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Framework for Aircraft Conceptual Design and Environmental Performance Studies

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Although civil aircraft environmental performance has been important since the beginnings of commercial aviation, continuously increasing air traffic and a rise in public awareness have made aircraft noise and emissions two of the most pressing issues hampering commercial aviation growth today. This, in turn, has created the demand for an understanding of the impact of noise and emissions requirements on the design of the aircraft. In response, the purpose of this research is to explore the feasibility of integrating noise and emissions as optimization objectives at the aircraft conceptual design stage, thereby allowing a quantitative analysis of the tradeoffs between environmental performance and operating cost. A preliminary design tool that uses a multiobjective genetic algorithm to determine optimal aircraft configurations and to estimate the sensitivities between the conflicting objectives of low noise, low emissions, and operating costs was developed. Beyond evaluating the ability of a design to meet regulations and establishing environmental performance trades, the multidisciplinary design tool allows the generation of conventional but extremely low-noise and low-emissions designs that could, in the future, dramatically decrease the environmental impact of commercial aviation, albeit at the expense of increased operating cost. The tool incorporates ANOPP, a noise prediction code developed at NASA Langley Research Center, NASA Glenn Research Center's Engine Performance Program engine simulator, and aircraft design, analysis, and optimization modules developed at Stanford University. The trend that emerges from this research among the seemingly conflicting objectives of noise, fuel consumption, and NO_x emissions is the opportunity for significant reductions in environmental impact by designing the aircraft to fly slower and at lower altitude.

Introduction

THE continuing growth in air traffic and increasing public awareness have made environmental considerations one of the most critical aspects of commercial aviation today. It is generally accepted that significant improvements to the environmental acceptability of aircraft will be needed if the long-term growth of air transport is to be sustained. The Intergovernmental Panel on Climate Change has projected that, under an expected 5% annual increase in passenger traffic, the growth in aviation-related nuisances will outpace improvements that can be expected through evolutionary changes in engine and airframe design.[1]

Commercial aircraft design processes have focused primarily on producing airplanes that meet performance goals at minimum operating costs. Environmental performance has been considered mostly at a postdesign analysis phase, during which adjustments are made to satisfy the noise and emissions requirements of individual airlines or airports. This sequential design approach does not guarantee that the final aircraft is of overall optimal design with respect to operating costs and environmental considerations, but it served its purpose as long as only localized, minor adjustments were necessary to bring aircraft into environmental compliance. However, following the gradual tightening of environmental requirements, the cost and complexity of achieving compliance in the postdesign phase has increased significantly.

To illustrate the point, consider the Airbus A380, which had to be modified well into the design phase, at the request of airlines, to meet nighttime restrictions at London Heathrow airport. The modification involved using an engine fan larger than required for lowest fuel consumption, which necessitated a redesign of the engine, nacelle, pylon, and wing. These modifications resulted in a increase in fuel burn for a small cumulative noise reduction and was considered an expensive tradeoff.[2]

On the emissions front, the International Civil Aviation Organization (ICAO)'s Committee on Aviation Environmental Protection, at its 6th meeting in early 2004, concluded that it could not demand a reduction of aircraft NO_x of more than 12% relative to today's aircraft‡ for new aircraft entering service in 2008. The issue was not related to technology risk: existing combustors can today attain this level of emissions performance. The reason was a lack of information regarding interrelationships: the impact of further NO_x reductions on noise and other emissions was not fully understood. Demanding a reduction in one type of emissions only to obtain an increase in another, by an unknown quantity, was not a viable solution.

There is therefore a need for integrating environmental considerations at an early stage of the aircraft design process and for more systematic investigation and quantification of the tradeoffs involved in meeting specific noise and emissions constraints. This research contributes by proposing a conceptual design tool structured to generate optimized preliminary aircraft designs based on specified mission parameters, including environmental and cost-related objectives. Existing aircraft design codes were extensively modified to incorporate the parameters required to model environmental performance. A multiobjective genetic algorithm was created to explore the design space, while noise prediction codes and an engine simulator were integrated into the automated design process.[3]

The design tool also enables users to evaluate the sensitivities of optimized designs to variations in operating and environmental requirements and to compare the merits of various trade cases. Because all aspects of the aircraft are considered simultaneously, the design tool allows for optimal aircraft configurations to be obtained.

Aircraft Noise

Although considerable progress has been made to reduce the noise signature of airliners, the public's perception of noise continues

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‡Data available online at http://www.ueet.nasa.gov/toi/viewtoi.php?id=119 [cited 17 May 2004].

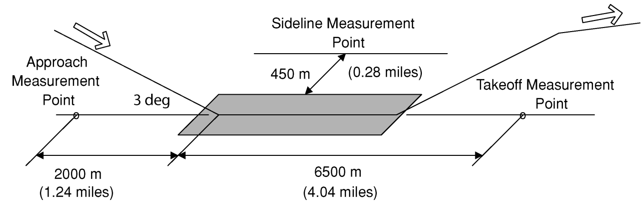

Fig. 1 ICAO certification noise measurement points.[7]

to grow, as evidenced by the ever-increasing number of public complaints. This can be attributed to increasing air traffic as well as further encroachment by airport-neighboring communities. In the United States, 60% of all airports consider noise a major problem, and the 50 largest airports view it as their biggest issue.[4] As a result, noise has become a major constraint to air traffic. A survey of the world's airports reveals a twofold increase in the number of noise-related restrictions in the past 10 years,[5] including curfews, fines, operating restrictions, and quotas.

The historical trend in aircraft noise has shown a reduction of approximately 20 EPNdB since the 1960s, largely because of the adoption of high-bypass turbofans and more effective lining materials. Reductions since the mid-1980s have not been as dramatic.[6] The point seems to have been reached where future improvements through technological advances will be possible only by significantly trading off operating costs for environmental performance. Quantifying the terms of this tradeoff, which will be critical for the efficient design of future aircraft, is one of the main objectives of this research.

Noise Prediction

The ICAO and Federal Aviation Administration issue noise certifications based on measurements of approach, sideline and flyover noise made at three points during the landing and takeoff cycle (LTO), as illustrated in Fig. 1 (Ref. 7). Noise is recorded continuously at these locations during takeoff and landing. The total time-integrated noise, known as effective perceived noise level (EPNL), must not exceed a set limit, itself based on the maximum takeoff weight of the airplane and the number of engines. Jet noise typically dominates in sideline and flyover noise. On approach, high-bypass-ratio engines operate at reduced thrust and are relatively quiet, making airframe noise a relevant component.

Aircraft Noise Prediction Program (ANOPP) is a semiempirical code developed and updated continuously by the NASA Langley Research Center.[8,9] It incorporates publicly available noise prediction schemes and models noise from a variety of sources, including fan noise, jet noise, and airframe noise. By using engine data supplied from the engine performance code, and aircraft geometry and LTO data supplied from other analysis routines, ANOPP computes near-field sound spectra for each noise source. The ANOPP propagation module is then run to determine the tone-corrected perceived noise levels as measured at the ICAO certification points, before ANOPP computes the time-averaged EPNLs.

Noise Reduction

Bypass Ratio

As noted earlier, jet engines produce most of the sideline and flyover noise measured during the certification process. It follows that engine design is critical to the noise performance of the aircraft. Along with advances in liner materials, high-bypass-ratio engines have been the single largest contributor to aircraft noise reduction.

The particular importance of bypass ratios in this respect is well known: increasing the bypass ratio can have a dramatic effect on fuel efficiency, noise, and emissions. By increasing the amount of airflow directed around the combustion chamber relative to the amount of air passing through it, mixing between the flows on exit is increased, and exhaust velocities reduced. The result is a considerable decrease in jet noise and overall engine noise (Fig. 2): increasing bypass ratios from 6 to 14 results in a cumulative noise reduction of 8 dB. These results were obtained with the design tool developed as part of this research for a 280-passenger aircraft.

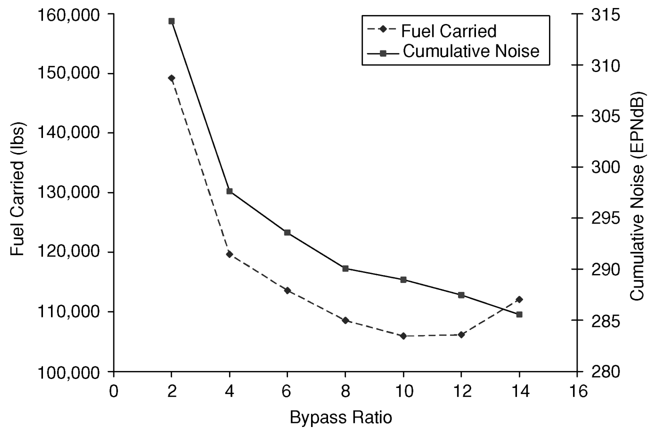

Fig. 2 Impact of increasing bypass ratio on cumulative certification noise and total fuel required to complete the mission.

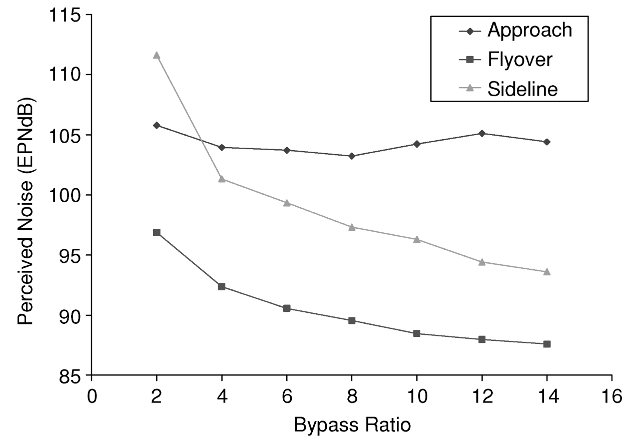

Fig. 3 Noise measured at the three certification points as a function of bypass ratio.

The impact on emissions and operating costs of increasing bypass ratio is not as obvious.[10] Figure 2 also illustrates the variations for cost-optimized aircraft in total fuel carried (which largely determines both cost and emissions performance) as a function of the bypass ratio. Although fuel consumption improves by about 9% when the bypass ratio increases from 4 to 8, it increases again when the bypass ratio exceeds 10. The relative deterioration of the fuel consumption for high-bypass engines is caused in part by the significant parasite drag associated with their large fans. In addition, for a given thrust requirement at cruise conditions, high-bypass-ratio engines will typically have excess sea-level static (SLS) thrust. For instance, an engine with a bypass ratio of 10 can produce about 20% less thrust at 31,000 ft than a engine with a bypass ratio of 6 having identical SLS thrust. As a result, whereas high-bypass-ratio engines have low noise emissions because of reduced exhaust velocities, some of this advantage is offset by the need to increase the SLS thrust (i.e., oversize the engines) to achieve the required cruising altitude thrust.

The noise measured at each of the certification points for the same aircraft, as a function of bypass ratio, is shown in Fig. 3. Note that sideline and flyover noise both gain significantly from the decrease in jet velocities associated with increasing bypass ratios. At the reduced throttle settings required at approach, however, jet noise is not a dominating factor. Airframe and fan noise are the most important contributors in this regime. This is illustrated by the relatively flat approach noise data shown in Fig. 3.

Having achieved significant progress in reducing jet noise, the focus of most current research is on reducing fan and airframe noise, currently seen as the limiting factors in the manufacturers' present ability to improve aircraft noise performance on approach.

Climb Performance

Another method of reducing certification noise involves increasing the distance between the aircraft and the measurement point. One option is a steeper climb. The balance between increased noise at the source and the improved climb performance afforded by larger engines is delicate and therefore perfectly suited for an optimization process.

Although beyond the scope of this research, operational procedures for existing aircraft, such as thrust cutback, steeper descents, and continuous descent approaches can offer significant reductions in noise.

Engine Emissions

The release of exhaust gases in the atmosphere is the second major environmental issue associated with commercial airliners. The world fleet releases approximately 13% of CO_2 emissions from all transportation sources, or 2% of all anthropogenic sources.[11] The expected doubling of the fleet in the next 20 years[§] will certainly exacerbate the issue: the contribution of aviation is expected to increase by a factor of 1.6 to 10, depending on the fuel consumption scenario.

Current emissions regulations have focused on local air quality in the vicinity of airports. Emissions released during cruise in the upper atmosphere are recognized as an important issue with potentially severe long-term environmental consequences, and ICAO is actively seeking support for regulating them as well.

Local and Cruise Emissions

Both particulate and gaseous pollutants are produced through the combustion of jet kerosene.

Reactants: Air: N_2, O_2
Fuel: C_nH_m, S

Products: CO_2, H_2O, N_2, O_2, NO_x, UHC, CO, C_{soot}, SO_x

The greenhouse gases carbon dioxide CO_2 and water H_2O are the major products. Minor emissions formed during combustion include nitrous oxides (NO_x), unburned hydrocarbons (UHC), carbon monoxide (CO), and smoke (C_{soot}).

ICAO regulations for the LTO cycle cover NO_x, CO, UHC, and smoke emissions.[12] NO_x are the main regulated pollutants, accounting for 80% of regulated emissions during the cycle. For certification purposes, they are computed based on the combustor emission index (EI, expressed in grams of NO_x released per kilogram of jet fuel used) and engine fuel flow (expressed in kilograms/second). Fuel flow itself is a strong function of power setting during the LTO cycle, which involves four different throttle modes, mandated by the ICAO. The engine is run in a test facility, and the various segments of the cycle are simulated as follows: 0.7 min for takeoff (full throttle), 2.2 min for climb (85% throttle), 4 min for approach (30% throttle), and 26 min for taxi/idle (7% throttle). The amount of NO_x produced during the LTO cycle is computed as the sum of the emissions for the preceding four modes (expressed in kilograms):

$$NO_x = \sum \text{fuel flow} \times EI_{NO_x} \times \text{time in mode}$$

The combustor emission index is estimated as a function of P_3, the combustor entrance pressure, and T_3 and T_4, respectively, the entrance and exit temperatures in the combustor (personal communication with S. Jones, Aerospace Engineer, Airbreathing Systems Analysis Office, NASA Glenn Research Center, Dayton, Ohio, 2003) (units are psia and Rankine):

$$EI_{NO_x} = 0.004194 T_4 (P_3/439)^{0.37} e^{(T_3 - 1471)/345}$$

During cruise, NO_x emissions become relatively unimportant (0.3% of the mass flow emerging from the engine) compared to other emissions, including CO_2, CO, and SO_2, which account for over 6% of the mass flow. Because the carbon and sulphur necessary to form these emissions are found in the jet fuel, it follows that cruise emissions are directly proportional to the amount of fuel burned in flight. Consequently, an aircraft can be optimized for cruise emissions by introducing fuel weight as an objective to be minimized at the conceptual design stage, which leads to a four-way tradeoff between operating cost, cruise emissions, and the already discussed NO_x emissions and noise objectives.

Reduction Methods

Combustor and Engine Cycle

The two methods that allow a reduction in emissions at the level of the powerplant include improving the combustor to yield a lower emissions index (that is, reduce the amount of pollutant emitted per kilogram of fuel burned) and choosing an engine cycle that yields lower fuel flow (to reduce the amount of fuel consumed). Increasing the overall engine pressure ratio promotes more complete combustion, resulting in reduced fuel flow. The tradeoff is higher NO_x emissions caused by the increased combustion temperature, leading to increased dissociation of nitrogen, and consequently a higher NO_x EI. Although improvements to the combustor could decrease the amount of NO_x or CO_2 released into the atmosphere, these are generally conflicting requirements. Typically, changing the operating conditions or combustor configuration to reduce NO_x emissions increases the quantity of CO_2 and unburned hydrocarbons produced.[13]

In particular, as the bypass ratio of large turbofans is increased, the resulting power requirements of the larger fan mandate that more energy must be extracted from the low-pressure turbine. This typically leads to higher pressures, combustion temperatures, and NO_x production. In fact, total aviation NO_x emissions increased faster than total fuel consumption over the last few decades because of the higher pressure ratios (and therefore combustion temperatures) demanded by the more fuel-efficient high-bypass-ratio engines. Other types of emissions, however, have decreased per unit of fuel consumption.

This increase in NO_x production can be partially offset through detailed combustor design, which is beyond the scope of the present conceptual design tool. Advanced double-annular, lean premixed, and rich/quench/lean combustors could all be subsequently incorporated if data were made available relating design parameters (combustion temperature, overall pressure ratio) with emissions indices.

Cruise Altitude Effects

Contrail formation[14] is another issue that is receiving increased attention. Although the long-term impact on climate change as a result of increasing water content at altitude is uncertain, one possible solution to minimize contrails is to operate the aircraft at lower cruise altitudes to increase ambient temperatures.

The advantages of decreasing cruise altitude are two-fold: contrail formation would be dramatically reduced, and the *net* total impact of other emissions could be reduced, as the aircraft would be operating outside of the sensitive tropopause. Figure 4 (Ref. 15) illustrates these effects for two fuels: kerosene and hydrogen. In the case of kerosene, reducing the cruise altitude from 11 to 9 km reduces the net impact of NO_x by half because the aircraft has traveled out of the troposphere and H_2O by 75% because of the prevention of contrail formation. However, the net impact of operating the aircraft at this off-design altitude, from a fuel efficiency perspective, is apparent: CO_2 effects increase by a third. A separate Boeing study supports this general trend, concluding that operating an existing aircraft in the 747-400 class at lower altitudes would increase CO_2 production by 15% and NO_x emissions by up to 25% (Ref. 16). To minimize this degradation in performance, an aircraft would have to be designed specifically to operate at these lower altitudes, which is discussed in the Results section. It must be noted, however, that there are complications to operating an aircraft a lower altitudes, the most important being weather.

As a side note, although hydrogen fuel is not considered as part of this research it is interesting to note that, being the major byproduct of so-called "clean" combustion, water effects would be as much as three times more important than with kerosene fuel at a cruise altitude of 11 km.

[§] Data available online at http://www.boeing.com/commercial/cmo [cited 8 April 2003].

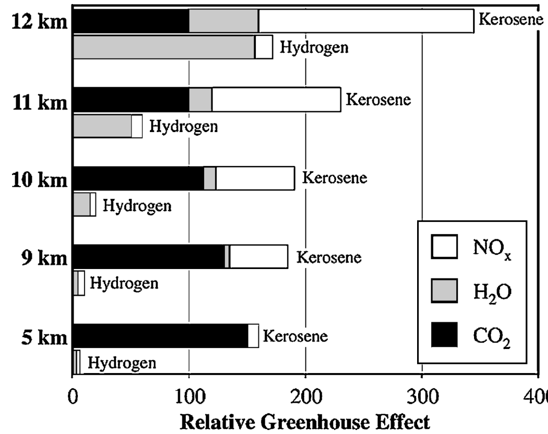

Fig. 4 Effect of fuel type and cruise altitude on net greenhouse effects.

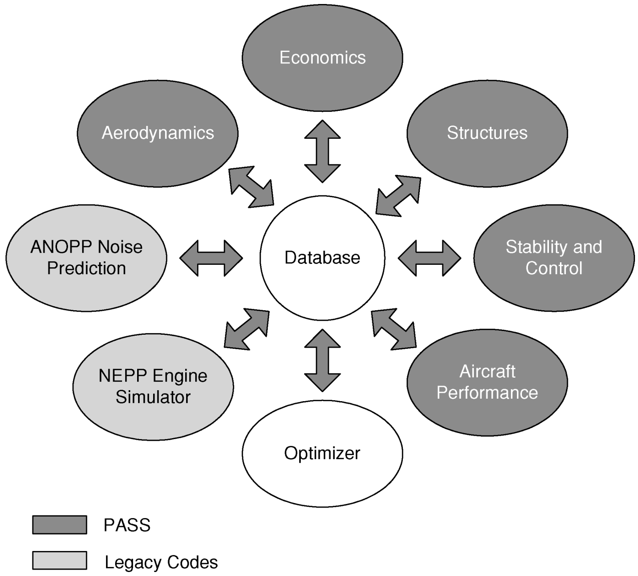

Fig. 5 Design framework: the PASS aircraft design modules, noise prediction, and engine simulator are coupled with an optimizer and a database manager.

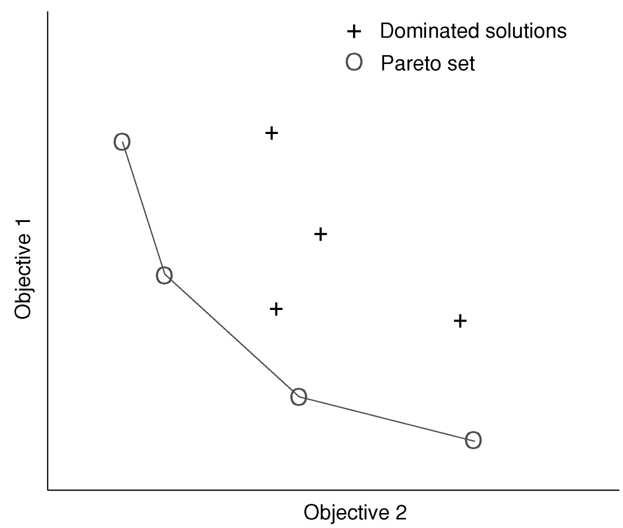

Fig. 6 Example two-objective minimization problem showing the Pareto set.

Aircraft Aerodynamics

The advantages of reducing fuel flow, at the engine level, on the production of emissions have been discussed earlier. At the aircraft level, drag contributes directly to the thrust requirements. Improving the aerodynamic efficiency of an aircraft by reducing drag, and therefore reducing the amount of thrust required, can result in a decrease of required fuel and related emissions.

Reducing the aircraft cruise Mach number is one solution to reducing drag, for example. This must be carefully balanced with other mission requirements, however, and highlights the importance of considering the aircraft as a whole. New technologies, such as increased laminar flow and induced drag-reduction methods, are promising in their ability to increase the aerodynamic efficiency and reduce the fuel consumption of the aircraft. These are discussed in more detail in the Results section.

Design Tool

Aircraft Design and Optimization

The design tool is structured around PASS, a program for aircraft synthesis studies,[17] the ANOPP, NASA Glenn's NEPP (NASA Engine Performance Program) for engine simulation,[18] a genetic multiobjective optimizer, and a database management module.

The PASS design modules are used to analyze key aspects of the aircraft, including aerodynamics, performance, stability/control, structures, and economics. They offer the resolution required to capture environmental concerns and are amenable to optimization. The engine performance and noise estimation codes are coupled to the aircraft performance and operating cost modules.[19,20] An illustration of the framework is shown in Fig. 5.

The multidisciplinary analysis of the aircraft and the optimizing of its design are performed within a design environment, known as the Collaborative Application Framework for Engineering (CAFFE) (see Ref. 21), in conjunction with the optimizer. CAFFE provides for easy reconfiguration of the design tool: adding or removing design variables, objectives, and constraints is done via a simple graphical interface, which affords the rapid execution and robustness needed for optimization.

Any parameter introduced in the database can be set as an objective, a variable, a constraint, or a fixed numerical value. Consequently, the design tool allows great flexibility in selecting objective functions and in exploring the sensitivity of optimized designs to changes in specifications or constraints. Objective functions can include performance parameters (for instance takeoff weight, operating cost, or range), as well as environmental parameters (certification noise and emissions levels). The latter can also be set as constraints, with the user specifying the level of environmental friendliness required of the aircraft: from slight improvements over designs optimized for minimal cost, to "silent" and "clean" aircraft. Design variables typically include parameters pertaining to aircraft configuration, propulsion, and mission profile.

Multiobjective Optimization

Genetic algorithms[22] mimic nature's evolutionary principles in searching for optimal solutions. Such algorithms are particularly well suited to multiobjective optimization problems because they can handle large populations of solutions, which they drive toward optimality through a generational process of selection and elimination. Over the course of multiple generations, increasingly optimal "nondominated" solutions (i.e., solutions that are not outperformed by others having better scores on all objectives) are identified and retained.[23] For each generation, a ranking approach is used to evaluate the relative dominance (performance) of each solution and to determine the set of nondominated, rank 1 solutions, known as the Pareto set.

The concept is illustrated for a two-objective minimization problem in Fig. 6. Of the eight solutions shown, four are dominated because at least one other solution shows better scores on both objectives. The Pareto set contains the solutions offering the best tradeoff between the two objectives for the current generation: for these solutions, any improvement in performance relating to one objective is possible only by accepting a reduction of performance in the other. Through the generations, the genetic algorithm drives

Table 1 Variable names, units, and minimum and maximum allowable values for the optimization problems

Variable	Min	Max
Maximum takeoff weight, lb	280,000	550,000
Wing reference area, ft^2	1,500	4,000
Wing thickness over chord, %	0.07	0.20
Wing location along fuselage, %	0.2	0.6
Wing aspect ratio	4.0	15.0
Wing taper ratio	0.1	0.7
Wing sweep, deg	0.0	40.0
Horizontal tail area, ft^2	225	600
Sea-level static thrust, lb	40,000	100,000
Turbine inlet temperature, °F	3,000	3,300
Bypass ratio	4.0	15.0
Engine pressure ratio	40.0	60.0
Initial cruise altitude, ft	20,000	40,000
Final cruise altitude, ft	20,000	50,000
Cruise Mach number	0.65	0.95

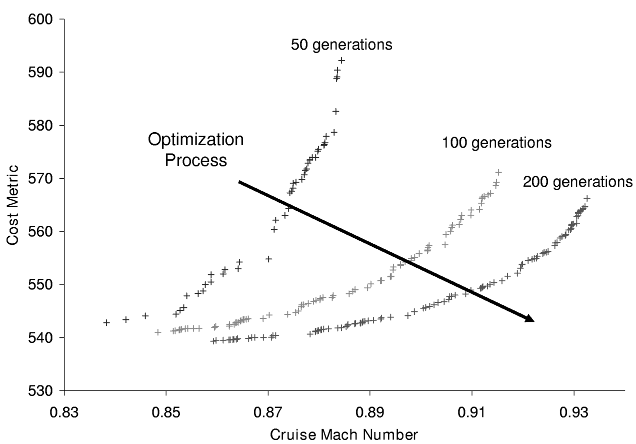

Fig. 7 Pareto front indicates the set of nondominated solutions in a given generation. The optimization process drives the population toward their optimal values.

the population toward better solutions. This is illustrated in Fig. 7: a 200-seat, 6000-n mile range aircraft is optimized simultaneously for both minimum cost and maximum cruise Mach number.

With each generation, the Pareto front is pushed toward higher Mach numbers and lower costs. Eventually, the front no longer progresses, and the set of optimal tradeoffs between Mach number and cost is obtained. Selecting one solution among those belonging to the Pareto set typically requires information extraneous to the optimization problem (for instance, technical risk, certification, or operational requirements).

The uncertainty associated with the approximate methods used in this conceptual design tool could be propagated through the optimization process. The outcome would be a distribution of solutions, as opposed to the current single-point deterministic result for each design. This probabilistic approach would allow the user to understand, and quantify, the impact of modeling error on the conceptual design process. The computing cost associated with generating such a Pareto "band" (as opposed to a well-defined front), however, would be considerable.

Multiobjective Trade Studies

Aircraft Mission, Variables, and Constraints

This section illustrates the optimization process performed by the design tool in the case of a 280-passenger, twin-engine airliner with a 6000-n mile range, and takeoff, cruise, and landing performances in line with industry standards for similarly sized aircraft. The 15 design variables are listed in Table 1, split in three groups: aircraft geometry, engine parameters, and performance. Constraints are shown in Table 2.

Table 2 Constraints for the optimization problems

Constraint	Value
Cruise range, n mile	≥ 6000
Takeoff field length, ft	≤ 9000
Landing field length, ft	≤ 8000
Engine-out climb gradient	≥ 0.024
Drag-to-thrust ratio	≤ 0.88
Stability margin	≥ 0.18
Wing cruise lift coeff. margin	≥ 0.01
Tail rotation lift coeff. margin	≥ 0.01
Tail cruise lift coeff. margin	≥ 0.01
Tail landing lift coeff. margin	≥ 0.01
Wing span, ft	≤ 260.0

Table 3 Data for the optimal extreme designs obtained with the single-objective genetic algorithm

Parameter	Design A min cost	Design B min fuel	Design C min NO_x	Design D min noise
Objectives				
Relative cost	1.0	1.02	1.10	1.26
Fuel carried, lb	119,018	106,707	129,605	138,840
LTO NO_x, kg	30.88	29.68	14.04	41.09
Relative noise, EPNdB	0.0	−5.13	3.66	−14.98
Variables				
Max. takeoff weight, lb	372,539	352,515	419,842	473,532
Wing reference area, ft^2	3,461	2,942	4,283	3,578
Wing t/c,%	11.7	13.5	12.8	11.5
Wing location, %	39.2	41.2	43.6	48.2
Wing aspect ratio	7.38	9.99	9.81	14.43
Wing taper ratio	0.10	0.10	0.21	0.1
Wing sweep, deg	33.70	26.17	18.80	14.25
Horizontal tail area, ft^2	929	766	1220	1,431
SLS thrust (per engine), lb	68,404	67,311	60,954	100,000
Thrust-to-weight ratio	0.367	0.382	0.290	0.422
Turbine inlet temp.,°F	3,203	3,215	3,071	3,300
Bypass ratio	9.59	10.35	10.48	14.87
Engine pressure ratio	59.91	59.63	40.23	59.78
Init. cruise altitude, ft	32,937	30,746	29,170	31,674
Final cruise altitude, ft	40,790	38,734	39,843	35,486
Cruise Mach number	0.844	0.739	0.691	0.664

Operating Cost vs Cruise Emissions, LTO NO_x Emissions, and Noise

The process of obtaining a low-rank Pareto front can be significantly accelerated by first computing the extreme points of the fronts. This is done by running a single-objective version of the genetic algorithm. These optimal designs are subsequently inserted into the initial population of the multiobjective problems.

The resulting Pareto fronts of fuel carried, NO_x emissions, and relative cumulative noise vs cost are shown in Fig. 8. The reference for all relative data is the min-cost design (design A). Key parameters for the optimized extreme designs are summarized in Table 3.

The configuration leading to minimum operating cost (design A) was computed first by running the design tool. This aircraft is considered as the baseline and is representative of existing aircraft that are optimized for minimum operating cost. Reflecting the impact of block time (including the effects of crew costs) on the operating cost function, the cruise Mach number is higher than would be required for minimal fuel burn (design B). Fuel plays a dominating role in the cost calculation, as illustrated by the similarities in the designs for minimum cost and minimum fuel carried (and therefore, minimum cruise CO_2, SO_2, and H_2O). This tight coupling is also reflected in the relatively small fuel-cost trade space. (Notice that the fuel-cost Pareto front is narrow.) At the engine level, noticeably, both designs attain high fuel efficiency via large pressure ratios and high turbine inlet temperatures. Optimizing the aircraft for lowest fuel yields a 10% decrease in fuel carried (propagating through the design to yield a 5.4% decrease in maximum takeoff weight) for a cost increase of 2% relative to min-cost design A. Because block time is no longer a design driver, design B flies slower (Mach 0.74

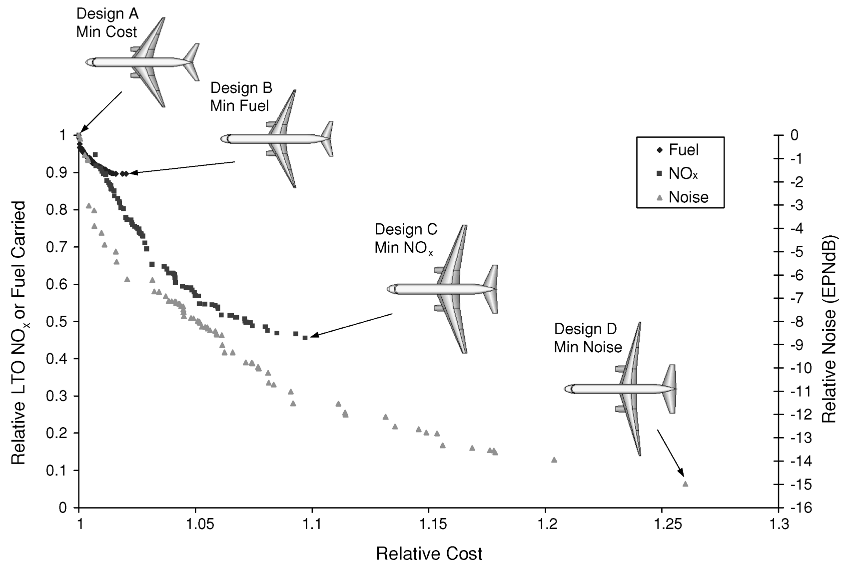

Fig. 8 Pareto fronts of fuel carried, LTO NO_x, and cumulative certification noise vs operating cost. Only rank 1 designs are shown. Average rank for all fronts is under 4.

vs 0.84) and therefore lower (30,746 vs 32,937 ft) than design A to minimize fuel burn.

The generation of NO_x emissions is a strong function of combustor exhaust temperature and compression ratio. Design C therefore compromises fuel efficiency for low NO_x emissions by reducing the engine overall pressure ratio and combustor temperature. The resulting 11% reduction in sea-level static thrust relative to the min-cost design mandates that the aircraft fly slower (Mach 0.69, close to the lower allowable limit, vs Mach 0.84) and at lower altitudes. (The initial cruise altitude is reduced from approximately 33,000 to 29,000 ft.) The result is a 54.5% drop in LTO NO_x emissions for an 10% and 9% increase in operating cost and fuel consumption, respectively.

These divergent requirements for min-NO_x and min-fuel designs are well illustrated by a wide, and very smooth, Pareto front. As a result of the lower cruise Mach number, wing sweep is reduced from 34 to 19 deg for the min-NO_x aircraft. With significantly reduced available thrust, the wing taper ratio is increased from 0.10 to 0.21 to increase the maximum lift coefficient during takeoff and initial climb. For similar reasons, the wing area is enlarged by 23%, contributing to an increase in maximum takeoff weight of 13%. Combined with lower available thrust, the climb performance of the min-NO_x design is significantly deteriorated: thrust-to-weight ratio drops to 0.290, resulting in the highest cumulative certification noise of any design, over 3.5 dB louder than the baseline design A.

The large fan necessary to reduce noise to the minimum (design D, with a bypass ratio very close to the maximum allowable value of 15) requires more power, resulting in the selection of the highest allowable combustion temperatures and overall engine pressure ratio. The result is a 15 cumulative EPNdB reduction in noise relative to the min-cost design, equivalent to a 25-fold reduction in noise energy distributed over the three certification points. The penalty is a 26% increase in operating cost and 16% in fuel carried, along with NO_x emissions that are 33% higher because of the increased combustion temperature.

In a bid to reduce noise, the sea-level static thrust is raised from 68,404 to 100,000 lb (the maximum allowable), a 46% increase. This higher thrust enables the aircraft to climb faster, increasing the distance to the flyover certification point and decreasing measured noise. These enormous, and therefore very heavy, engines cause a 27% maximum takeoff weight increase relative to design A. The large frontal area, and therefore increased drag of the design, leads the aircraft to fly slower than the min-cost candidate (Mach 0.66 vs Mach 0.83). Similarly to the min-NO_x aircraft, the reduced cruise Mach number results in a reduced sweep of 14 deg. A summary quantifying the trades between designs is shown in Table 4.

Table 4 Fuel carried, LTO NO_x, or cumulative noise can be traded with operating cost

For this increase in cost, %	Can reduce one of these by: Fuel carried, %	LTO NO_x, %	Cumulative noise, EPNdB
1	7	10	3
2	10	25	6
9	10	54	10
25	10	54	15

The importance of fuel consumption in operating costs is readily apparent when comparing the first two columns of Table 4. The trade space between these two objectives is very limited, as it is possible to reduce fuel consumption by only 10%, regardless of the increase in operating cost. It is also worthwhile to note the high cost of decreasing cumulative noise. For a 2% increase in operating cost, LTO NO_x could be reduced by as much as 25%, whereas a cumulative noise reduction of only 6 EPNdB could be attained at a similar cost. These figures illustrate the fundamental difficulties associated with noise reduction at the source and point toward the benefits of noise shielding as an alternative reduction mechanism.

Cruise Emissions vs LTO NO_x Emissions

To explore the interrelationship between the conflicting requirements of reducing NO_x and fuel-based emissions (CO_2, H_2O, and SO_2), the multiobjective optimizer was applied to the min-NO_x/min-fuel problem. The resulting Pareto front is shown in Fig. 9, with design B (min-fuel) and design C (min-NO_x) the extreme points discussed earlier.

According to these results, a decrease in LTO NO_x of 12% (as recommended by ICAO for new aircraft after 2008 under CAEP/6) would require an increase of approximately 1.5% in fuel consumption and related emissions. As the demand for reductions in NO_x increases, this penalty grows: the next 12% require a further 3.5% increase in fuel. These results illustrate the delicate tradeoff that must be resolved as new regulations come into play: What is the "value" of trading one type of emissions for another?

Noise vs Cruise vs LTO NO_x Emissions

This tradeoff approach is expanded to include a third objective, cumulative noise. The surface that is obtained and the location of the three extreme points are shown in Fig. 10. Note that all objective data are shown in quantities relative to the extreme design at which they are maximum. The conflicting design requirements for

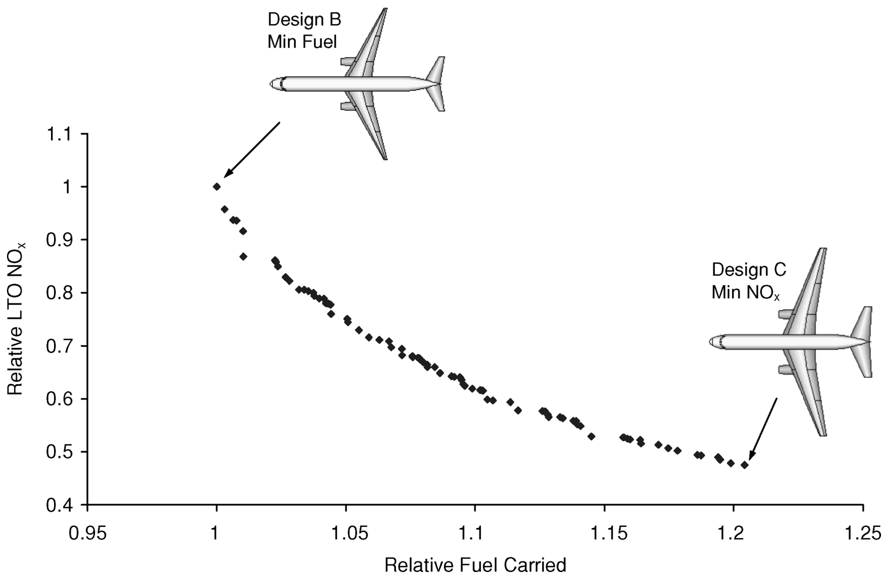

Fig. 9 Pareto front of LTO NO$_x$ vs fuel carried. Only rank 1 designs are shown (average rank = 3.47).

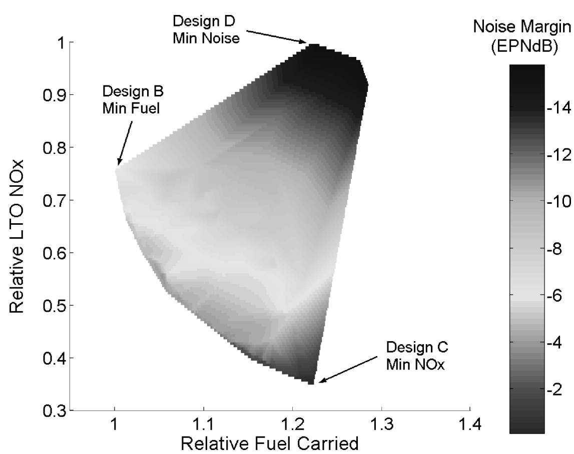

Fig. 10 Pareto surface of LTO NO$_x$ vs fuel carried vs cumulative noise. Only rank 1 designs are shown.

the min-noise (design D) and min-NO$_x$ (design C) aircraft are well illustrated here: the min-noise aircraft is the design with highest NO$_x$, and, conversely, the aircraft with lowest NO$_x$ is the noisiest. Indeed, designs D and C are costly to obtain and require almost complete deterioration of the other two objectives. The minimum fuel design (design B), however, is obtained without entirely forgoing reductions in noise or NO$_x$ emissions.

The usefulness of this Pareto surface is not limited to the extreme designs. Every design on the surface is optimized for a combination of noise, fuel, and NO$_x$ performance; the impact of reducing one objective on the two others can be estimated directly from the surface. Displaying three objectives also allows the selection of the objective to forego in order to improve the design. If the goal is to trade noise and fuel efficiency for a 20% decrease in NO$_x$, for example, a whole family of designs is applicable. Each aircraft features a different fuel and noise trade to attain the desired reduction in NO$_x$. The final decision for selecting the appropriate design lies with the user: higher-level information, such as certification or operational requirements, is required.

Cruise Altitude Study

Reducing the cruise altitude of commercial aircraft would reduce contrail formation and potentially reduce the net impact of aircraft emissions. Today's aircraft operate at 30,000–40,000 ft, the optimal altitudes considering range and cruise speed. To minimize the impact on fuel economy, the aircraft needs to be designed to operate at these altitudes. The single-objective version of the genetic algorithm was run with the initial cruise altitude fixed to 24,000 and 28,000 ft. A maximum cruise climb of 4000 ft is allowed. Data for the optimized designs are shown in Table 5. As expected, designs E and F are designed to fly slower (Mach 0.762 and 0.728 for designs E and F, respectively) to negotiate the increased drag inherent to lower altitude cruise. The overall geometry of the aircraft is shown in Fig. 11.

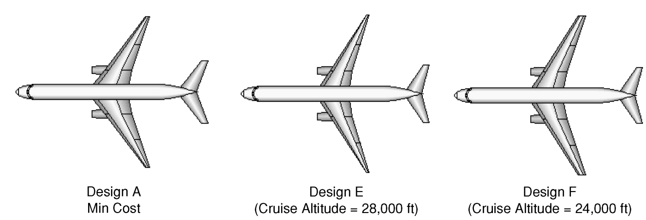

Fig. 11 Aircraft optimized for cruise altitudes of 28,000 ft (design E) and 24,000 ft (design F).

Table 5 Data for the cost-optimized designs with initial cruise altitude fixed at 28,000 ft (design E) and 24,000 ft (design F) compared to the optimized design for minimum cost (design A)

Parameter	Design A	Design E	Design F
Objectives			
Relative cost	1.00	1.04	1.07
Fuel carried, lb	119,018	112,950	127,069
LTO NO$_x$, kg	30.88	31.74	29.85
Relative noise, EPNdB	0.0	−3.87	1.85
Variables			
Max. takeoff weight, lb	372,539	357,802	374,525
Wing reference area, ft^2	3,461	2,955	3,502
Wing t/c, %	11.7	14.8	13.6
Wing location, %	39.2	40.6	39.2
Wing aspect ratio	7.38	9.39	8.15
Wing taper ratio	0.10	0.10	0.22
Wing sweep, deg	33.70	29.41	29.51
Horizontal tail area, ft^2	929	778	732
SLS thrust, lb	68,404	71,106	63,602
Turbine inlet temp., °F	3,203	3,220	3,228
Bypass ratio	9.59	9.88	9.59
Engine pressure ratio	59.91	59.61	60.00
Init. cruise altitude, ft	32,937	28,000	24,000
Final cruise altitude, ft	40,790	33,023	29,531
Cruise Mach number	0.844	0.762	0.728

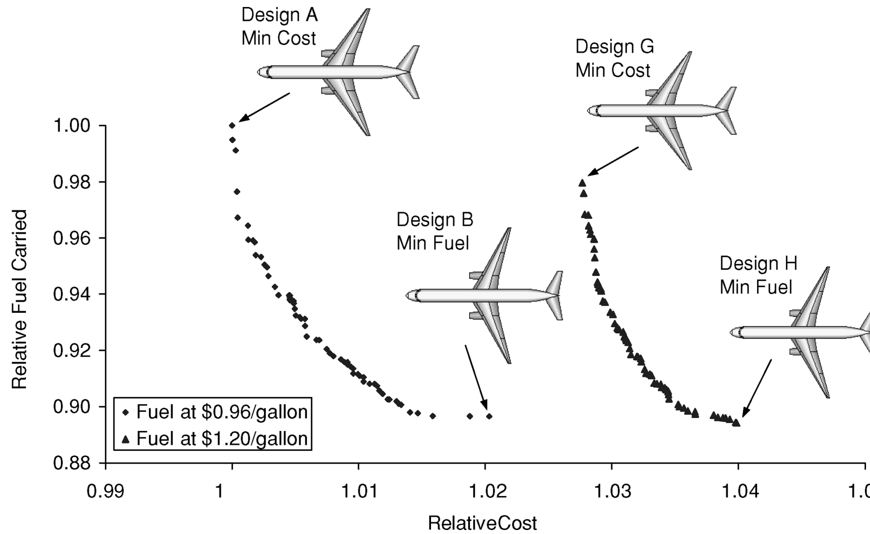

Fig. 12 Impact of increasing fuel cost by 25% is reflected on the fuel-operating cost Pareto front.

The corresponding increase in operating cost is 4% for design E and 7% for design F. The amount of fuel carried is decreased by 5% if the aircraft is designed to fly at 28,000 ft, a similar altitude to the aircraft optimized for min-fuel, design B. This cruise altitude seems to offer the best tradeoff between drag and thrust lapse, therefore minimizing the fuel requirements. On the other hand, the higher drag of operating the aircraft at a lower design altitude of 24,000 ft results in a 7% increase in fuel carried.

Changes in NO_x production are minimal: with all three designs optimized for minimal operating cost, the optimizer is driven to select high pressure ratios and combustion temperatures, regardless of cruise altitude.

The purpose of operating aircraft at lower altitudes would be to reduce the net impact of the emissions on the atmosphere. Accurately estimating these net effects requires more information than the amount of emissions generated by the engines. To truly understand the effects of the combustion products on the atmosphere, a detailed study of the propagation and absorption characteristics of the troposphere is required. This study, however, shows probable costs impacts to aircraft that might in the future have to cruise at lower altitudes when the effects of contrails are more fully understood and regulated.

Contribution of Fuel Cost to Total Cost

The impact of fuel cost on the aircraft design can be investigated using the design tool. By increasing the cost of fuel by 25%, from $0.96 per gallon to $1.20 per gallon, the Pareto front illustrating the optimal tradeoff between fuel carried and operating cost is shifted toward higher operating costs (Fig. 12).

Design B (min-fuel carried at $0.96 per gallon) and design H (min-fuel carried at $1.20 per gallon) carry an essentially identical fuel load: both are optimized for minimum fuel carried, regardless of fuel cost.

The minimum cost design with fuel at $1.20 per gallon (design G), on the other hand, carries 2% less fuel than the minimum cost design at $0.96 per gallon (design A): with increasing fuel costs, designs that carry less fuel are preferred. The decreased drag that yields this reduction in required fuel stems from the lower cruise speed (0.832 vs 0.844), which, however, causes an increase in block time and overall operating costs. Overall, the 25% increase in fuel price results in only a 3% increase in operating cost. The two min-fuel and min-cost aircraft are geometrically very similar, reflecting the relatively low importance of fuel cost as a design driver (Table 6).

Impact of Future Technologies

Increased laminar flow, greater use of composites in the aircraft structure, and reduced induced drag are three examples of advanced technologies studied with the design tool: 1) increased laminar flow—for wing sweeps under 20 deg, laminar flow extends over 60% of the chord; 2) composite structure—a factor of 0.8 is applied to the aircraft structural weight; and 3) 10% reduction in induced drag.

Table 6 Data for the optimized designs with fuel cost at $0.96 per gallon (designs A and B) and $1.20 per gallon (designs G and H)

Parameter	Design A min cost	Design B min fuel	Design G min cost	Design H min fuel
Fuel cost, $/gallon	0.96	0.96	1.20	1.20
Objectives				
Relative cost	1.0	1.02	1.03	1.04
Fuel Carried, lb	119,018	106,707	116,592	106,430
LTO NO_x, kg	30.88	29.68	30.18	28.30
Relative noise, EPNdB	0.0	−5.13	−1.49	−5.90
Variables				
Max. takeoff weight, lb	372,539	352,515	367,881	356,868
Wing reference area, ft^2	3,461	2,942	3,451	3,184
Wing t/c, %	11.7	13.5	12.7	13.7
Wing location, %	39.2	41.2	38.6	40.4
Wing aspect ratio	7.38	9.99	7.54	9.97
Wing taper ratio	0.10	0.10	0.10	0.10
Wing sweep, deg	33.70	26.17	34.59	27.31
Horizontal tail area, ft^2	929	766	882	779
SLS thrust (per engine), lb	68,404	67,311	67,791	64,732
Thrust-to-weight ratio	0.367	0.382	0.369	0.363
Turbine inlet temp., °F	3,203	3,215	3,219	3,220
Bypass ratio	9.59	10.35	10.30	10.98
Engine pressure ratio	59.91	59.63	59.91	59.79
Init. cruise altitude, ft	32,937	30,746	32,198	30,805
Final cruise altitude, ft	40,790	38,734	41,668	39,219
Cruise Mach number,	0.844	0.739	0.832	0.755

These technologies, meant to improve aerodynamic efficiency or reduce structural weight, are of interest because they also have significant impact on the environmental performance of the aircraft. Figure 13 illustrates the changes to the aircraft fuel-NO_x performance. Data for the extreme designs are summarized in Table 7. The advanced technology min-NO_x aircraft (design K) produces 34% less NO_x per LTO cycle than the conventional min-NO_x aircraft (design C), at 9% lower operating cost.

Similarly, the advanced min-fuel candidate (design J) requires 27% less fuel (and therefore produces 27% fewer fuel-proportional emissions) to complete the mission while releasing 32% fewer NO_x emissions than the conventional min-fuel aircraft (design B). Taking advantage of the drag benefits associated with increased laminar flow, the two advanced designs feature wing sweep under 20 deg, without any impact on cruise Mach number, a benefit of the thinner wing afforded by the reduced fuel capacity requirement.

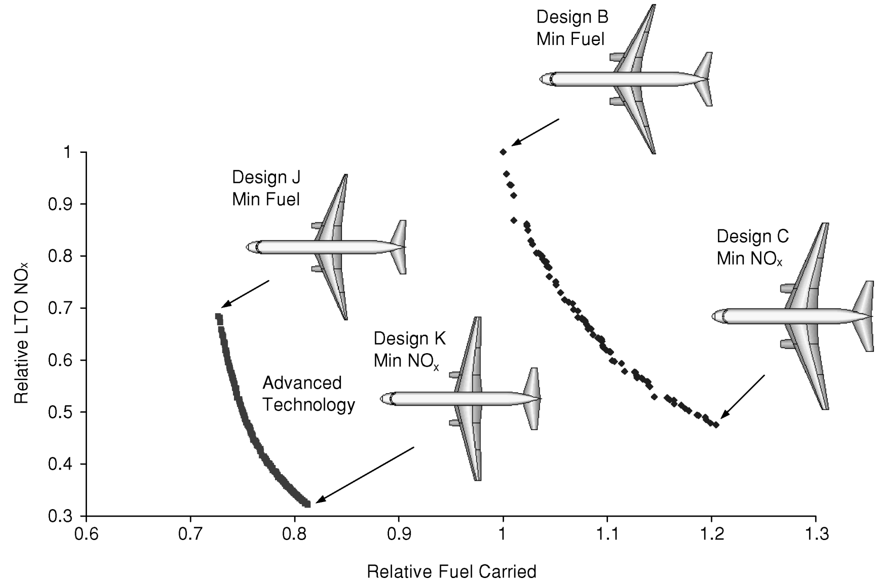

Fig. 13 Benefits of increased laminar flow, reduced induced drag, and lower structural weight are illustrated on the fuel-cost Pareto front.

Table 7 Data for optimized min-fuel and min-NO_x conventional designs B and C and advanced technology designs J and K

Parameter	Design B min fuel	Design C min NO_x	Design J min fuel	Design K min NO_x
Objectives				
Relative cost	1.02	1.09	0.96	1.00
Fuel carried, lb	106,707	134,796	78,243	87,485
LTO NO_x, kg	29.68	14.36	20.18	9.47
Relative noise, EPNdB	−5.13	3.66	−5.50	−0.80
Variables				
Max. takeoff weight, lb	352,515	407,516	304,611	333,634
Wing reference area, ft^2	2,942	3,887	3,122	3,855
Wing t/c, %	13.5	12.8	12.9	12.8
Wing location, %	41.2	48.1	41.3	44.7
Wing aspect ratio	9.99	8.94	10.00	9.96
Wing taper ratio	0.10	0.39	0.10	0.21
Wing sweep, deg	26.17	11.22	19.81	12.10
Horizontal tail area, ft^2	766	953	870	1,099
SLS thrust (per engine), lb	67,311	60,264	46,525	41,120
Thrust-to-weight ratio	0.382	0.296	0.422	0.246
Turbine inlet temp., °F	3,215	3,147	3,222	3,135
Bypass ratio	10.35	10.32	11.50	12.18
Engine pressure ratio	59.63	40.27	59.36	40.05
Init. cruise altitude, ft	30,746	28,381	32,372	30,114
Final cruise altitude, ft	38,734	33,288	40,097	38,718
Cruise Mach number	0.739	0.669	0.725	0.669

Incorporating these advanced technologies negates some of the adverse effects of optimizing the aircraft for min-noise or min-emissions. Indeed, the advanced min-NO_x aircraft (design K) generates 30% of the NO_x emissions generated by the conventional min-cost design (design A), at the same operating cost. From the reduced structural weight and fuel load (and therefore maximum takeoff weight), the two advanced designs require approximately 30% less installed thrust, resulting in a cumulative noise reduction of 5.5 EPNdB for design J and 0.8 EPNdB for design K.

One advantage of the design tool is that the Pareto front can be used to decide which objective(s) should benefit from these advanced technologies. This further illustrates the role of tradeoffs early in the design phase.

Conclusions

The objective of this research was to determine the feasibility of including environmental performance during the initial phase of aircraft design. A design tool was developed using a multidisciplinary, multiobjective genetic algorithm to quantify the tradeoffs between aircraft noise, emissions, and operating cost at the conceptual design level. In-house conceptual design tools, as well as engine and noise models available from NASA, were integrated into the optimization framework. The application of this design approach was successful in producing optimal solutions and Pareto fronts illustrating the trade space of these designs. The ability of a conceptual tool to predict the consequences of design changes, however, is heavily dependent on validation: because of the uncertainty in modeling noise and emissions, it is important that the design tool be compared to additional experimental results and existing, usually proprietary, databases.

The study established a tradeoff between noise, emissions, and cost performance. The resolution of these diverging requirements will largely depend on the environmental regulations applying to the markets served by the aircraft. Significant reductions in emissions and perceived noise were found to be possible for aircraft specifically optimized with these objectives in mind. For an increase in operating cost of 9%, NO_x emissions could be reduced by as much as 51%, whereas cumulative certification noise could be lowered by 15 EPNdB for a cost increase of 25%. With total fuel consumption as an objective, a decrease in CO_2 and other fuel-related emissions of 10% is feasible, albeit at an increase in cost of 2%. Quantifying these trades with tools similar to the one described will become essential as stricter regulations are adopted.

The relative importance of reducing one emission level over another requires significant studies into the mechanisms of the global atmosphere. Indeed, with the eventual adoption of cruise emissions restrictions, developing an appropriate metric is essential. As we have seen, simply quantifying the amount of emissions generated by the aircraft is not sufficient; the properties of the atmosphere mean that the diffusion and mixing of the emissions are crucial. Accurate models of these mechanisms near the troposphere are critical in understanding the net impact of aircraft emissions on the global atmosphere, particularly for contrails. Further enhancing the design tool by incorporating the details of the mission profile would also allow a more accurate estimate of the emissions release schedule. Finally, assessing the changes to airspace capacity caused by lower and slower aircraft would be essential. In addition to new challenges for air traffic control, integrating these new designs with potentially vastly different cruise speeds would require extensive schedule and equipment assignment changes.

As noise and emissions become ever more important design drivers, unconventional designs might offer the only viable solution to ensure commercial aviation continues its spectacular growth. In addition, unconventional aircraft might eventually offer truly ultra-quiet and clean operations, potentially revolutionizing air transport by enabling aircraft to operate closer to major cities than ever before.

The one trend that emerges from this research among the seemingly conflicting objectives of noise, fuel consumption, and NO_x emissions is the opportunity for significant reductions in environmental impact by designing the aircraft to fly slower and at lower altitude. The larger fan frontal area of min-noise designs, the reduced thrust capabilities of min-NO_x engines, and the reduced drag mandated by the min-fuel aircraft: all of these requirements point toward "slower, lower, greener."

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References

[1]Penner, J. E., *Aviation and the Global Atmosphere*, Cambridge Univ. Press, Cambridge, England, U.K., 1999, pp. 1–15.

[2]Pacull, M., "Transport Aircraft Noise Technologies," *Proceedings of the International Symposium: Which Technologies for Future Aircraft Noise Reduction?*, Association Aéronautique et Astronautique de France, Verneuil sur Seine, France, 2002.

[3]Antoine, N. E., "Aircraft Optimization for Minimal Environmental Impact," Ph.D. Dissertation, Dept. of Aeronautics and Astronautics, Stanford Univ., Stanford, CA, Sept. 2004.

[4]Sietzen, F., Jr., "New Blueprint for NASA Aeronautics," *Aerospace America*, Aug. 2002, p. 25.

[5]Erickson, J. D., "Environmental Acceptability," Office of Environment and Energy, presented to the Federal Aviation Administration, Washington, DC, 2000.

[6]Smith, M. J. T., *Aircraft Noise*, Cambridge Univ. Press, Cambridge, England, U.K., 1989.

[7]*ICAO Annex 16 Volume I—Aircraft Noise*, 3rd ed., International Civil Aviation Organization, Montreal, 1993.

[8]Gillian, R. E., *Aircraft Noise Prediction Program User's Manual*, NASA Langley Research Center, Hampton, VA, 1982.

[9]Zorumski, W. E., *Aircraft Noise Prediction Program Theoretical Manual, Parts 1 and 2*, NASA TM-83199-PT-1 and PT-2, Feb. 1982.

[10]Antoine, N. E., and Kroo, I. M., "Aircraft Optimization for Minimal Environmental Impact," *Journal of Aircraft*, Vol. 41, No. 4, 2004, pp. 790–797.

[11]Penner, J. E., *Aviation and the Global Atmosphere*, Cambridge Univ. Press, Cambridge, England, U.K., 1999, p. 6.

[12]*ICAO Annex 16 Volume II—Aircraft Engine Emissions*, 2nd ed., International Civil Aviation Organization, Montreal, 1993.

[13]Lefebvre, A., *Gas Turbine Combustion*, Taylor and Francis, Philadelphia, 1999, pp. 331–335.

[14]Penner, J. E., *Aviation and the Global Atmosphere*, Cambridge Univ. Press, Cambridge, England, U.K., 1999, pp. 76–79.

[15]Penner, J. E., *Aviation and the Global Atmosphere*, Cambridge Univ. Press, Cambridge, England, U.K., 1999, p. 257.

[16]Garrison, M., DuBois, D., and Baughcum, S., "Aircraft Emission Inventories & Scenarios," Ultra-Efficient Engine Technology Program (UEET) Technology Forum, Oct. 2003.

[17]Kroo, I. M., "An Interactive System for Aircraft Design and Optimization," AIAA Paper 92-1190, Feb. 1992.

[18]Klann, J. L., and Snyder, C. A., *NEPP User's Manual*, NASA, March 1997.

[19]"Standard Method of Estimating Comparative Direct Operating Costs of Turbine Powered Transport Airplanes," Air Transportation Association of America, Washington, DC, Dec. 1967.

[20]Schaufele, R., *The Elements of Aircraft Preliminary Design*, Aries Publixations, Santa Ana, CA, 2000, pp. 311–323.

[21]Kroo, I. M., and Manning, V. M., "Collaborative Optimization: Status and Directions," AIAA Paper 2000-4721, Sept. 2000.

[22]Goldberg, D. E., *Genetic Algorithms in Search, Optimization, and Machine Learning*, Addison Wesley Longman, Boston, 1989.

[23]Deb, K., *Multi-Objective Optimization Using Evolutionary Algorithms*, Wiley, Hoboken, NJ, 2001.

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