalized (rubber engine) designs. This article concludes with a discussion on the merits of optimization studies in aircraft project design and offers some suggestions for changes to the strategies adopted.

Introduction

INITIAL aircraft project design always presents difficult decision areas to designers. Once a particular aircraft configuration has been finalized it is too expensive to introduce major changes. Considerable pressure is exerted on the project team to "get it right." The situation is further complicated by the changing technical and commercial environment surrounding the design. Some of the possibilities for change include the choice of engine supplier, improvements in engine performance, introduction of new airframe and aircraft systems, technology improvements, the emergence of new competitor aircraft, and changing operational and regulatory frameworks. The designers are therefore concerned with the specification of the initial design and the strategy for future aircraft development. The chosen aircraft configuration is unlikely to be exactly matched to the initial operational specification but it must not be compromised to an extent that the first design is uncompetitive. It is within this context that the value of the optimum design method should be judged.

The industrial design team places strong emphasis on component design aspects. These are pursued in fine detail and constitute substantial technical effort. Past experience has shown that careful control of the aircraft detail design in the early stages offers the best method of avoiding technical difficulties later in the design cycle. Broader-based optimization studies can be considered as complementary to this detail design effort. Together they provide both micro- and macro-design scenarios which help the designers in their difficult choice of initial aircraft specification and in subsequent developments.

In the early stages of the design when the aircraft geometry and performance criterias have not been fixed, the optimization studies are used to identify the absolute "best" configuration with respect to various operational specifications. This enables the designers to judge the sensitivity of the design with respect to variations of the aircraft geometrical and performance parameters. Once the baseline design has been established the optimization studies are used to evaluate the tolerance available in the selection of aircraft operational parameters. Configurational features (e.g., rear-engine position) can also be assessed to show the quantifiable penalties/benefits of the proposal. After the initial design has been formulated, designers are concerned with opportunities from alternative engines and the potential for aircraft stretch.

The stretch studies are mainly concerned with the tradeoff between engine power and wing area. Such studies indicate the limitations of engine size and thereby the suitability of particular engines. Simulation of different engine types is also feasible in such studies. This allows comparison of available engines to be made within the framework of the total aircraft design. Improvements to the basic configuration of the aircraft (e.g., change of flap type) can also be investigated to show the tradeoff between different aircraft options. Later in the project design phase such studies can be related to particular engine development.

This type of study raises the question of what is the optimum combination of aircraft and engine changes. Such relationships provide the designer with a knowledge of the absolute best design, allowing him to judge the "penalties" inherent in his chosen configuration. These "generalized" design studies provide a theoretical framework which is also useful in the teaching of aircraft project design methods to graduate engineers.

Optimization Method

In previous work[1–3] a multivariate optimization program developed by the Royal Aerospace Establishment (RAE) had been linked to aircraft performance and design equations to produce an optimum aircraft configuration for turbo-prop commuter aircraft flying multistage missions. Since these studies were completed Strobanski[4] (and others) at RAE improved the mathematical optimization method to produce RQPMIN (recursive quadratic programming minimization).

RQPMIN is essentially a gradient-search procedure which progressively matches the step-size to the progress along the design surface. An unconstrained design space is assumed. All constraints are accounted for by the introduction of a penalty function added to the objective function. At subsequent stages of the search this penalty function is "tightened" to allow the search to move closer to the constraint boundaries. The search is continued until either the design slope is equal to, or less than the input tolerance, or when no further progress is possible.

Since the constraints are transformed into continuous functions it is unlikely that the evaluated design point will lie exactly on the theoretical constraint boundary. The optimizer requires a second tolerance to be specified which dictates the acceptable displacement of the optimum point from the boundary. The assignment of the tolerance values for the constraints and objective function is a critical aspect of the

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problem definition. Edwards[5] described the effects of tolerance selection and the stability of the original RAE optimizer and showed how these may lead to substantial variability in the selection of the optimum design point.

In the original form, RQPMIN only output the optimum aircraft specification (i.e., design parameters at the point in the search when the design surface slope is within the tolerance). In general, the designer would like to know more about the design than just the optimum point. For example, he may wish to progressively relax one or more of the design parameters to assess the sensitivity of the design to such changes. To allow the designer to perform a manual search around the optimum point, the optimization method was modified to permit a single-pass to be made through the synthesis model. Repeated application of the single-pass facility and storage of the output values in a data base offers the possibility to investigate specific changes. In this way the sensitivities of selected design variables to changes in constraints and the changes to output parameters due to different values of design variables can be analyzed. This facility also allows the designer to systematically investigate the design surface in the region of the optimum design. A subprogram automatically generates these results and prints the graphs.

The architecture of the program is shown in Fig. 1. After calling various program administration modules the main aircraft synthesis module is executed. For a single-pass study the resulting program output is printed and the program ends. For an optimization study RQPMIN is called. This progressively adjusts the values of the variables and repeatedly calls the aircraft synthesis module. At the end of the optimization routine the final values of the program variables and output parameters are printed. If a plot of the design surface around the optimum point is required, the program transfers to the peri-optimum subprogram which conducts a series of single passes through the synthesis module and then curve-fits the data for chosen parameter displays.

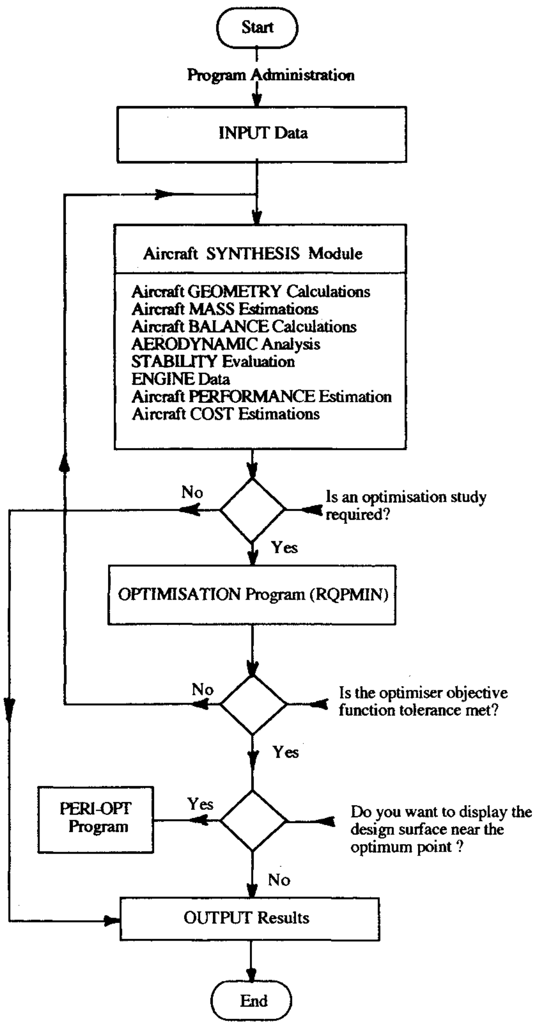

Fig. 1 Program architecture.

Initial Studies

The turboprop aircraft synthesis module used in earlier optimization work was modified to account for the turbofan engine data, fuselage pressurization, introduction of composite materials, modifications in aircraft operational procedures, and updated cost.

Market analysis indicated a stage length of 1000 nm (single stage), balanced field length of 5300 ft, and WAT performance at +25 deg ISA/SL. The initial design studies were conducted around a 40-seat baseline design.

The first optimized design suggested an aircraft with substantially less wing area and higher wing aspect ratio than the comparative configuration under detail investigation by the manufacturers. Further analysis indicated that the project design team was building a limited stretch potential into the layout as insurance against suspected weight growth, the introduction of larger engines, and modified operational requirements. To match the company design, the landing field length was tightened from 5300 to 4660 ft. This provided a geometrically similar aircraft to the company design (Fig. 2). Comparing these first two designs shows the following penalties: +1.89% maximum takeoff mass, +3.45% aircraft price, and +3.72% aircraft direct operating cost (DOC) per flight. The cost of the manufacturer's design "insurance" is seen to be high but later investigations showed the strategy to be wise.

The engine manufacturers had offered the option of emergency thrust boost for the baseline engine but at a higher engine price. With the optimization methods it was possible to assess the value of this feature by comparing the optimum designs with and without boost. The advantage of the emergency boost (8%) were shown to be: −1.93% takeoff mass, −1.87% aircraft price, and −0.76% DOC/flight. The aircraft price reduction could be assessed against the increase engine price to show the value of the boost option to the aircraft manufacturer.

Several configurational studies were then conducted to determine the sensitivity of the baseline design to geometric and operational aspects.

Wing Geometry

The optimum design configuration selected wing taper ratio at the minimum permitted value (0.24) and wing thickness

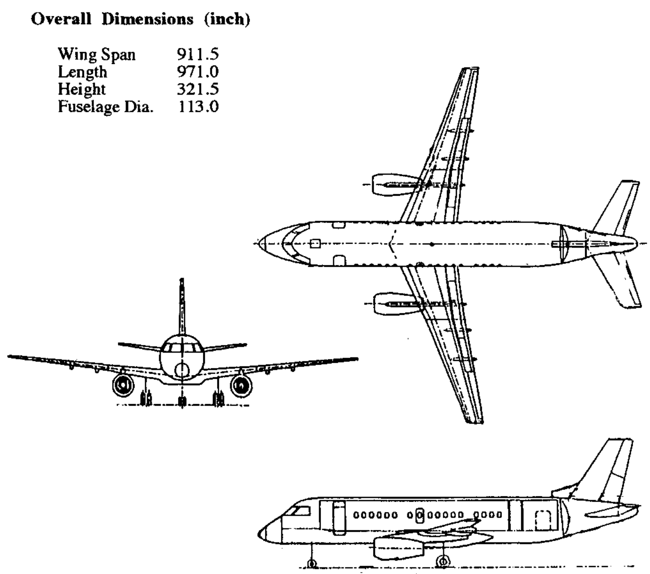

Fig. 2 Baseline aircraft configuration.

ratio at 0.15 (i.e., maximum permitted). To investigate the sensitivity of the design to the selection of these values, a series of optimizations were performed with taper and thickness at fixed values. The results are shown in Figs. 3 and 4. Although taper ratio is seen to be less sensitive than thickness ratio, it still represents a significant change. Over the range of values considered (0.24–0.35) optimum designs show: +2.37% wing area, +1.16% aircraft price, +1.06% takeoff mass, and +0.93% DOC/flight.

Wing thickness is seen to be more influential. Over the range of values considered (11–15%) the thickest section shows: −3.74% wing area, −5.57% aircraft price, −6.98% aircraft empty mass, −2.80% DOC/flight, and −4.28% on takeoff mass.

Thinner wing sections reduced aircraft drag giving a saving of 2.93% on trip fuel for the optimum design. The study highlighted the desirability to select the maximum taper and thickest wing possible from aerodynamic, structural, and manufacturing considerations. A taper ratio of 0.24 and an average wing thickness ratio of 0.15 were regarded as the limits for future work. Some advantage could be envisaged for the use of wing sections thicker than 15%, but this was not investigated.

In the above optimizations, wing aspect ratio (AR) was included as a design variable. As taper ratio reduced, optimum aspect ratio was seen to be relatively insensitive (changing from 9.22 to 9.01). Choice of wing thickness was shown to be more sensitive, as thickness reduced aspect ratio increased (from 9.22 to 10.34). The preferred aspect ratio/wing thickness combinations is seen to be incompatible with wing stiffness requirements as the larger span designs are associated with a smaller structural wing box.

The strong influence of wing thickness on optimum design configuration indicated the need to carefully model the effect

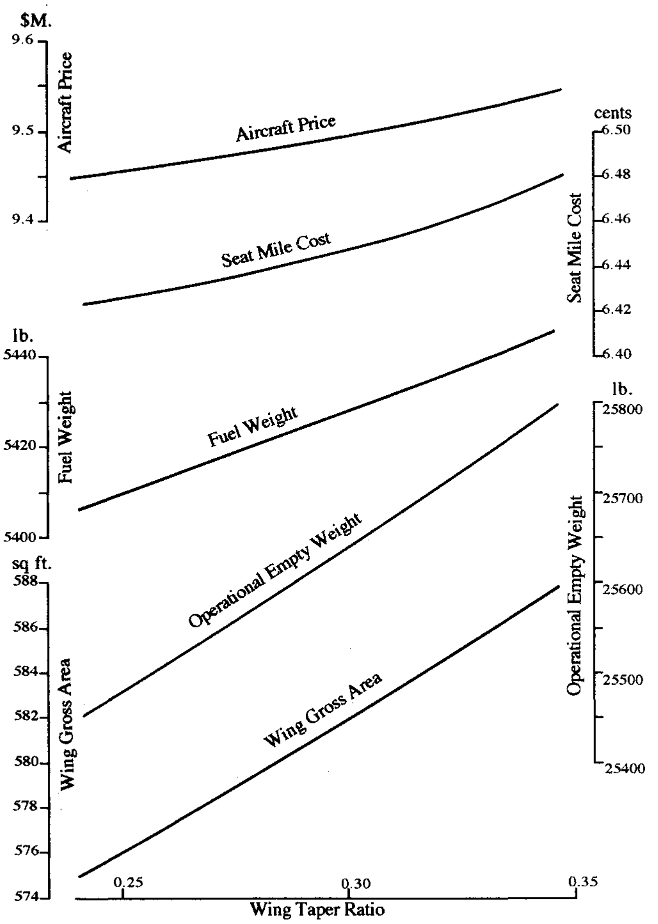

Fig. 3 Wing taper ratio sensitivity.

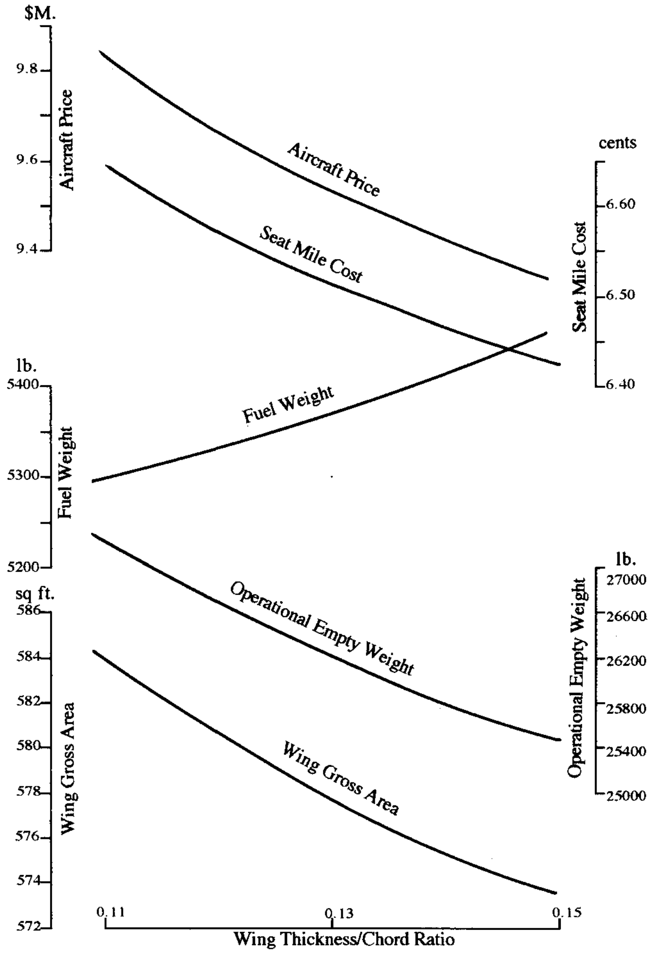

Fig. 4 Wing thickness ratio sensitivity.

of wing thickness in the synthesis program. With this in mind, the estimating model was compared to the more detailed estimations made by the manufacturers and adjusted to provide a more accurate prediction method.

Aspect Ratio (AR)

The initial studies indicated the tendency of the optimizer to select high values for AR in order to improve climb gradients in the critical balanced field length/weight-altitude-temperature (BFL/WAT) conditions. In these sensitive engine power/aircraft weight ratio cases, AR is selected high in preference to other aircraft parameters. To investigate this effect, a series of aircraft optimizations were conducted at fixed values of aspect ratio (10.5–7.5). The baseline specification was used in all cases. The results are shown in Fig. 5. The lower aspect ratio designs are only feasible with large wing area, this makes them uneconomic. The optimum value of aspect ratio is shown to be 9.22. Aspect ratios fixed below this value exhibit large increases in all design parameters. The critical nature of WAT/BFL constraint in these designs forces an increase in wing area to satisfy the single-engine climb gradient. Aspect ratios above the optimum are seen to have only a modest increase in DOC and wing area but larger increases in aircraft empty mass. This study showed the advantage of selecting aspect ratio in the range 9.0–10.0.

Mission Studies

The design program is capable of analyzing multistage flight profiles. This facility was used in a series of studies to show the influence of different flight profiles on the optimum design point. Three missions were compared to the baseline single-stage 1000-nm specification: 1) four stages of 200 nm; 2) three stages of 250 nm; and 3) two stages of 400 nm. For each mission two wing configurations were investigated: 1) aspect ratio unconstrained; and 2) AR = 9.0. With the limited engine power available on the baseline aircraft, the 4 × 200 mission was shown to be unfeasible for both wing configurations. All the other studies gave acceptable designs. All the feasible multistage flights, although covering less total range, used substantially more fuel than the single-stage mission. This was due to the saw-tooth profiles adopted, the reduced proportion of the total time spent in the cruise phase, and the penalties of extra ground maneuver fuel. No general conclusions could be drawn from this series of designs except that multistage flight profiles are seen to have substantial influence on the choice of initial configuration, and therefore, must be carefully considered. All subsequent optimizations were conducted on the single-stage mission to allow comparison with the industrial design studies of a similar flight profile.

Engine Position

The turboprop studies conducted in our previous optimization work[3] had shown the advantages of positioning the engines on the rear fuselage, however, many of these benefits relate particularly to the propeller and are not appropriate to turbofan designs. To investigate the effects of rear-engine installation on the baseline aircraft, two further optimizations were performed (AR = 9.0, AR-free). As expected, the rear-engine installation was shown to increase the fuselage mass, shorten tail arm (thereby increasing tail areas and masses), and increase wing mass (due to reduced wing inertia relief). Together with other changes, the baseline aircraft takeoff weight is increased by 3123 lb (8%). This, coupled with the limited engine thrust, forces a substantial (126 ft^2 = 22%) increase in wing area to meet the single-engine climb requirement. The extra drag reduces cruise speed which in turn increases block time by 487 s (6%) and seat mile cost by 10%. Allowing AR to increase and relaxing the landing field length requirement brought the wing area increases down to 40 ft^2 (7%) with the aspect ratio raising to 10.41. In this case the rear engine layout is still 5.5% heavier and there is a 4%

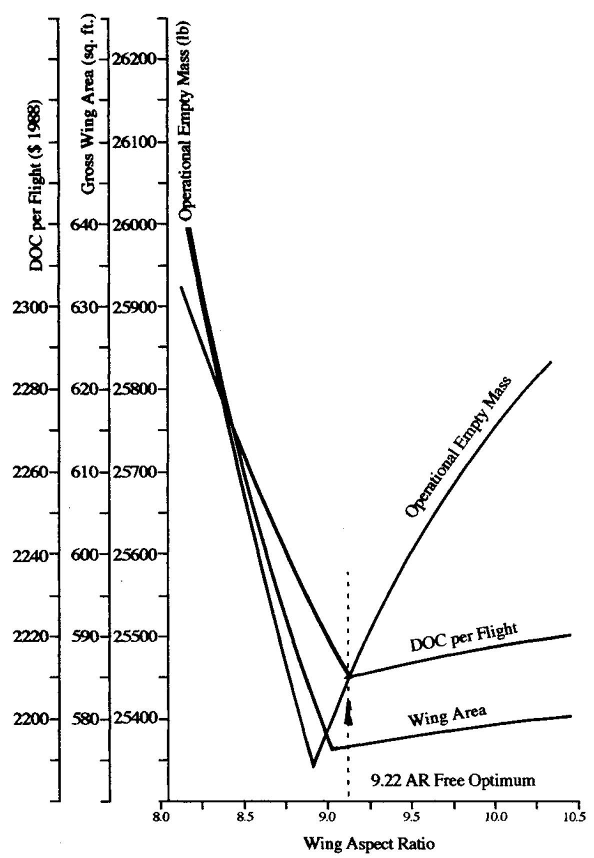

Fig. 5 Wing aspect ratio sensitivity.

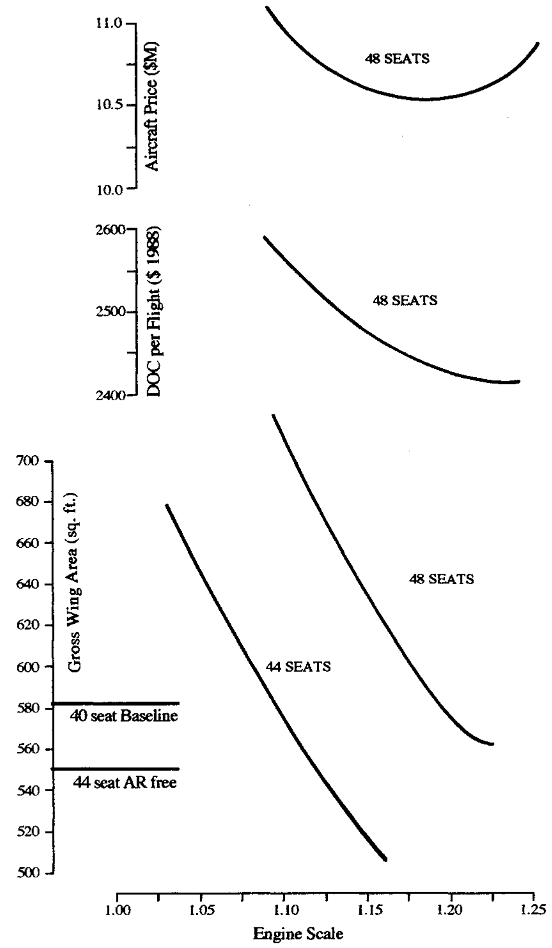

Fig. 6 Aircraft stretch study.

Table 1 Objective function study (restricted landing field length and AR)

	MWING	MTO	MFUEL	DOC	SMC	MCRUZ
Mass of wing (MWING)	3,954	37,812	5,581	2,625	7.55	0.62
Takeoff mass (MTO)	4,060	37,548	5,251	2,543	7.31	0.62
Mass of fuel (MFUEL)	4,605	38,036	5,107	2,503	7.19	0.62
Direct operating costs (DOC)	4,543	38,425	5,467	2,226	6.60	0.77

Table 2 Objective function study (relaxed landing field length and unrestricted AR)

	MWING	MTO	MFUEL	DOC	SMC	MCRUZ
Mass of wing (MWING)	3,456	36,481	5,260	2,506	7.20	0.63
Takeoff mass (MTO)	3,552	36,214	4,943	2,380	6.84	0.65
Mass of fuel (MFUEL)	4,357	36,885	4,683	2,443	7.02	0.62
Direct operating costs (DOC)	4,416	37,708	5,316	2,188	6.13	0.79

Table 3 Objective function study (wing design parameters for best designs)

	Aspect ratio		Wing area	
	AR-free	AR < 9	AR-free	AR < 9
Mass of wing (MWING)	10.92	8.92	467.94	566.44
Takeoff mass (MTO)	10.65	8.72	464.71	562.55
Mass of fuel (MFUEL)	13.00	9.00	470.78	568.78
Direct operating costs (DOC)	11.86	9.00	482.04	580.87

increase in DOC. Although the study methods may assess these configurational changes too critically, it does show that the rear-engine position may lead to significantly less efficient designs and confirmed the importance of weight control for this type of turbofan aircraft.

Aircraft Stretch

Although the baseline optimization studies showed that the available engine was well-matched to the 40-seat baseline aircraft specification, the relationship between engine and aircraft stretch was of interest. One- and two-seat row extensions to the fuselage cabin were considered (44 and 48 seats) together with a range of fixed increases in engine scales (1.10–1.25). All these designs had landing and balanced field lengths set to a maximum of 5300 ft. The results are shown in Fig. 6. The 44-seat design without power increase is only feasible if the AR is allowed to increase. All the designs with larger engines were feasible with AR fixed at 9.0. The optimum (minimum DOC) 48-seat configuration is seen to require an engine increase of about 22%. Using the same wing area as the original baseline would require engine scales of +8% for the 44-seat version and 18% for the 48-seat aircraft. These studies justified the overwinging of the initial design to allow reduced engine thrust increases for the stretched aircraft.

Objective Function Sensitivity

The optimization method accepts different definitions of the objective function. The sensitivity of the optimum design parameters with respect to this choice is of interest. A series of optimizations was conducted on the baseline design for 1) minimum wing mass; 2) minimum takeoff mass; and 3) minimum fuel mass, and compared to the previously used objective function of minimum DOC per flight. The results for restricted landing field length, and AR are shown in Table 1.

The optimization program is seen to be working correctly by the fact that in each case, the objective function value is less than the values selected in other cases. It is clear that substantial (18%) savings are possible between different choices of objective function. This indicates the necessity to carefully consider the choice of objective function before the aircraft optimization studies are started.

Relaxing the aspect ratio and landing field length constraints shows (Table 2) a similar trend to that in Table 1 but with reduced values in each case.

The choice of objective function effect on wing design is seen in Table 3. These results are reassuring since they indicate that within the feasible design region the wing area is not too sensitive to objective function choice. No allowance was made in the design equations for torsional stiffening which may affect some of the very high aspect ratio design selected above. The effect on optimum flight profile [cruise Mach number (MCRUZ)] is clearly seen in Tables 1 and 2. For the minimum DOC cases a high cruise speed is selected to reduce block time, whereas, for the minimum mass cases much lower speeds are selected. In the reduced cruise speed cases the thrust setting in cruise is only about 70% of the value used for the DOC case. The increased block time adds about 1 cent (18%) to aircraft seat mile cost (SMC) for the 1000-mile stage, but the reduced aircraft weights lower aircraft price by about $300,000.

It was felt that this study confirmed the selection of minimum DOC per flight as the correct choice of objective functions for subsequent studies.

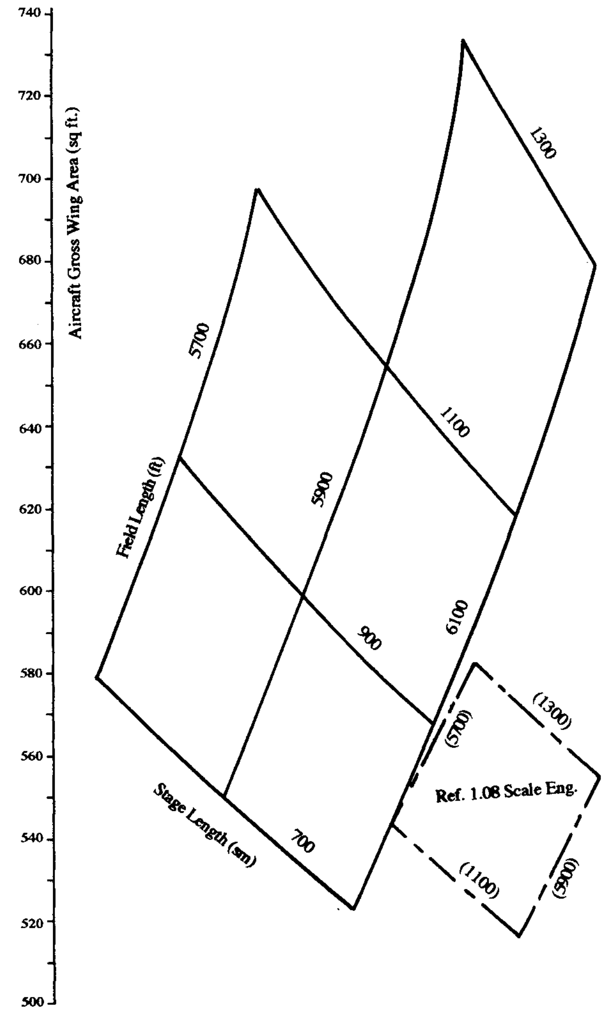

Fig. 7 Optimum aircraft—wing area (current engine).

Stretch Studies

The initial optimization studies and later market analysis indicated the need to stretch the aircraft operational envelope (range, field, and seats). A new engine with greater thrust than the original specification became available during the period of the study. A series of optimizations was undertaken to investigate aircraft stretch potential within three engine development scenarios: 1) current engine (takeoff thrust 6800 lb); 2) near-term engine (with thrust increased by 8% in all operating conditions); and 3) far-term engine (maximum development potential, with thrust increased by 40.8% from the current specification).

In the first two studies the baseline aircraft is stretched to 56 seats. In the third study 68, 72, 76, and 80 seat versions of the aircraft are analyzed.

Current Engine

Stages of 700, 900, 1100, and 1300 satute miles and field lengths of 5700, 5900, and 6100 ft were investigated. All specifications were shown to be feasible except the heaviest (1300/

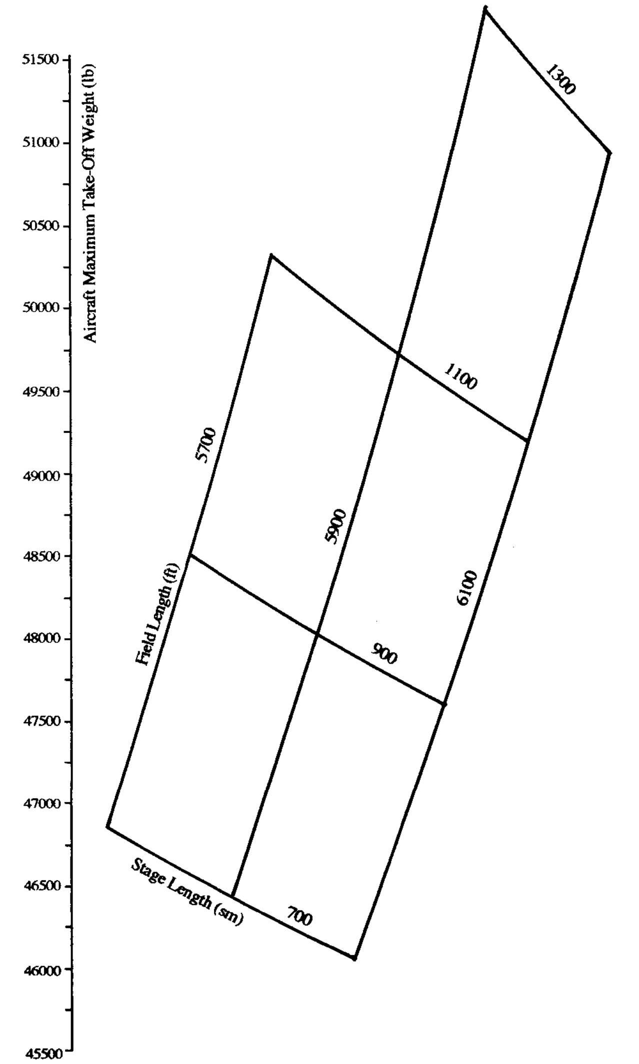

Fig. 8 Optimum aircraft—aircraft takeoff weight (current engine).

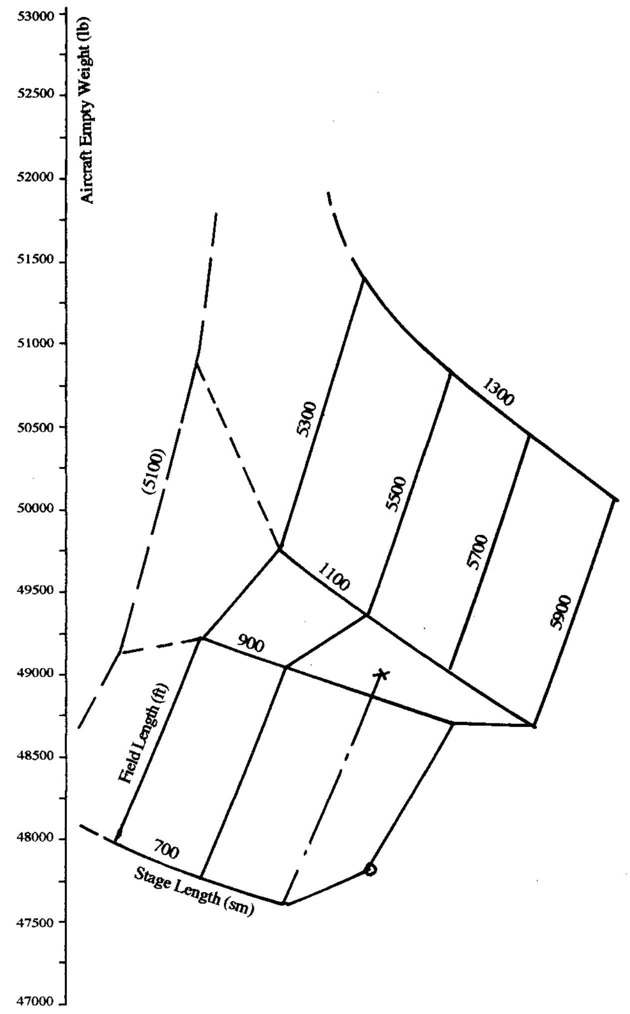

Fig. 9 Optimum aircraft—wing area (near-term engine).

5700). The study suggests an upper limit of about 52,000 lb aircraft takeoff weight (MTO) for the current engine thrust. Development from the previous 40-seat baseline configuration wing design could be achieved with simple wing tip and trailing-edge extensions. Figures 7 and 8 show the aircraft to be more sensitive to changes in field length than stage distance. A 10% change in field length requires a 100-ft^2 wing area increase, whereas a 10% stage alteration affects the area by only 25 ft^2. Alternatively, a 10% change in wing area can be shown to give a 20% (200 sm) increase in stage distance or a 7% (400 ft) reduction in field length. These results confirm the desirability of specifying field performance as wide as the market will allow.

Near-Term Engine

The near-term engine studies are shown in Figs. 9–11. The extra power available overcomes the problem identified for the heavy aircraft of the previous study. No upper limit on aircraft weight was identified by the optimum aircraft designs considered. This suggested the potential for further aircraft stretch (60 or 64 seats). Additional optimization studies indicated that the 60-seat design is feasible with the near-term engine but this design does require substantial wing area increase above the current wing design. The larger 64-seat configuration was shown to be unfeasible.

The 56-seat aircraft designed for the shorter stages are seen to be overpowered (BFL and WAT uncritical). This leads to a change in the active design constraint from takeoff/climb to landing. To assess the extent of the overpowering effect extra designs were studied with a reduced field specification (5100 ft). All the extra optimizations produced feasible designs as shown in the extensions to the plots in Figs. 9 and 10.

The shortest stage aircraft slightly violates the landing field constraint. This may be due to relaxed optimizer tolerances which are unduly influenced by the overpowered designs but, in general, the reduced field requirements avoids the previous problems of overpowering. Comparison of the current and near-term results for the 1100/1300 stages at 5700/5900 fields show the tradeoff on aircraft wing area for the 8% engine thrust increase (Fig. 7). A reduction of 150-ft^2 wing area and 1200-lb takeoff weight is possible with the increased thrust engine. These may be regarded as extremely beneficial cost-effective trades since the cost of engine development would be substantially less than corresponding aircraft price and operating cost increases.

The near-term engine combined with the slightly extended wing was investigated by cross-plotting from the results in Fig. 9. The resulting tradeoff between stage distance and field length is shown in Fig. 11 together with $\pm 5\%$ sensitivity lines for wing area.

Far-Term Engine

Aircraft size and operating envelopes were substantially extended for this study. The results are plotted in Figs. 12 and 13. As the aircraft size and stage increased towards the top of the range, the available power is unable to satisfy the WAT/BFL requirements. In such cases the optimizer is unable to find a feasible design point. This affected the 76-seat aircraft at maximum stage and all the 80-seat aircraft except for the shortest stage distance. All the unfeasible designs exceed

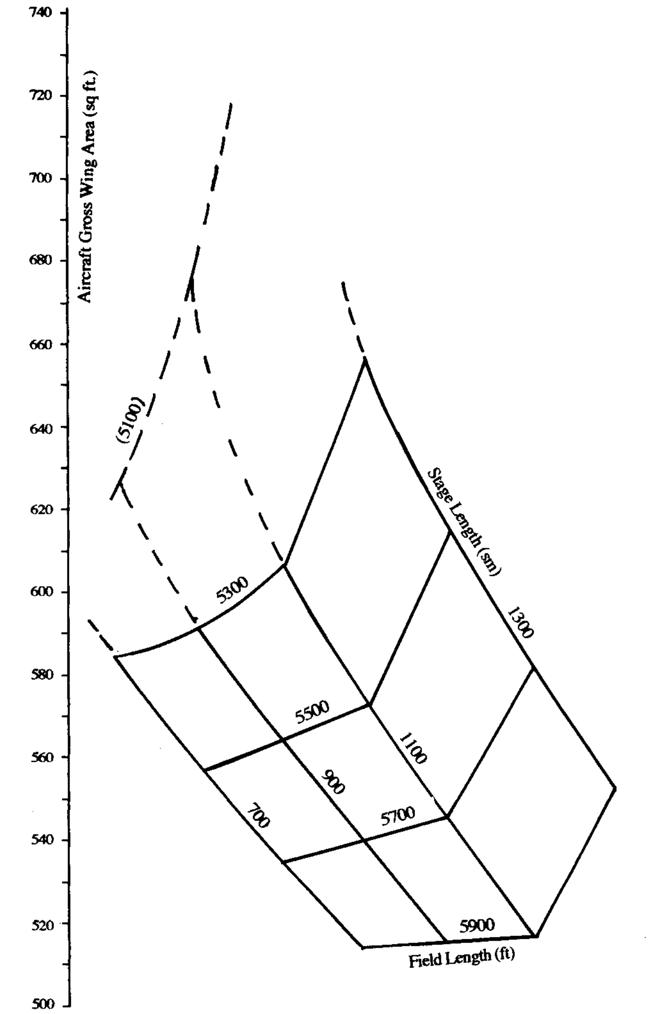

Fig. 10 Optimum aircraft—aircraft empty weight (near-term engine).

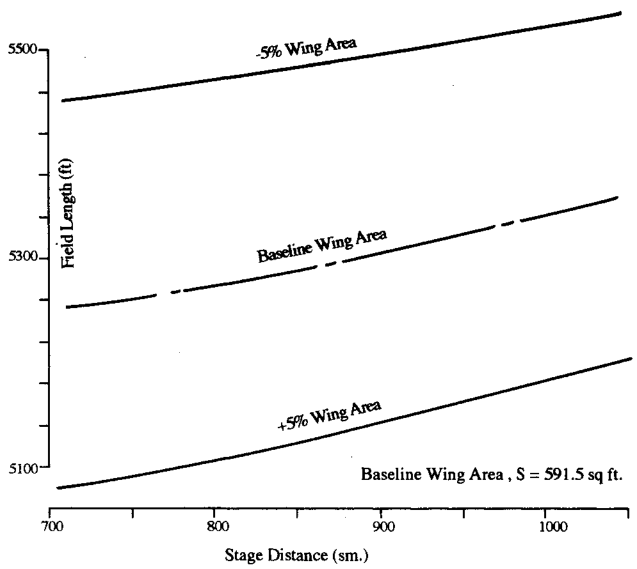

Fig. 11 Trade-offs for field and stage length (near-term engine).

65,300-lb takeoff weight which seems to suggest this limit for the far-term engine stretch.

For aircraft specifications which were overpowered, the optimizer switches the critical constraint from takeoff (WAT/BFL) to landing (i.e., similar to some of the near-term results). This occurred at aircraft maximum takeoff weights below 61,000 lb. Overpowering is shown to provide no advantage to the aircraft.

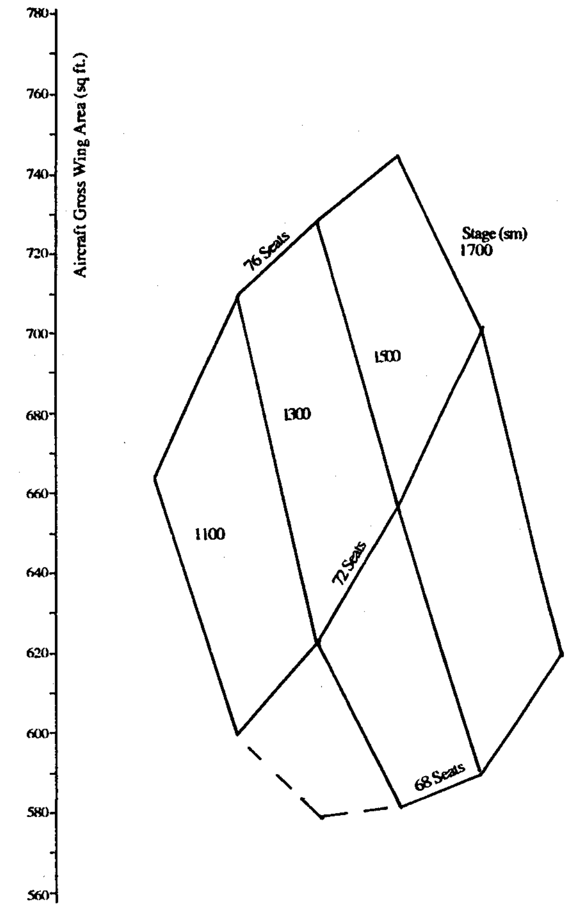

Fig. 12 Optimum aircraft—wing area (far-term engine).

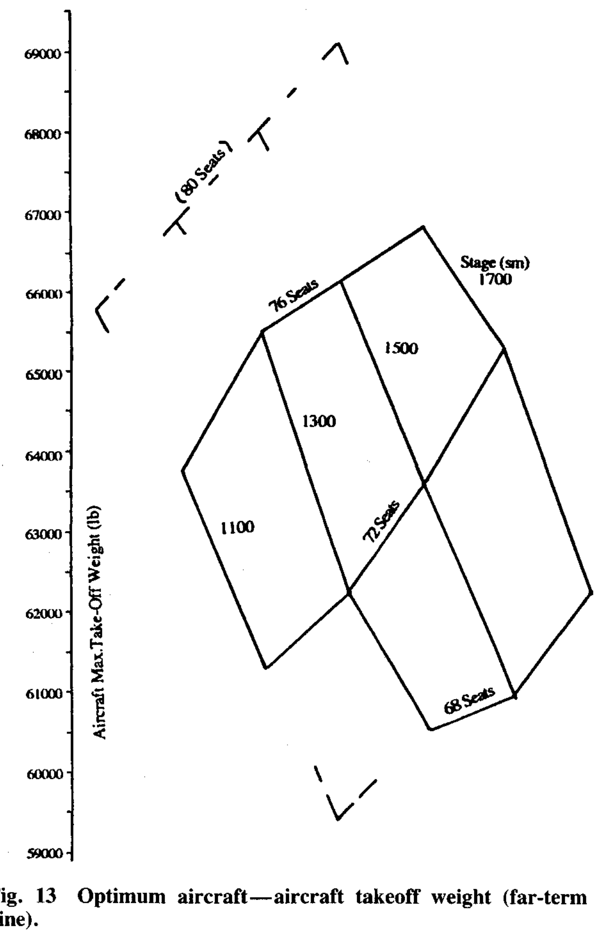

Fig. 13 Optimum aircraft—aircraft takeoff weight (far-term engine).

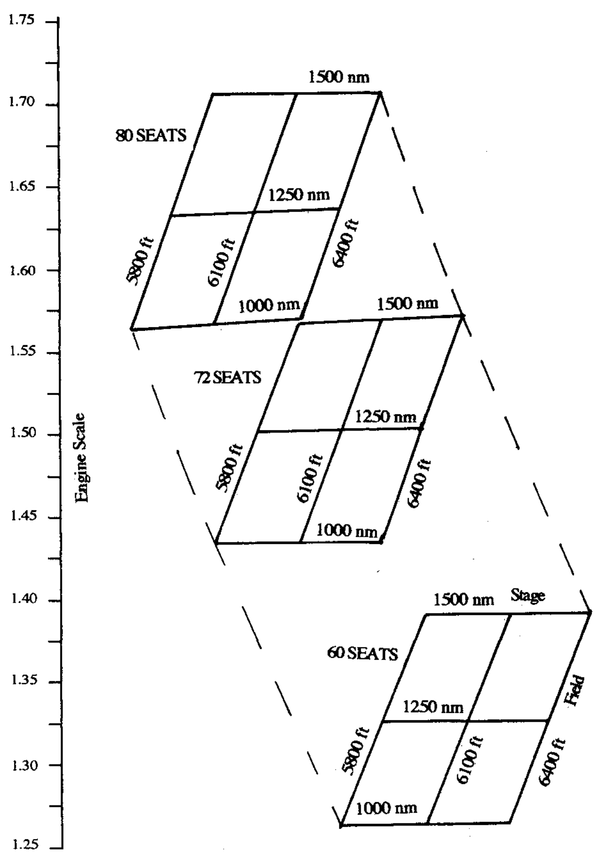

Fig. 14 Optimum aircraft—engine size (generalized designs).

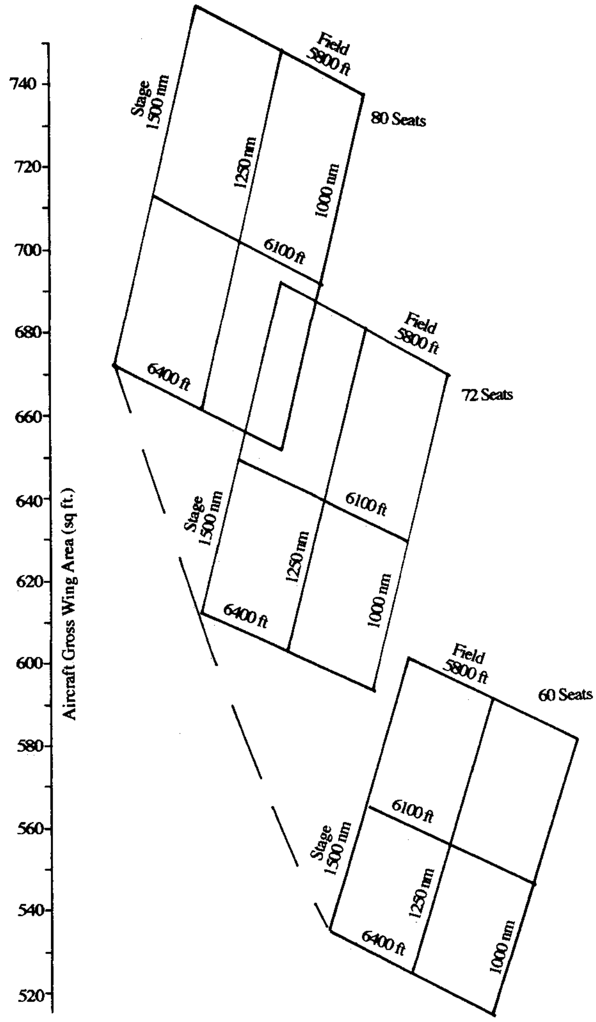

Fig. 15 Optimum aircraft—wing area (generalized designs).

The different influences exerted on the design by both under- and overpowering showed the far-term engine to be well matched to the 72-seat design at the stages and field considered.

Generalized Designs

The optimizer was modified to incorporate "engine scale" as a design variable. This change allows the selection of optimum engine size in combination with aircraft geometry and mission parameters. The "generalized" studies considered aircraft in the range 60–80 seats, 1000–1500-mile stage, and field length in the range of 5800–6400 ft. The resulting engine scales for the optimum aircraft are shown in Fig. 14.

Since increased engine power is identified by the optimizer to be more economic than increased aircraft size (wing area, flap size, etc), the overall design strategy becomes straightforward and matches traditional (noncomputer) methods. The program selects a wing area to meet the landing field requirement and then selects an engine scale and takeoff flap setting in combination to satisfy the WAT/BFL specification. Takeoff flap settings are slightly larger than would be expected, but this may be due to inaccuracy in flap modeling. The design strategy forces engine scale to be relatively insensitive and the wing area to be highly dependent on field length specification. Since engine size increase is identified as cheaper than wing structure modifications, it may be economical to use more sophisticated flaps. This aspect has not been investigated because a satisfactory function to estimate flap weight and cost could not be determined within the time scale available. This type of investigation could form the basis for an extension to the current work. Figure 14 confirms the unfeasibility of designs with the far-term engine size used in the previous study.

Over the range of stages considered (1000–1500 nm), the required engine improvement (for a particular aircraft size) is seen to be approximately 12%. The same engine increase is shown to be required for changes between aircraft size (60–70 seats) for a given stage specification. This equates to about 8% thrust increase. This may be regarded as within the near-term (less than 5 years) engine development period.

In association with the engine stretch discussed above, a wing area increase of approximately 15% as shown in Fig. 15 would be necessary. This may present more difficulty to the manufacturer than corresponding engine changes which supports overwinging of the original configuration as a prudent design strategy. As the aircraft size increases, the change in engine scale requirement reduces and the wing area increase drops to about 8%. It may be possible to achieve this area increase with wing tip and wing chord extensions from an existing design. Part of the reduction in area increase is due to the law of diminishing return. The engine scale requirements show relative insensitivity to field length specification. This is shown clearly in the aircraft weight carpet plot (Fig. 16). Stage distance is considered over a much wider range of values (50% increase) and this produces a 6% aircraft weight change. The plots for seat mile cost (Fig. 17) show the powerful influence of "number of seats" and the relative insensitivity of stage distance beyond 1250 nm. Again, the influence of diminishing returns can be observed between the 60–72 and the 72–80 aircraft stretches.

In summary, many design strategies can be argued from these results, especially in the cases for which the engine and aircraft sizes are unconstrained. This situation does not often occur in industrial design projects as limitations on size and cost aspects will dominate. The cost analysis has shown the advantage of increasing size up to about 68 seats with a stage at 1250 nm and a field length relaxed as far as the market allows. The sensitivity of the design surface to wing size variation confirms the designer's natural instinct to slightly overwing the initial configuration.

The size of aircraft considered in this study would require an engine with development potential to about 12,000 lb takeoff thrust. This would relate to a current engine of about 8500 lb. None of the engines considered in the industrially related studies matched this specification.

Observations

In all the optimization studies, the design model was seen to be well-behaved and the resulting design surface was relatively smooth. Repeated searches from different starting values showed the "evenness" of the surface without local depressions. The optimum designs were seen to frequently reside at the intersection of constraint boundaries. As the type of problem was generalized, (with less constraint on wing geometry and engine size) the optimizer was shown to select a design strategy similar to the traditional project method. Recognizing this similarity increased confidence in the optimization methodology.

Optimization accuracy was a continuous cause for concern. The optimization method demands a much finer tolerance than the estimating equations can guarantee. This means that the influences from the individual aircraft parameters may be incorrectly represented. Design equations used in the synthesis model have been taken from previous well-established project methods. Traditionally, such relationships have been developed to provide reasonably accurate predictions of the gross effect on the overall design of the aircraft and have not been too concerned with individual components. This aspect has been demonstrated in the analysis of weight prediction methods in which some of the statistically best relationships, from an overall viewpoint, have been those with the fewest aircraft variables. Such methods would be unsuitable for detail optimization studies as the influence of all design parameters are required to conduct a representative search. The situation is further complicated by the need to accurately represent all the design variables in the equations and for such relationships to be quickly evaluated. The balance to be drawn between analysis methods which reflect the variability of the parameters with sufficient accuracy and the simplification of the relationships to permit rapid evaluation, represents a major difficulty in the developments of optimization methods. For the model described here, the selection of appropriate methods benefited from the work done earlier on turboprop designs and the close industrial collaboration that existed.

Optimization methods of the type used in the RQPMIN program can be criticized for inefficiency. Although there is little doubt that the mathematical methods used in the search routines are well-designed and use the best methods available, they still involve considerable internal manipulation of data to determine the derivatives of the design surface functions at each point considered. It has been estimated that approximately half of the total calculation time for a particular study is used for such internal processing. The remaining time is used for repeated passes through the synthesis module. At each pass a complete aircraft is analyzed (weight, balance, drag, lift, performance, and cost). Typically between 5000–20,000 such aircraft are analyzed for each optimization run. At the end of the process only the final (optimum) aircraft design details are made available. For both the inefficiency of internal computation and the discarding of previous designs, the effectiveness of the optimization method must be

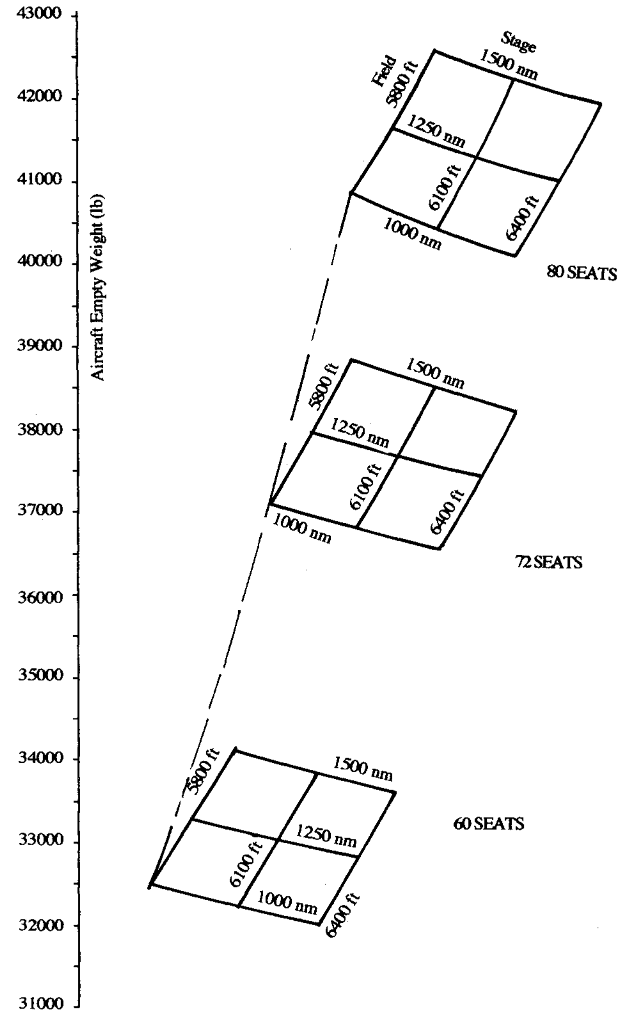

Fig. 16 Optimum aircraft—aircraft empty weight (generalized designs).

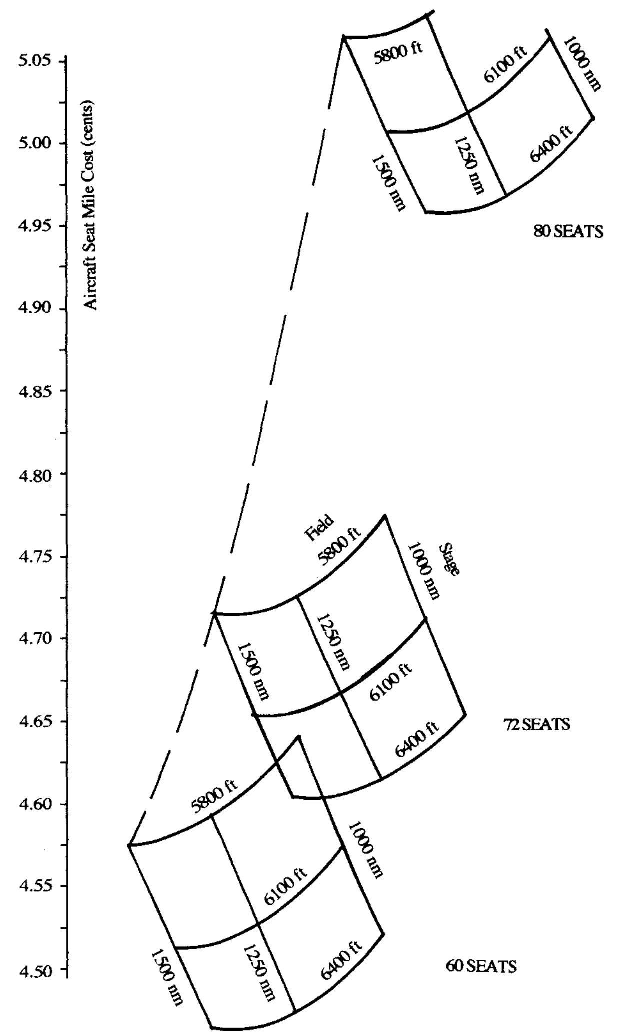

Fig. 17 Optimum aircraft—seat-mile cost (generalized designs).

challenged. As computer technology improves, the need for sophisticated search methods may be reduced. Optimization methods may be based on fast repetitive processes with a simple (perhaps pseudorandom) strategy for selecting the design points. The best series of designs could then be offered to the designers for further consideration. With such a process the synthesis model would not need to be compromised by the optimization search methods. Discontinuities and constraint boundaries should not present problems to such methods. A selection strategy would be required to reduce the time spent in analyzing designs in the unfeasible regions (i.e., areas of constraint violations). Further work concerning in-depth investigation of alternative "optimization methods" is currently being studied.

Although the optimization method mimicked traditional manual methods for the less constrained (generalized) studies, they were considered to be an improvement over traditional parametric studies because all aircraft are based on the common objective function. The optimization model correctly selected designs for different objective functions but indicated the need to carefully consider the choices. The selection of objective function was shown to have only a small influence on the optimum aircraft geometry. The study confirmed the decision to use "DOC per flight" as the principal optimization function.

Conclusions

The first phase of the work demonstrated some of the different ways in which the optimizer/design model could be used in initial project design. The following detailed conclusions are typical of those that may be drawn from such work:

1) The 40-seat baseline specification and the original engine are well-matched but do not offer any immediate stretch potential unless the AR upper limit could be raised.

2) Comparability between the multistage missions and the 1000-nm single-stage is not clearly shown, but the definition of the optimum aircraft configuration is not too sensitive to this choice. All subsequent designs were based on the single-stage flight profile to allow comparison with industrial estimates.

3) The rear-engine layout is less efficient than the corresponding wing-mounted configuration. The penalties for rear engine location on the baseline specification include an increase in DOC/flight of approximately 10%.

4) Stretching the aircraft and retaining the baseline wing area and aspect ratio would require 8 and 18% more thrust for the 44- and 48-seat designs, respectively. If the wing could be enlarged less engine stretch would be required.

The stretch studies identified the suitability of a new engine for particular aircraft development:

1) The current engine is well-suited to the 56-seat stretched baseline aircraft but identified a maximum aircraft weight limit of about 52,000 lb.

2) The near-term engine development is seen to overpower the short-range 56-seat designs but is suitable for the longer stage designs. This engine could allow a reduction in field length to about 5000 ft for the 56-seat aircraft.

3) The near-term engine would allow a further stretch to 60 seats if stage length was restricted to a maximum of 1300 sm. The engine is not powerful enough for the 64-seat design.

4) The tradeoff between engine thrust increase and aircraft parameters (area and weight) is seen to be substantially in favor of engine improvements.

5) The far-term engine development is well matched to the stretched 72-seat aircraft but would be unsuitable for the 80-seat designs.

6) The influence of AR choice is seen to be powerful. All the power-critical designs in the study would have benefited from a relation in the fixed 9.27 value used.

The high zero-fuel weight ratio of commuter aircraft signals a high susceptibility to weight changes. This was confirmed by the initial optimization studies. Such aircraft will therefore benefit from the use of efficient project design methods and the adoption of advance technologies.

Aircraft and engine stretch studies provide the most effective use of the optimization method. They allow the sensitivity of all the aircraft parameters to be displayed against aircraft size and mission specifications. Such information has been shown to be valuable in the definition of future aircraft development strategies.

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