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MULTIOBJECTIVE AIRCRAFT DESIGN OPTIMIZATION FOR LOW NOISE AND EMISSIONS

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Abstract

Increasingly tight noise and emissions restrictions have led airlines to demand that the environmental performance of future commercial aircraft be given equal weight with traditional performance metrics, such as range and operating cost. The consequence of this requirement is that, to optimize future aircraft, environmental considerations will need to be taken into account as early as possible in the design process — a significant departure from established practice. This research explores the feasibility of integrating noise and emissions requirements at the conceptual design stage, thereby allowing a quantitative analysis of the trade-off between operating performance and environmental impact. To this end, a preliminary design tool is proposed, which uses a multiobjective genetic algorithm to determine optimal aircraft configuration and to estimate the sensitivities between the conflicting objectives of low noise, emissions, and operating costs.

1 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 need for a breakthrough is underscored by the prediction 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].

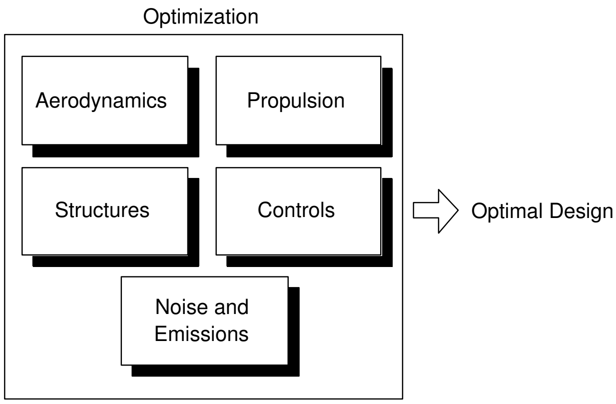

Fig. 1 Simultaneous consideration of all aspects of aircraft design can yield truly optimal designs.

There is therefore a clear need for integrating environmental considerations into the core of the aircraft design process, and for investigating more systematically the tradeoffs involved in meeting specific noise and emissions performance requirements. This research intends to contribute by proposing a conceptual design tool that generates optimized preliminary aircraft configurations based on specified mission and environmental parameters. The design space allows for simultaneous consideration of all parameters, which produces globally optimal designs (Figure 1).

The design tool also enables users, *inter alia*, to evaluate the sensitivities of optimized designs

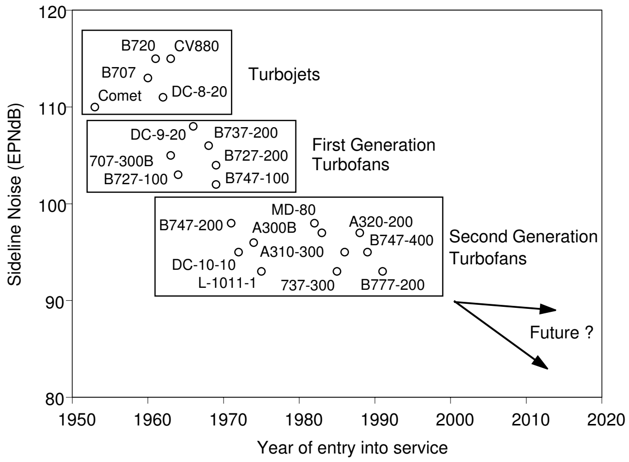

Fig. 2 The progress in noise reduction is illustrated by a select number of commercial aircraft of the past 50 years.

to variations in operating and environmental requirements, and to compare the merits of various trade cases [2, 3].

2 Noise

While considerable progress has been made to reduce the noise signature of airliners, the public's perception of noise continues to grow, as illustrated 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. As a result, noise has become a major constraint to air traffic. In the US, 60% of all airports consider noise a major problem and the fifty largest airports view it as their biggest issue [4]. A survey of the world's airports reveals a two-fold increase in the number of noise-related restrictions in the past ten years [5], including curfews, fines, operating restrictions, and quotas.

The historical trend in aircraft noise has shown a reduction of approximately 20dB since the 1960s [6] largely due to the adoption of high bypass turbofans and more effective lining materials. Reductions since the mid-eighties have not been as dramatic (Figure 2). The point seems to have been reached where future improvements through technological advances will be possible only by significantly trading off operating costs

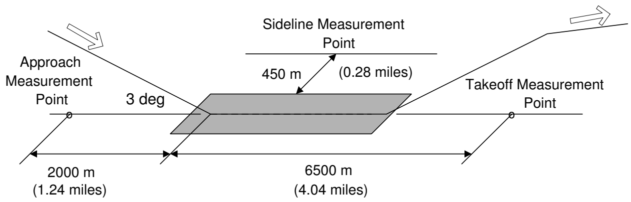

Fig. 3 ICAO certification noise measurement points.

for environmental performance. The outlook is that further reductions in the environmental impact of commercial aircraft will exact increasingly severe penalties in operating costs. Quantifying the terms of this trade-off, which will be critical for the efficient design of future aircraft, is one of the main objectives of this research.

2.1 Noise Prediction

The ICAO and FAA issue noise certifications based on measurements of approach, sideline and climb noise made at three points during the landing and takeoff cycle (LTO), as illustrated in Figure 3. 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 climb noise. On approach at low power, high bypass ratio engines are relatively quiet, making airframe noise a relevant component.

ANOPP (Aircraft NOise Prediction Program) is a semi-empirical code developed and updated continuously by NASA Langley [7]. It incorporates publicly available noise prediction schemes and models noise from a variety of sources, including fan noise [8], jet noise [9], and airframe noise [10]. 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. A propagation module is run next to determine the tone-corrected perceived noise levels as measured at the ICAO certification points, before ANOPP computes the time-averaged Effective Perceived Noise Levels (EPNL) values.

2.2 Noise Reduction

Because jet engines produce most of the takeoff 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 turbofan engines have been the single largest contributor to aircraft noise reduction.

The particular importance of bypass ratios in this respect is well known: 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. However, because of their large fans, high bypass ratio engines show large frontal areas and significant parasite drag, which increases fuel consumption. Moreover, to meet given thrust requirement at cruise conditions, they typically must be designed with excess sea-level static (SLS) thrust, which also affects fuel consumption. The consequence of the above is that increasing the bypass ratio will tend to deteriorate fuel efficiency, which impacts operating costs as well as emissions. There is therefore, a three-way tradeoff between noise, emissions and operating costs, which needs to be resolved in optimizing the design of future aircraft.

3 Emissions

The release of exhaust gasses 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 twenty years [12] 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.

3.1 Combustion

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 gasses 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 soot (C_{soot}).

3.2 Local and Cruise Emissions

ICAO regulations for the LTO cycle cover NO_x, CO, unburned hydrocarbons, and smoke emissions [13]. NO_x are the main pollutant, accounting for 80% of emissions during the cycle. For certification purposes, they are computed based on the combustor emission index (EI, expressed in g of NO_x released per kg of jet fuel used) and engine fuel flow (expressed in kg/s), itself a strong function of power setting during the LTO cycle, which involves four different throttle modes. The time spent in each mode is assumed as follows: 0.7 minutes for take off (full throttle), 2.2 minutes for climb (85% throttle), 4 minutes for approach (30% throttle), and 26 minutes 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 four modes above (expressed in kg),as shown in Equation 3.2 below.

$$NO_x = \sum \text{Fuel Flow} \times EI_{NO_x} \times \text{Time in Mode}$$

The combustor emission index EI (g of NO_x released per kg of fuel) 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 [14] (units are psia and Rankine):

$$EI_{NO_x} = 0.004194\, T_4 \left(\frac{P_3}{439}\right)^{0.37} e^{\frac{T_3-1471}{345}}$$

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. Since 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 burnt in flight. Consequently, an aircraft can be optimized for cruise emissions by introducing a fuel weight requirement at the design stage, which leads to a four-way trade off between operating cost, cruise emissions and the already discussed NO_x emissions and noise requirements.

3.3 Emissions Reduction

While improvements in combustor design hold promise for reducing the amount of NO_x or cruise emissions released into the atmosphere, these are generally conflicting requirements. Typically, changing the operating conditions or combustor configuration to reduce NO_x emissions tends to increase the quantity of CO_2 and other cruise emissions [15], and vice-versa. For instance, reducing combustion temperature and the overall pressure ratio of the engine can promote a reduction in NO_x emissions [16], but the penalty is a less complete combustion, resulting in higher fuel consumption and cruise emissions. Other technological considerations come into play as well: 'quiet' high-bypass ratio engines require that more power be extracted from the low-pressure turbine that drives their large fan, and this typically mandates higher combustion temperatures, leading to higher NO_x production. In fact, while cruise emissions (per kg of fuel consumption) have tended to decrease, total aviation NO_x emissions have increased faster than fuel consumption over the last few decades, reflecting the importance given to low noise and high fuel efficiency. The increase in NO_x production can be partially offset through detailed combustor design, but this is well beyond the scope of this research.

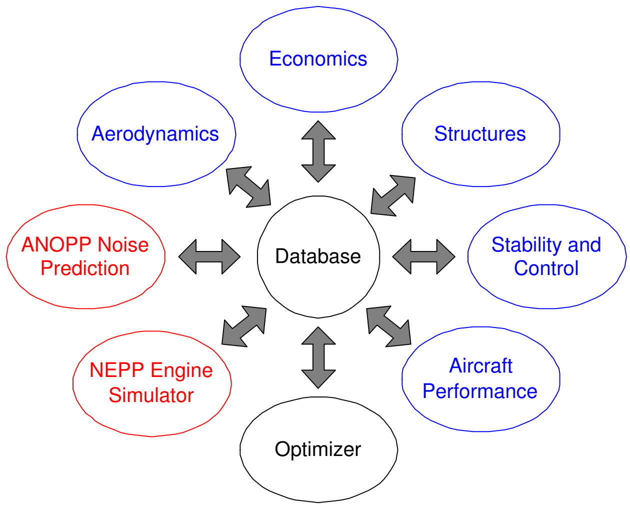

Fig. 4 The Caffé Design Framework: the PASS aircraft design modules (in blue), noise prediction, and engine simulator (in red) are coupled with an optimizer and a database manager.

4 Aircraft Design and Optimization

The design tool is structured around PASS, a program for aircraft synthesis studies [17], the ANOPP noise prediction program, NASA Glenn's NEPP (NASA Engine Performance Program) for engine simulation [18], a genetic multi-objective 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 Figure 4.

The multidisciplinary analysis of the aircraft and the optimizing of its design are performed within the Caffé design framework, in conjunction with the optimizer [21]. Caffé 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

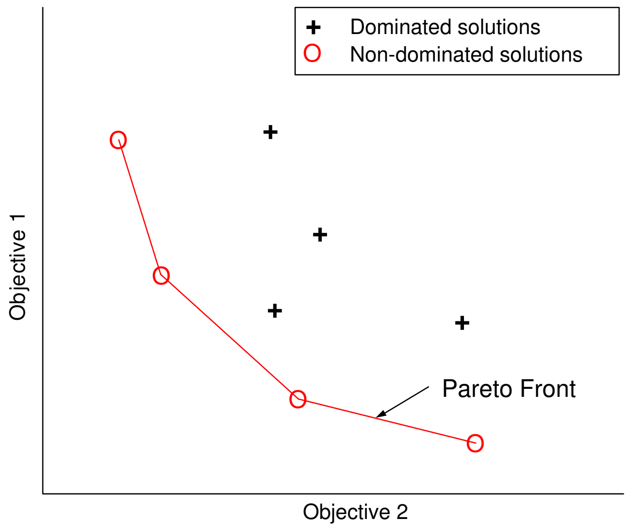

Fig. 5 An example 2-objective minimization problem showing the Pareto set.

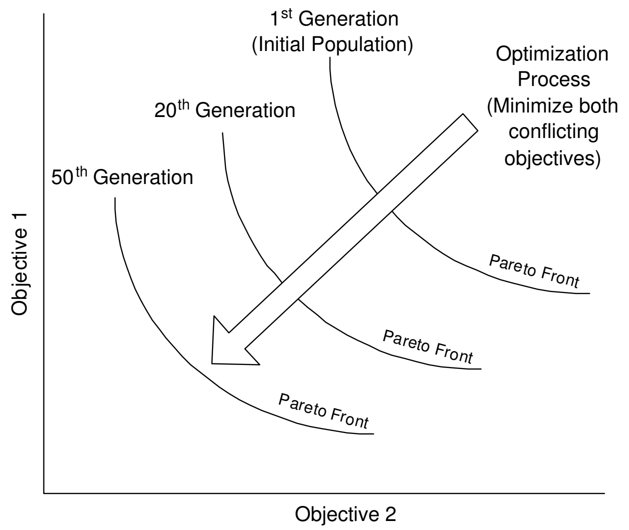

Fig. 6 The optimization process drives the population towards their optimal values.

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 may include performance parameters (for instance take-off weight, direct operating cost, or range), as well as environmental parameters (certification noise and emissions levels). The latter may 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 low cost, to ‘silent’ and ‘clean’ aircraft. Design variables typically include parameters pertaining to aircraft configuration, propulsion, and mission profile.

5 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 towards optimality through a generational process of selection and elimination. Over the course of multiple generations, increasingly optimal ‘non-dominated’ solutions (i.e. solutions which are not dominated 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 of each solution and to determine the set of non-dominated, ‘Rank 1’ solutions, known as the Pareto Set.

The concept is illustrated for a two-objective minimization problem in Figure 5. 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 trade-off 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 the population towards better solutions (Figure 6). Eventually, the quality of the population stops improving and the resulting Pareto set contains the optimal solutions.

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).

Variable	Units	Min	Max
Take-Off Weight	lbs	280,000	550,000
Wing Ref. Area	ft^2	1,500	4,000
Wing t/c	%	0.07	0.13
Wing Location	%	30	60
Wing Aspect Ratio	—	4.0	15.0
Wing Taper Ratio	—	0.05	0.7
Wing Sweep	deg	0.0	40.0
Horizontal Tail Area	ft^2	225	600
SLS Thrust	lbs	40,000	100,000
Turbine Inlet Temp.	°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

Table 1 Design variables

Constraint	Units	Value
Cruise Range	n.miles	$\leq$ 6,000
Takeoff Field Length	ft	$\leq$ 9,000
Landing Field Length	ft	$\leq$ 8,000
Engine Out Climb Gradient	—	$\geq$ 0.024
Drag-to-Thrust Ratio	—	$\leq$ 0.88
Stability Margin	—	$\geq$ 0.18
Wing Cruise C_L Margin	—	$\geq$ 0.01
Tail Rotation C_L Margin	—	$\geq$ 0.01
Tail Cruise C_L Margin	—	$\geq$ 0.01
Tail Landing C_L Margin	—	$\geq$ 0.01
Wing Span	ft	$\leq$ 260.0

Table 2 Constraints

6 Trade Studies

This section provides an example of the optimization process and trade-off investigation which can be performed with the design tool for a 280-passenger, twin-engine airliner with a 6,000 nm range, and takeoff, cruise, and landing performances in line with industry standards for similarly-sized aircraft. Four parameters are used alternatively as objective functions or constraints, depending on the purpose of the particular optimization run: relative operating cost, fuel carried (lbs) also a proxy for cruise emissions, LTO emissions (kg of NO_x) and noise (EPNdB). The other design variables and constraints are those listed in Tables 1 and 2, respectively.

6.1 Extreme Designs

Table 3 summarizes aircraft configuration for the extreme optimized designs having minimum cost (Design A), minimum fuel and cruise emissions (Design B), minimum LTO emissions (Design C) and minimum noise (Design D). The Pareto fronts shown in Figure 7 further illustrate the tradeoffs (for ease of interpretation, performance of the various designs is expressed relative to Design A).

Design A was obtained by running the design tool without specifying any noise or emissions constraint. It corresponds to the baseline aircraft optimized simply for operating cost, and is broadly representative of older existing commercial aircraft. It is worth noting that the cruise mach number of this design is higher than required for minimum fuel consumption (Design B), which reflects the importance of block time in the cost function.

Design B (minimum fuel carried) corresponds to the optimized aircraft having minimum fuel consumption and cruise emissions. Because the cost of fuel is a very large component of operating cost, this design is very similar to Design A. This tight coupling is also reflected in the narrow fuel carried vs. cost Pareto front, reflecting the small size of the fuel-cost trade space. Notably, both designs attain high fuel efficiency via large pressure ratios and high turbine inlet temperatures. Design B yields a 9% decrease in fuel carried for a cost increase of 2% relative to Design A.

In Design C, emissions during landing and takeoff are kept to an absolute minimum by reducing overall engine pressure ratio and combustor temperature. The resulting optimized design shows a large relative reduction of 53.5% in LTO NO_x, the penalty being a 13% increase in fuel cost, and an 11% increase in operating cost. Because of relatively low engine thrust, Design C flies slower, at Mach 0.65 (minimum allowable cruise speed) and at a lower altitude (initial cruise altitude of 26,000ft) than the baseline Design A. However, the wide and smooth, NO_x vs. cost Pareto Front shows that a broad range of options would be available to the aircraft designer in re-

	Units	Design A Min Cost	Design B Min Fuel	Design C Min NO_x	Design D Min Noise
Objectives					
Relative Cost	—	1.0	1.02	1.11	1.20
Fuel Carried	lbs	119,300	108,643	135,249	133,282
LTO NO_x	kg	30.72	31.07	14.28	40.45
Noise Margin	EPNdB	0.0	-3.37	3.09	-14.01
Variables					
Max. Take-Off Weight	lbs	370,680	358,451	416,037	457,527
Wing Reference Area	ft^2	3,361	2,922	4,004	3,470
Wing t/c	%	11.6	12.6	12.6	11.4
Wing Location	%	40.3	41.8	48.6	45.8
Wing Aspect Ratio	—	7.49	9.97	9.58	13.37
Wing Taper Ratio	—	0.065	0.071	0.397	0.056
Wing Sweep	deg	31.38	25.44	9.00	18.02
Horizontal Tail Area	ft^2	898	777	1,085	1,374
SLS Thrust (per engine)	lbs	68,860	70,049	60,267	99,286
Thrust-to-Weight Ratio	—	0.371	0.390	0.290	0.434
Turbine Inlet Temp	°F	3,203	3,188	3,176	3,287
Bypass Ratio	—	9.97	9.98	10.65	14.93
Engine Pressure Ratio	—	59.87	59.85	40.01	59.66
Init. Cruise Altitude	ft	32,457	31,317	26,152	28,529
Final Cruise Altitude	ft	41,375	38,457	33,693	33,842
Cruise Mach Number	—	0.826	0.751	0.651	0.680

Table 3 Objectives and variables for the optimized extreme designs.

solving the tradeoff between NO_x emissions and other performance parameters.

Design D corresponds to the minimum noise, quietest aircraft possible under the specified design parameters. Unsurprisingly, it has engines with by-pass ratios close to the maximum allowed (15) and maximum allowed combustion temperature and engine pressure ratio to generate the power needed to drive the large turbofans. The result is a 14 EPNdB cumulative noise reduction (noise margin) relative to the baseline design, equivalent to a 25-fold reduction in noise energy. The penalty is a 20% increase in operating cost and 12% in fuel carried, relative to the baseline design, along with NO_x emissions that are 32% higher. The high sea level static thrust (essentially the maximum allowable, with 99,286 lbs, a 44% increase over the baseline) is due to two phenomena. First, higher thrust is required by the high bypass-ratio engines to ensure adequate cruise altitude performance. Second, this excess thrust results in a very high thrust-to-weight ratio (0.434), allowing the engines to be operated at reduced throttle during climb, with a significant reduction in measured noise. Because of the large frontal area of the engines, Design D shows relatively high drag and flies slower than the baseline aircraft (Mach 0.68 vs. Mach 0.83). It is also considerably heavier due mainly to the weight of its large engines. The noise vs. cost Pareto Front, shown in Figure 7, quantifies the tradeoff between these two objectives It is very broad, which means that the aircraft designer would have again a large range of optimal designs to choose from in resolving the tradeoff.

A summary, quantifying the cost, noise, emissions, and fuel consumption tradeoffs discussed above, is presented in Table 4.

6.2 LTO vs. Cruise Emissions

To explore the relationship between the conflicting requirements of reducing both LTO NO_x emissions and cruise emissions, the design tool carried out an optimization run using both types of emissions as objective functions. The resulting Pareto front is shown in Figure 8. Accord-

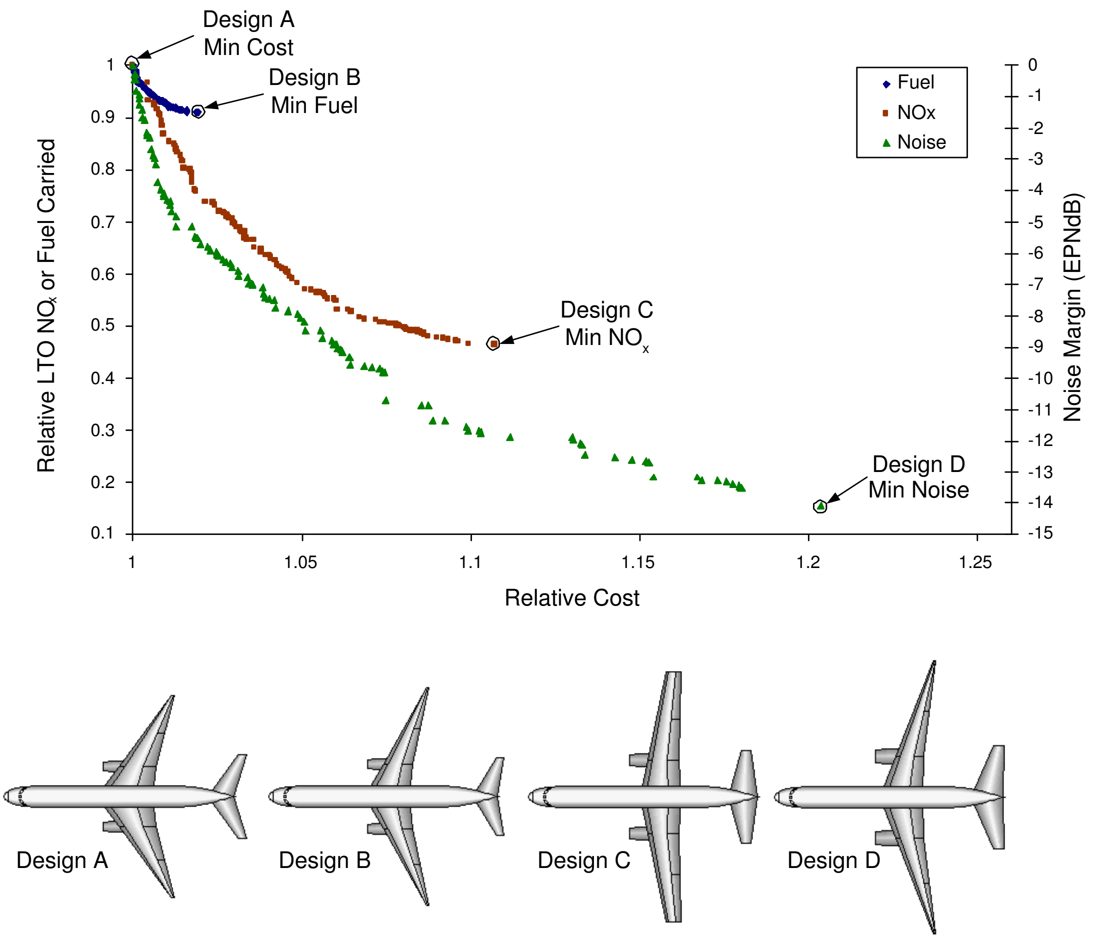

Fig. 7 Pareto fronts of fuel carried, LTO NO_x, and cumulative certification noise vs. operating cost. Only Pareto set designs are shown.

For this cost increase	Can reduce one of these by		
	Fuel	LTO NO_x	Cumul. Noise
1%	7%	10%	3 EPNdB
2%	9%	25%	6 EPNdB
10%	9%	54%	9 EPNdB
20%	9%	54%	14 EPNdB

Table 4 Fuel carried, LTO NO_x, or cumulative noise can be traded for an increase in operating cost.

ing to these results, a decrease in LTO NO_x of 12% (as recommended by ICAO for new aircraft after 2008 under CAEP/6) would cause an increase of approximately 2% in fuel consumption and cruise emissions. For larger reductions in NO_x, the penalty become heavier: a further 4% increase in cruise emissions and fuel consumption would be the price for another 12% reduction in LTO NOx. These results illustrate the delicate environmental trade-off that must be resolved as new regulations come into play: what is the "value" of trading one type of emissions for another?

6.3 Noise vs. LTO and Cruise Emissions

This trade study can be expanded further by including a third objective, such as noise performance (measured as EPNdB), into the optimization process. Figure 9 presents the corresponding results in graphic form. With the three objectives of EPNdB, LTO NO_x and fuel carried (proxy for cruise emissions), the Pareto set of optimal aircraft designs takes the form of a surface, of which every point corresponds to the optimized, rank 1 aircraft configuration for the cor-

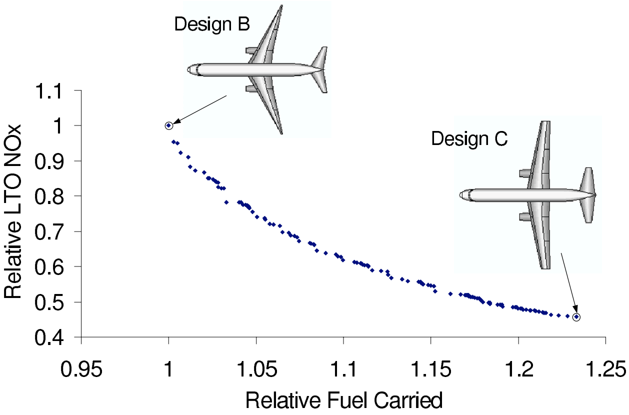

Fig. 8 Pareto front of LTO NO_x vs. fuel carried. Only Pareto set solutions are shown.

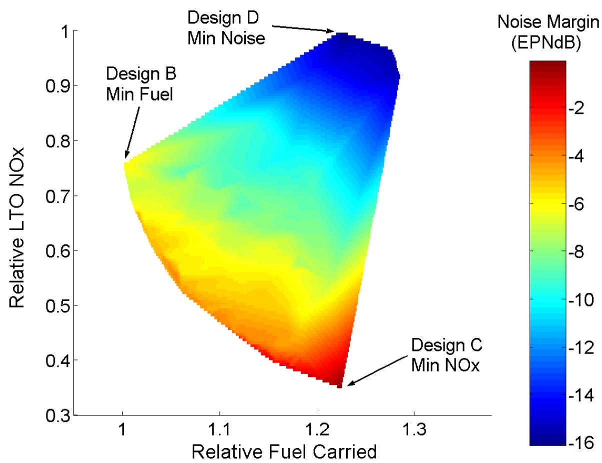

Fig. 9 Pareto surface of LTO NO_x vs. fuel carried vs. cumulative noise. Only Pareto set solutions are shown.

responding values of EPNdB, LTO NO_x and fuel carried. Because all designs on the Pareto surface are optimal, improving performance of any design against one objective inevitably leads to a deterioration in performance against one of the other objectives (or both of them). The tradeoffs can be read directly from Figure 9, which also gives the user the option of deciding which objective to forgo in order to achieve a performance improvement in a specific area. For instance, if the goal is to reduce EPNL by 6 dB, all the points located in the yellow zone of the Pareto surface correspond to optimized designs that yield the required improvement and are acceptable. Performance against the other two objectives (LTO NO_x and fuel carried) varies for each design, as can be readily read off Figure 9. As for the optimizations discussed earlier, the final decision for selecting the most appropriate design will again be based on extraneous considerations.

The extreme limits of the Pareto surface correspond to three extreme designs (labeled B, C and D) discussed earlier (Figure 7). The conflicting design requirements for minimum noise (Design D) and minimum NO_x (Design C) aircraft are well illustrated here: the low-noise aircraft is also the design with highest NO_x, and conversely, the aircraft with lowest NO_x is the noisiest. Moreover, both designs are close to the top of the range for fuel carried, which denotes poor fuel efficiency and high cruise emissions. The conclusion is that designs showing low LTO emissions or low noise are costly to obtain and lead to a steep deterioration in other performance areas. In contrast, the minimum fuel design (Design B) can be obtained with relatively modest deteriorations in noise and LTO NO_x emissions.

7 Conclusion

The objective of this research was to determine the feasibility of including environmental performance considerations at the conceptual phase of aircraft design. Noise and engine models available from NASA and the PASS aircraft design modules were used as the basis for a multidisciplinary design optimization framework. A multiobjective genetic algorithm was developed to produce optimal designs based on specific mission profiles and constraints, and to quantify the underlying tradeoffs. This approach was successful. It highlighted the tradeoffs that exist between operating and environmental performances, and also between noise and emissions. In optimizing the design of future aircraft, these tradeoffs will need to be resolved in the light of regulations imposed by governments and local communities on aircraft operation and nuisances.

Finally, it must be noted that the design tool developed for the research was based on publicly available codes and data, primarily as a research tool to help evaluate alternative preliminary aircraft designs. Extending its use to more detailed design work would require further validation of the results it yields, through comparison with experimental results and proprietary industry databases.

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