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Conceptual Optimal Design of Environmentally Friendly Airliners: A Review of Available Methodologies and their Integration into a Consistent Framework for Everyday Use

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Abstract

Airplane design involves complex system integration and must comply with a set of requirements, which are set up by certification authorities, customers, manufacturing, and that coming from market studies. From the traditional perspective of an airline, an interesting airplane is one that is capable of generating the highest revenue with minimum cost-a maximum profit airplane. In later years, however, the airline industry is swiftly broadening its consideration of what constitutes a nice-to-buy airplane. Not only economics but also environmental considerations are taking part in fleet-planning considerations-a trend spurred by environmental-aware passengers. In a move to comply with this trend, airplane conceptual design has incorporated methodologies for preliminary assessment of airplane noise and emissions. As more approaches become available to address these issues, the choice between the most suitable methodologies becomes tougher. The present work analyzes some methodologies in order to select a subset of them. The objective is the evaluation of such methodologies and their integration into a framework to airliner conceptual design. In order to test the design methodologies and the optimization techniques, the authors selected two test airplane categories: first, a long range, transcontinental jet; and a mid-size regional jet. Design tasks based on optimization with noise footprint, direct operational cost, and emission profile or a combination of them as objectives are presented and analyzed.

Keywords: Aircraft design; Multi-disciplinary design and optimization; Airplane noise; Airplane emissions; Aviation; Air transport

Nomenclature: a: Speed of sound; ANOPP: NASA's Aircraft Noise Prediction Program; AR: Aspect ratio; BPF: Blade passage frequency; BPR: By-pass ratio; CFD: Computational Fluid Dynamics; $C_{L,Max}$: Maximum lift coefficient; dB: Decibel; D: Drag; D_{FAN}: Fan diameter; DOC: Direct Operating Cost; D_p: Total emission of pollutant p in the LTO cycle; E_{Ip}: Emission's index of pollutant p; f: Function; FF: Total engine fuel flow; FPR: Fan pressure ratio; F_∞: Rated engine thrust; F(Sr): Spectral function; LFL: Landing field lengt; LRJ: Long-Range Jet; LTO: Landing-Takeoff Cycle; LW: Landing weight; M: Mach number; mac: Mean aerodynamic chord; MRJ: Mid-range Regional Jet; MTOW: Maximum Takeoff Weight; NO_X: Nitrogen Oxides; OEW: Operating empty weight; OPR: Overall Pressure Ratio; p: pressure; p_{ref}: Reference pressure; r_0: Reference distance; RoC: Rate of climb; RSS: Rotor-stator spacing; SAR: Specific range in still air; SFC: Specific fuel consumption; SPL: Sound pressure level; Sr: Strouhal number; S_W: Wing reference area; t_{mode}: Time in mode; LTO-cycle; TOFL: Takeoff field length; TOW: Takeoff weight; V_j: Engine exhauts speed; W: Actual airplane weight [N]; θ: Angle between source and receptor [deg]; r: Sweep hgjkkjjdeg].

Introduction

This work is concerned with airliner conceptual design taking into account noise and emission constraints. In this highlight, a framework for conceptual design that was developed at Instituto Tecnológico de Aeronáutica (ITA) in MATLAB® Language [1] is described and some test cases are carried out and analyzed. A brief review of airliner design evolution is presented as well in order to provide some background to the design tools under consideration.

Airplanes are highly complex machines whose design involves a series of compromises starting as early as the design phase concerned with project feasibility. Following demands from environmental-aware passengers and environmental-related taxes, airlines are pushing manufacturers to design airplanes more environmentally friendly. This pressure originated in the wake of the early jetliners, which were noisy and produced copious amounts of emissions. With the advent of the oil crisis of the early 1970's, these airplanes also became costly to operate, leading airlines to demand better products from the airplane manufacturers.

A palliative solution to the noise generated by older airplanes was the incorporation of hush kits in the wake of ICAO's Stage 3 rules. These kits are indeed a device to reduce noise produced by low-bypass turbofan engines, which are part of older commercial airplanes. Modern aircraft equipped with high-bypass turbofan engines are able to comply with modern aviation noise abatement laws and ICAO regulations. Hush kits are employed on many older freight and passenger aircraft that are still in service, such as the Boeing 727 and 737-200, Douglas DC-8 and DC-9, and Tupolev Tu-154. Hush kits are usually fitted to older aircraft, small business jets and other aircraft that are relatively small to accommodate large, high-bypass turbofan engines. The latter ones are manufactured with hush kits installed, a more economical way to meet noise restrictions than expensive engine or design changes.

The oil crisis also stroke hard one of the first Western regional jet airplanes, the VFW-Fokker 614 (Figure 1). The VFW 614 was a twin-engine jetliner designed and built in West Germany [2]. The VFW-614

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Figure 1: VFW-614 twinjet (Photo author: Eduard Marmet via Wikimedia Commons).

airliner was produced in small numbers by VFW-Fokker in the early- to mid-1970's. A first glance on Figure 1 reveals that the aircraft presented an unconventional configuration, with two untested at that time M45H turbofans, which were mounted in an overwing configuration. This arrangement was used to avoid the structural weight penalties of rear-mounted engines and the potential ingestion problems of engines mounted under the wings. This unusual configuration allowed for a shorter undercarriage and a continuous flap, enabling improved operations from short runways [2]. The jetliners from the size of the VFW-614 turbofan airplane only found a successful trajectory 20 years later, with the service entry of the Embraer ERJ-145 and the Canadair (later Bombardier) CRJ-100.

After the oil crises appeared, the aircraft industry quickly delivered higher efficient airplanes. Engineers from aircraft manufacturers, universities and research centers not only worked hard to improve operation economics, but they also turned their attention to understanding and modeling noise and emissions from aircraft. On the airplane design side, several improvements were introduced in this period: widespread use of supercritical airfoils, efficient winglets, high by-pass turbofan engines, numerical techniques for flow analysis (CFD), digital fly-by-wire systems, and multi-disciplinary design and optimization frameworks to name just a few. Interestingly, these improvements all have a common feature: they rely on a great deal of detailed information and/or computer power to be fully explored. On the environmental side of the problem, models and methodologies were developed to predict airplane noise and engine emissions. Most of the research in this field was government-sponsored and resulted in semi-empirical models, which demanded lots of calculations and were usually left as a check after the airplane conceptual design.

As computational resources improved, the imbalance between the ever-so detailed airplane design and the still largely empirical assessment of environmental performance became even more apparent. This imbalance is even more pronounced for the conceptual designer, who is frequently asked for flexible and quicker analysis of new designs.

In the next chapter, an assessment of some available airplane conceptual design methodologies is presented. A subset of them was out selected for integration into a design framework that can be easily run in a desktop computer. A survey of optimization techniques and their suitability was also performed, as it enables the conceptual designer in his daily activities to quickly produce tradeoff studies of design solutions. Once the design framework was fully integrated, it formed the backbone of airplane design teaching and research at Instituto Tecnológico de Aeronáutica (ITA).

Airplane Design

Traditional airplane conceptual design methodologies are well documented in the available literature, with books trying to cover as many subjects as possible within a limited space. When selecting a group of design methodologies for automated conceptual design or airplanes, there are two basic questions that must be answered: what subjects should be dealt with and to what level of detail each of them should treated.

The first question will be addressed from the very beginning. For an airline, profit means survival and it is the major topic of interest. Once the airfare is dictated by the market, an interesting airplane is that of minimum acquisition and operating costs, which leads to the necessity of a cost estimating module for the framework.

A large fraction of airplane operating costs comes from its fuel consumption, which is a performance measure. In order to develop a performance module, other modules are required: an aerodynamic properties module, a flight mechanics module, and a weight and balance module. These for their turn, are based on an initial geometry definition module. These are the core modules for airplane design. Improvements can be made, once the initial set is complete, to incorporate a structural layout and analysis module, which would enable a more accurate calculation of airplane weight and an assessment of aero elastic characteristics.

Once the minimum set of modules is defined, the second question may be addressed. Its answer constitutes the bulk of this work, being detailed in the next sections. An interesting aspect to consider while answering the question is on whether the methodologies are updated or not-with the increasing interest in new materials and unusual configurations for future airplanes, these methodologies are being constantly revised.

Geometry

Definition of airplane geometry is one of most important deliverables in the conceptual design phase. Usually it consists in using basic input data to determine the basic layout and dimensions of the passenger section of fuselage, fuselage nose and tail cone, wing, horizontal and vertical tails, engine nacelle and pylon. Considering the traditional approaches of Roskam [3], Torenbeek [4], and Raymer [5] and the more recent one proposed by Isikveren [6], that proposed by Roskam was considered here as it is more straight-forward. A by-product is the total wetted area, which is required for aerodynamic drag coefficient and therefore for initial weight estimation. However, thanks to the improvement in computer power, higher levels of details for geometry modeling became standard procedure in the conceptual design phase.

Conceptual design traditionally performs mission analysis, sizing, and configuration down-select of candidate designs via empirical or low-fidelity physics analyses. The geometry parameters at this stage can, in practice define the overall shape or even the outer mold-ling of the aircraft to a degree sufficient for aerodynamic and flight analyses, or for simple structural analyses such as Simple Bending/Torsion Beam Theory. But they do not have the ability to generate completely realizable (3D and closed) geometry needed to fully define the aircraft or components for high-fidelity CFD analyses, FEA analyses, or rapid-prototyping systems. To overcome such barriers Haines proposes the use of a Constructive Solid Geometry with a bottom-up approach [7] Chaitanya et al. presented an up-down approach to model aircraft

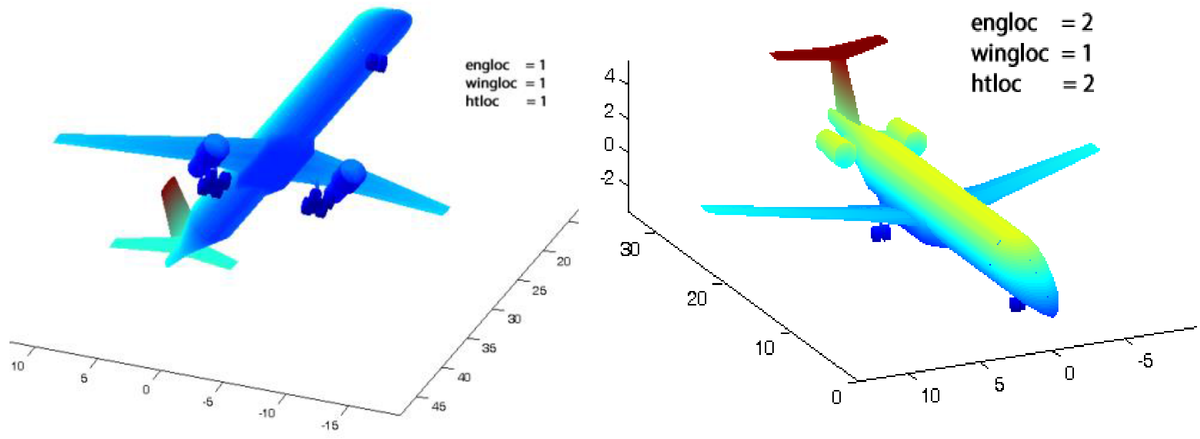

Figure 2: External surface creation.

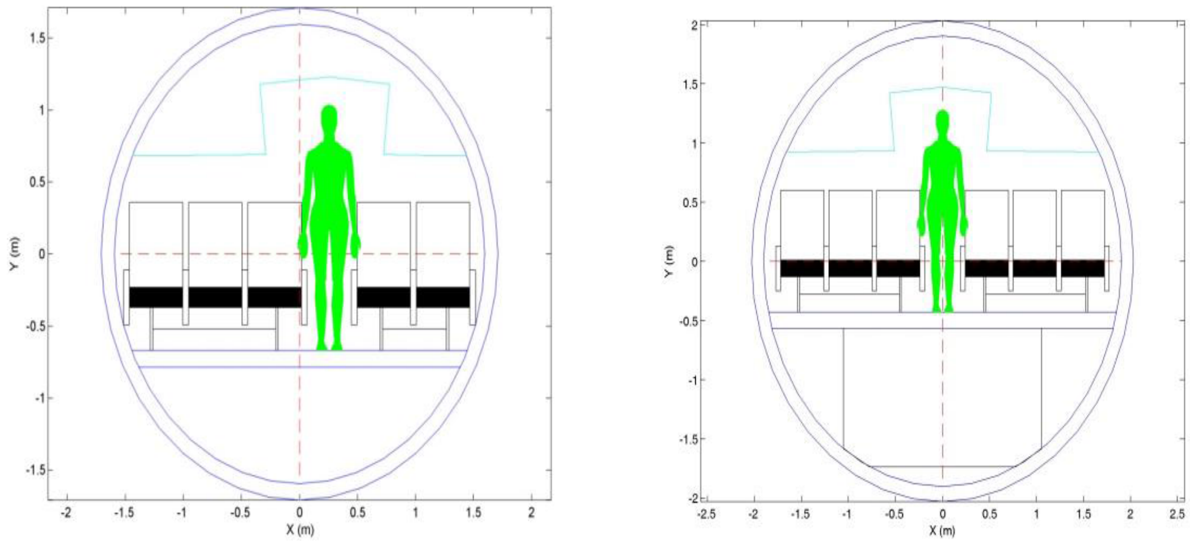

Figure 3: Cross sections created with the fuselage module.

geometries, a CAD tool designated RAPID [8]. Figures 2 and 3 show some airplane configurations and cross sections that the modeler of the present work is able to handle, respectively.

Aerodynamics

The choice of methods for aerodynamic properties calculation methods is broad: from empirical methods, through simplified theoretical methods, to complex numerical procedures (RANS, for example). A good compromise of fidelity and computer requirements was found in the numerical calculation of maximum wing lift coefficient for the clean wing using the vortex-lattice routines developed by Melin [9]. These were refined for flap and slat effects on wing maximum lift coefficient using the methodology outlined by Roskam [10]. Finally, pitch moment coefficient for airplane components are calculated was also calculated using this last methodology.

Weight, CG and inertia estimation

A good estimate of airplane weight in the conceptual design phase is crucial for the success of any automated design tool and is at the heart of any book or paper on the subject of airplane design. In this study, an iterative, combined approach is considered.

The initial estimation for the airplane dimensions is used to calculate an initial guess of airplane weight based on its wetted area, termed Class I method, following Roskam's approach [6]. This initial guess is then used for detailed estimate of airplane weight breakdown, in a Class II method. Airplane component weight estimation was based on Roskam [11] and Torenbeek [12], with some refinements from Isikveren [6] on elements that notably have undergone improvements in materials and manufacturing processes such as wings and tails. Class II estimated weights are iteratively refined until the difference between two consecutive iterations is lower than 0.5%, which then defines the weight convergence.

The information derived from Class II method is then used to estimate the position of the center of gravity and the moments of inertia of the airplane, which are required for flight mechanics analysis. This estimation follows the guidelines of Roskam [13].

Landing gear design

Landing gear layout and dimensions are not ordinarily determined in the conceptual phase. However, in order to properly estimate airframe noise, more detailed information on landing gear dimensions is required. This is obtained through the methodology proposed by Roskam [14], refined with information obtained in Currey [15]. The basic methodology consists of determining gear position (based on airplane balance on the ground from airplane attitudes and CG limit locations) and dimensions (from estimates of gear static and dynamic loads). Tire dimensions can be obtained from a table of manufacturers' standard values based on tire loads and limit speeds. The number of wheels is a design input.

Flight mechanics and handling qualities

Flight mechanics deal with the airplane stability, control and response. In order to assess these characteristics, an airplane aerodynamic model must be developed. This model consists of stability and control derivatives determined for the longitudinal and lateral-directional movements. US DATCOM is still the primary methodology with the refinements developed by Grassmeyer [16] and Leifsson [17] incorporated in the final calculation.

Airplane response to longitudinal and lateral-directional perturbations is obtained from simulations (Stevens & Lewis [18]) using the developed model. In the longitudinal movement, short period oscillations are analyzed, while in the lateral-directional movement, Dutch-roll is investigated. It is interesting to note that hardly any jet airliner meets the objective handling qualities' criteria set forth for military airplanes without the use of a yaw damper. On the other hand, designing a yaw damper during the conceptual design of an airplane requires system design information not readily available at this stage. In order to circumvent this, a mixed approach was adopted. Airplane response to Dutch-roll with no yaw-damper was simulated and compared to both the military (Hodgkinson [19]) and civil requirements (FAA [20]). A design would be considered satisfactory if it fulfills at least one of these sets of requirements.

Performance

Performance is usually a major selling point of any airplane and it usually drives airplane design (Eshelby [8]). Critical performance parameters include:

- Takeoff field length;
- Landing field length;
- Minimum required climb-out performance;
- Time to climb to cruising altitude;
- Minimum cruise altitude;
- Range;
- Fuel consumption.

For certification and operating purposes, the takeoff field length is the greater of the distances required to either accelerate and safely lift-off the ground or accelerate and come to a complete stop following the decision to reject the takeoff. Determining the takeoff field length is intrinsically the calculation of the distance required to safely accelerate the airplane through the minimum required speeds (FAA [20]): VSR, VMCA, VMCG, V1, VR, VLOFF, VMU, V2. Prior to detailed wind tunnel tests, during conceptual design phase, not all the required data is available for a detailed calculation of takeoff speeds. Although some authors have proposed simplified methods for the estimation of these speeds in recent papers, the most straight forward approach is still that of using data regressions of already certificated airplanes. The correlation proposed by (Roskam, 2005) is adopted; it takes the form of Eqn1:

$$TOFL=K_{TO}\cdot\frac{TOW^2}{S_W C_{L,Max} F_N} \qquad \text{(Eqn: 1)}$$

where K_{TO} is the regression coefficient. Despite being a very simple formulation, it adequately captures the trends in parameters change.

Similarly, landing field length (the required landing distance multiplied by a regulatory operational factor) may be calculated from data regressions on actual airplane data. An interesting approach for conceptual design is that proposed by Roskam [21], Eqn 2:

$$LFL=K_{LD}\cdot\frac{LW^2}{S_W C_{L,Max}} \qquad \text{(Eqn: 2)}$$

where K_{LD} is the regression coefficient.

The climb performance of an airplane is given by Eqn 3 (Torenbeek [12]):

$$RoC=\frac{(F_N-D)V}{W.(1+F_A)} \qquad \text{(Eqn: 3)}$$

where RoC is the rate of climb of the airplane, V is the true airspeed and FA is an acceleration correction factor that accounts for the fact that the true airspeed changes while climbing at constant calibrated airspeed. This equation is useful for calculation of minimum gradient in the takeoff climb-out, time, distance and fuel to climb and minimum cruise ceiling.

In order to calculate range and fuel consumption, instead of using the traditional, SFC-based Breguet range equation, a more practical approach is employed: the specific air range (SAR), which indicates the distance travelled on a given amount of fuel (Eshelby [22]). By setting a cruise speed schedule (max range cruise, long range cruise or cruise at a given Mach number), the integration of SAR gives the cruise range and/or the fuel consumed to fly a required distance.

Cost

Airplane costs are traditionally divided into direct operating costs (DOC) and indirect operating costs (IOC). The DOC is of utmost importance to the prospective airplane buyer because it is a good indicative of how profitable (and interesting) an airplane model can be. For DOC estimation, the method proposed by Roskam [13] was used. It consists of the determination of the following airplane costs:

- Flight-operations cost (DOC_{FLT}):
- Maintenance costs (DOC_{MAINT}):
- Depreciation costs (DOC_{DEPR}):
- Landing and navigation fees (DOC_{LNR}):
- Financing costs (DOC_{FIN}).

Total airplane DOC is then the sum of these costs, Eqn 4:

$$DOC: DOC_{FLT}+DOC_{MAINT}+DOC_{DEPR}+DOC_{LNR}+DOC_{FIN} \qquad \text{(Eqn: 4)}$$

Engine performance

In the conceptual design phase, engine performance is usually determined based on a desired thrust and an average SFC value. On the other hand, during the detailed development of the airplane, sophisticated engine models are used to predict both steady state and transient engine behavior. In this study, an intermediate approach was used.

Engine performance is largely a measure of its aerodynamic, thermodynamic and mechanical behavior. An aerothermodynamic engine model, with proper considerations on component efficiency, is a suitable tool for determining both thrust and fuel flow. This kind of model is usually set for the engine design point. With the certain assumptions, the use of component maps can be dropped and an off-design engine model can be produced in which different engine ratings and conditions can be simulated. NASA proposed a model of this kind (Benson, [23]), which was adopted here for engine performance assessment. The main design characteristics required for engine performance calculation are:

- By-pass ratio (BPR);
- Fan pressure ratio (FPR);
- Overall pressure ratio (OPR);
- Turbine inlet temperature (TIT);
- Fan diameter (D_{FAN}).

Component efficiency assumptions are made, representative of both the technology level considered (Grieb [24]) and operating characteristics (Bräunling [25]). Additionally, engine rating structure was defined in order to model the different engine operating conditions (takeoff, climb, cruise, idle), as is required for the complete performance, noise and emissions evaluation.

Airframe and Engine Noise Modeling

Modeling airplane noise prediction for conceptual design use must start at the definition of a suitability criterion from an industry perspective. Although several possible criteria unfold, the ultimate goal of an airplane is its long lasting use for passenger and cargo transport, which requires these airplanes to adhere to civil aviation certification requirements.

For type certification purposes, airplane noise must be assessed three defined conditions (FAA [26]), as shown in Figure 4:

These measurement points are defined in order to capture the effects of airplane performance (fly-over point), engine design (sideline point) and airframe characteristics (approach point) on the resulting noise signature.

Airplane noise models are usually divided into three levels of detail:

- Amplitude frequency, or level-1, models, where SPL(F): f(r, F, Θ, Π, Confg);
- Frequency correction, or level -2, models, where SPLΣ: f(r, Θ, Π, Config);
- Noise-power-distance, or level-3, models, where SPLΣ: f(r, Π, Config).

Although being the most elaborated models, type-1 models are the foundation for constructing a basic preliminary model of any aircraft type. They consist of a spectral analysis of the acoustic field around the aircraft due to the contributions of each of its noise sources. Type-1 models consider the distance from the airplane to the receiver (r), the frequency (F) and directivity (Θ) of the sound, the engine throttle setting (Π) and airplane configuration.

Type-2 models are derived by applying a frequency correction to the type-1 models based on a directivity pattern. Type-3 models, usually obtained from flight tests, consist of an integration of the noise over the acoustic field, i.e., directivity integration. It is the simplest model, being intended to enable estimations of local or regional influences of aircraft noise.

A type-1 model for predicting the complete airplane noise follows the structure defined in Eqn 5:

$$SPL_{\Sigma}(F): 10 \cdot \log_{10}[\Sigma_i 10^{0.1 \cdot SPL_i(F)}] \qquad \text{(Eqn 5)}$$

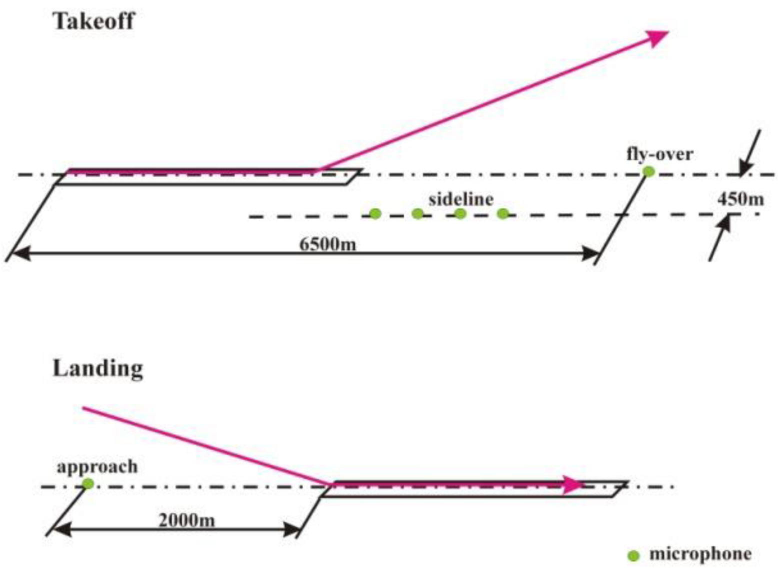

Figure 4: Noise certification points.

where SPL_i is the contribution of each noise source, structured as shown in Eqn 6:

$$SPL_i(F) = SPL(F) - \Delta SPL_\Theta - \Delta SPL_F - \Delta SPL_V - \Delta SPL_{int} - 20.\frac{r}{r_0} - \Delta SPL_{atm} + \Delta SPL_{gnd} \quad \text{(Eqn 6)}$$

where SPL(F) is the basic spectrum, which is corrected for directivity (ΔSPL_Θ), frequency shift (ΔSPL_F), relative movement of the source (ΔSPL_V), interference of sources (ΔSPL_{int}), atmospheric attenuation (20.r/r0) and absorption (ΔSPL_{atm}) and ground reflection (ΔSPL_{gnd}).

There are essentially three possibilities currently available for predicting these noise contributions: semi-empirical models, wind tunnel acoustic testing and detailed computational models.

Semi-empirical models were the first to be developed and are based on correlations of key design parameters and measured noise from airframe and engine components. Although relatively complex at the time they were developed, what made them be used as a final check on a proposed design, these methodologies are easy to implement and run fast on computers nowadays.

Wind tunnel acoustic testing, although an interesting resource is still largely expensive and time consuming for configuration definition. For the conceptual designer, it is mostly a final tuning to a design configuration before the detailed design phase.

Detailed models are based on Computational Aeroacoustics, a highly-sophisticated CFD analysis. The point here is quite simple: as airplane noise is generated essentially by pressure disturbances around the airplane, why not extending the computer models used to predict flow field properties around the airplane to predict their fluctuations? The drawback is that the analysis of a single flight condition may take hours, or even a few days, to run on computer grids. This approach does not lend itself to the estimation of noise generated during the takeoff and approach flight-paths.

Resorting to the semi-empirical models available, they usually present ways of estimating some noise metric or parameter at very limited conditions. However, there is one notable exception: the ANOPP models developed by NASA in the late 1970's. These models suit the approach of Eqn 6 because they:

- Enable the calculation of sound pressure levels at a reference distance from the source (1 m);
- Present directivity, spectral and speed corrections;
- Present a method for accounting for atmospheric absorption.

The ANOPP models are therefore chosen as the means for assessing airplane noise in this study. They are divided into engine and airframe methods, which for their turn are divided into their components' noise estimation. These methods are briefly described in the following paragraphs.

Engine noise

Engine noise is modeled in terms of the noise generated within its components: fan, compressor, combustor, turbines, nozzle and jet.

Fan and compressor noise is divided into the noise emitted forward of the engine, through the inlet duct, and that emitted through the fan discharge duct [27]. The noise emitted through the inlet duct consists of broadband noise, discrete-tone noise and combination-tone noise. The noise emitted through the fan discharge duct is essentially broadband noise and discrete-tone noise. The estimation of the noise produced by these two components is based on two key engine parameters for estimating the fan and compressor noise are the blade-passing frequency (BPF) and the rotor-stator spacing (RSS).

Engine core noise consists of the noise generated by the following sources: the combustion process, the flow around internal obstructions, scrubbing of the duct walls and entropy local fluctuations [28].

The mechanisms of noise generation for a turbine are comparable to those of a fan and a compressor and, therefore, divided into two types: discrete tone noise and broadband noise [29,30].

Jet noise originates from the shearing of layers of air at different temperatures, the hot one from the engine core and the cold one from the outside air. Modeling of the jet noise indicates that it is proportional to V8, in which V is the gas exhaust speed. Jet noise was estimated based on the methodology developed by Stone [31].

Table 1 presents the accuracy of engine component models when compared to actual engine data. A typical engine noise breakdown obtained with these component models is shown in Figure 5.

Airframe noise

Airframe noise prediction method consists of determining the sound pressure level for each airframe component: wing, flaps, slats, horizontal and vertical tail, nose and main landing gear. The method adopted here (ESDU [32]) was developed for the ANOPP by Fink in the early 1970's.

For each of the airframe components, the estimation method is based on Eqn 7:

$$SPL = 10.\log_{10}(p^2) + 10.\log_{10}\left(\frac{\rho^2 a^4}{p^2_{ref}}\right) - 20.\log_{10}\left(\frac{p_1}{p_0}\right)$$

The term p^2 is the mean-square acoustic pressure, Eqn 8:

$$p2 = \frac{p.b^2{}_w.\Theta(F,\theta).F(Sr)}{4.\pi.r^2.[1-M.\cos(\theta)]^4} \quad \text{(Eqn 8)}$$

The term $P.b_w^2$ is a function of Mach number of the form shown in Eqn 9:

$$P{\cdot}b_w{}^2{:}\ k_1{\cdot}k_3{\cdot}M^k{}_2 \quad \text{(Eqn 9)}$$

where k_1 and k_2 are constants and k_3 depends on the airframe component under consideration. Sr is the Strouhal number, which correlates flow oscillations and the sound produced at a certain frequency

Each airframe component has its own directivity function, Θ(F, Θ), and spectrum function F(Sr). Motion of the noise source is accounted for by the Doppler frequency factor, [1-M.cos(Θ)], and a source amplification factor, $[1-M.\cos(\Theta)]^4$.

A typical breakdown of airframe noise spectrum for the landing configuration is shown in Figure 6.

Component	Accuracy (dB)
Fan and Compressor	± 2.0
Combustor	± 5.0
Turbine	± 5.0
Jet	± 3.0

Table 1: Engine component model accuracy.

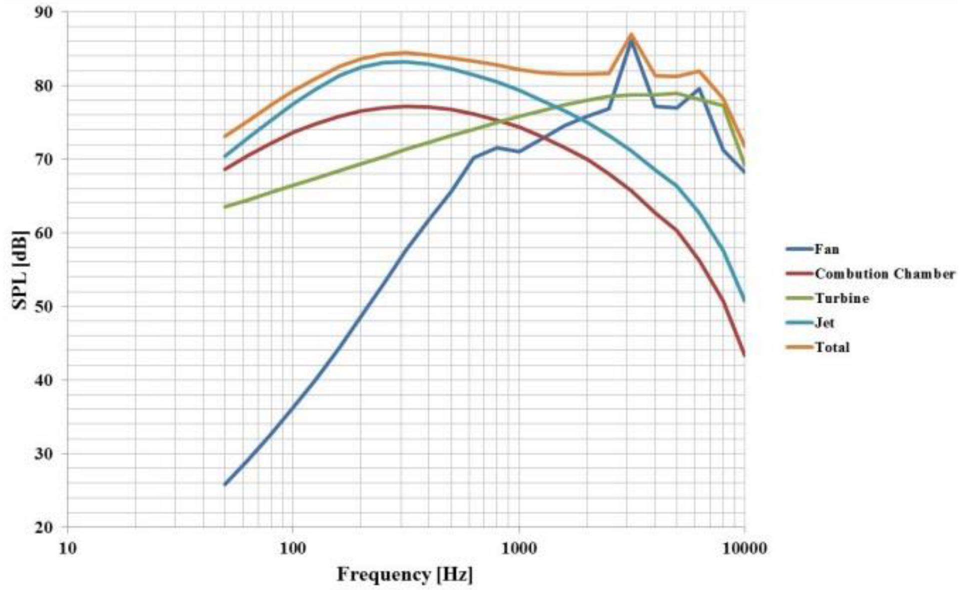

Figure 5: Typical engine noise breakdown (full throttle, θ=120 deg, 200 m, 80 m/s).

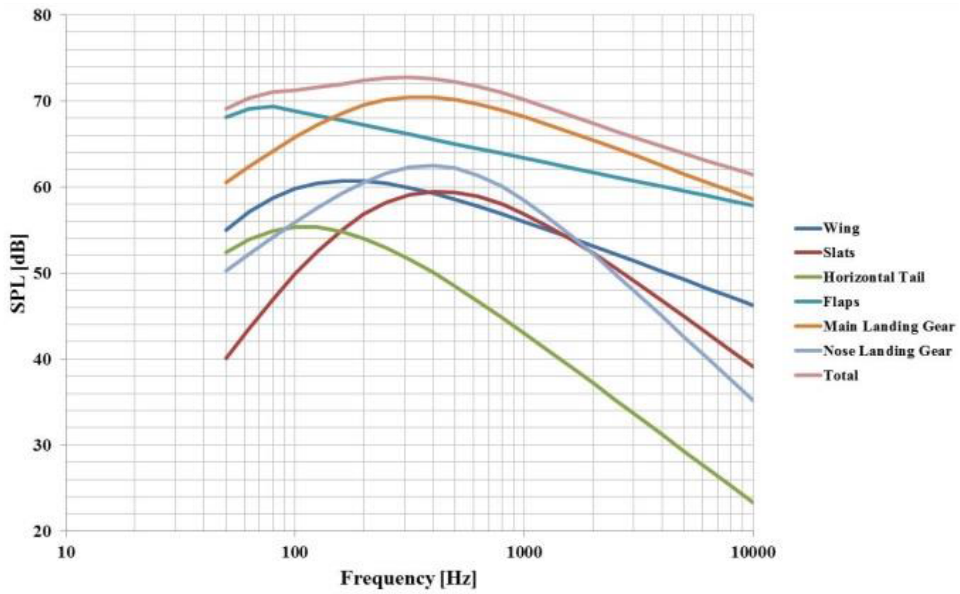

Figure 6: Typical airframe noise breakdown (θ=120 deg, 200 m, 80 m/s).

Atmospheric absorption

Atmospheric absorption is a key aspect to be considered when evaluating airplane noise. Although several models are available, the one proposed by Ruijgrok [33,34] is used here as it presents a good balance between fidelity and complexity.

The change in sound pressure level due to atmospheric absorption is determined using Eqn 10:

$$\Delta SPL_{atm} = \frac{\alpha . r}{100} \quad \text{(Eqn 10)}$$

where α is the absorption's coefficient, which is a function of air temperature and humidity.

Trajectories

The flight-paths for takeoff and approach noise assessment were derived from simple flight mechanic's considerations. The takeoff flight-path consists of an integration of airplane acceleration on the ground, followed by an integration of rate of climb data up to 3000ft above the runway. No thrust reduction (cut-back) was considered in the flight-path for simplicity. The approach flight path consists of calculating a standard-3 deg flight path approach in the landing configuration from 1500 ft down to 50 ft above the runway using RoC data.

Integrated model

The complete airplane noise model consisted of the integration of the flight-path generation functions with the engine and airframe noise estimation functions, and the atmospheric absorption function. Once the SPLs for the whole trajectories were obtained they were converted into Effective Perceived Noise Levels (EPNL) for the noise certification points (Smith [35]).

Emissions Modeling

As it was the case with noise, a practical standard is required to assess emissions modeling suitability. This standard is found in the certification procedures defined by ICAO in the annex 16 to its aviation convention [36].

Airplane emissions certification limits are defined based on the LTO-cycle shown in Figure 7. In this cycle, the engine is considered to operate for defined times at set throttle settings as per Table 2:

The total emissions during the LTO cycle for each pollutant p are given by the summation over the cycle as per equation:

$$D_p : \Sigma\,(FF \cdot EI_p \cdot t_{mode}) \qquad \text{(Eqn 11)}$$

Modelling emissions for airplane conceptual design consists of estimating the emissions index. Four different levels of modelling are usually defined: correlation (empirical), semi-empirical, multi-reactor and high-fidelity flow field models [37].

Empirical models are the simplest type of models, using correlations between recorded variations of emissions and critical engine operating parameters.

Semi-empirical models are obtained by considering the combustion chamber as a single thermochemical reactor; this model is characterized by average parameters based on engine cycle performance and experimentally gathered data on key parameters such as residence times, kinetic times and primary zone temperatures. Multi-reactor models simulate the combustion chamber by considering it as a network of thermochemical reactors; in these models, turbulent flow is sufficiently idealized so that typical rates of mixing can be prescribed parametrically and the time-dependent chemistry of pollutant formation computed exactly. Finally, high-fidelity flow-field simulations use numerical solution techniques for the governing flow equations in a domain representative of the combustor geometry; they require detailed kinetic mechanisms, large eddy simulations and complex three-dimensional geometry considerations, resulting in an intensive, complex and expensive computer use.

For preliminary airliner design, correlation models were adopted based on their good tradeoff between fidelity and computer running times. The authors conducted a survey of currently available empirical models. For fuel-burn-proportional emissions, the pollutant emissions indexes are constant as shown in Table 3:

For nitrous oxides, models usually derive from those developed by Lipfert in 1972. Several authors proposed variations on these models, usually based on total temperature and pressure at the entrance and exit of the combustor. Some models are even refined with data from the ICAO emissions database and in-company measured data. A model with a good balance between accuracy and complexity of the required data is that described by Antoine [38]. It is defined by the Eqn 12:

$$EI_{NO_x} = 4.194 . T_{t4} \cdot \left(\frac{p_{t3}}{439}\right)^{0.37} . e^{\left(\frac{T_{t3}-1471}{345}\right)} \qquad \text{(Eqn 12)}$$

where T_{t3} and T_{t4} are total temperatures at the combustor entrance and exit and P_{t3} is total pressure at its entrance.

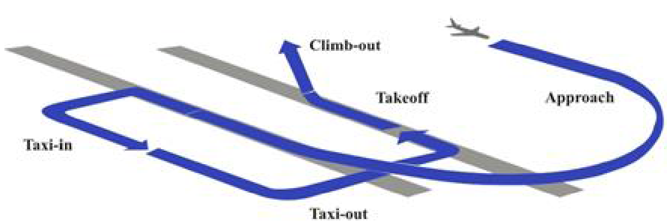

Figure 7: LTO cycle

Flight phase	Time [min]	Throttle [%F∞]
Takeoff	0.7	100
Climb	2.2	85
Approach	4.0	30
Idle / Taxi	26.0	7

Table 2: LTO cycle times and throttle settings.

Pollutant	EI [g/kg fuel]
CO_2	3155
H_2O	1240
SO_2	0.8

Table 3: Emissions indexes for fuel-burn-proportional emissions.

A few tests were run to check the suitability of the emissions modeling. Figure 8 shows the trends for emissions of a long-range airplane when engine parameters are varied:

Optimization Techniques

Design optimization addresses the issues of providing the best technical and/or economical solution to an engineering problem, i.e., one or more design performance measures are iteratively improved by better selection of design parameters [39-41]. A design optimization problem can be classified according to the number of objectives and disciplines involved as follows:

- SDSO – single discipline, single objective;
- SDMO – single discipline, multi-objective;
- MDSO – multi-discipline, single objective;
- MDMO – multi-discipline, multi-objective.

Design optimization is a current activity of any engineering branch. Several techniques and methods have been developed over the years to address this issue and they can be divided into three simple categories:

- Direct-search methods;
- Indirect search (gradient-based) methods;
- Nature inspired methods.

Choosing an optimization method for broad use in airplane conceptual design requires some analysis of the related issues. The first aspect to consider is that calculations usually rely on obtaining information from several different types of functions which may or may not be continuous and differentiable. Table interpolation is also performed routinely. Secondly, an automated design procedure may take from a few minutes to some hours to run a single case depending on the level of fidelity required for the results. Finally, the optimization method must be flexible enough to tackle both single-objective and multi-optimization problems with good converging characteristics

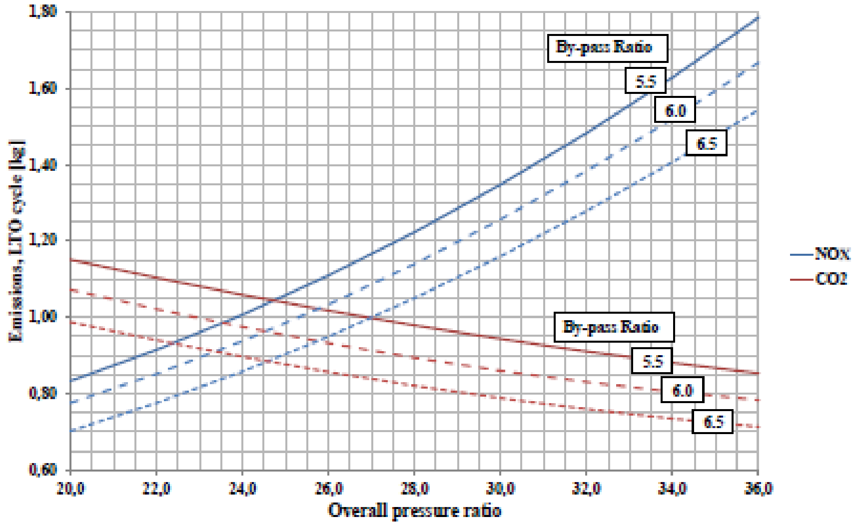

Figure 8: LTO NOX emissions as a function of engine parameters.

and without excessively increasing the computer running times. This flexibility is actually a sine qua non requirement: the designer must have not only the best solution for given design requirements and objectives but also some sensitivity analysis (like the Pareto Front) when other objectives are inserted into the optimization problem.

When all these aspects are considered, direct search and gradient-based methods are ruled out because their convergence is not guaranteed even after a large number of iterations and due to the requirement of continuously differentiable functions and derivatives.

Turning the attention to nature-inspired optimization, some methods are readily available:

• Simulated Annealing (SA);

• Particle Swarm Optimization (PSO);

• Ant Colony Optimization (ACO);

• Genetic Algorithms (GA).

These methods do not depend on function continuity and can deal with problems comprising continuous and discrete variables simultaneously.

Of all the common nature-inspired methods, the genetic algorithm easily stands out as an interesting choice due to its intrinsically vectorized approach to the optimization problem. There are already several variations of the multi-objective genetic algorithm such as:

• Vector-evaluated GA (VEGA);

• Multi-objective GA (MOGA);

• Non-dominated sorting GA (NSGA);

• Niched-Pareto GA (NPGA);

• Elitist non-dominated sorting GA (NSGA-II);

• Strength-Pareto Evolutionary Algorithm (SPEA).

Although each variation lends itself better to specific kinds of problems, an interesting compilation of comparisons was made by Deb [42]. These comparisons considered these methods for optimizing several different test functions of great complexity. The results of these comparisons consistently show the NSGA-II and the SPEA providing better convergence to the Pareto Front and better spread of solutions on the resulting front. This led to the choice of the NSGA-II as the method for the automated airplane design and optimization tool used at ITA.

Framework Validation Test Cases

In order to test the methodologies thus far compiled and described, two airliner design cases were considered:

• a long range, transcontinental jet to carry 250 passengers over a distance of 3,500nm, flying at 37,000ft and M0.80;

• a mid-range regional jet to carry 100 pax over a distance of 2000nm flying at 39,000ft and M0.80.

These designs were initially single-objective optimized for DOC, total noise and LTO NOX emissions. Then tradeoffs combining DOC and noise and DOC and NOX were performed, resulting in the corresponding Pareto fronts. Finally, a three objective optimization was performed.

For these optimizations, twenty-three design parameters were selected as input to the design process (Table 4): Optimization processes were carried out considering 300 generations with 100 individuals in the population.

Long range transcontinental jet

In the first round of optimizations, the design was optimized for DOC (LRJA), total noise (LRJB) and emissions (LRJC). Results are presented in Table 5:

Figures 9-11 show the optimized LRJ airplanes.

Figures 12-14 show the multi-objective optimization results, indicating the tradeoffs in airplane design for minimal environmental impact.

Mid-range regional jet

In the first round of optimizations, the design was optimized for

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Symbol	Description
SW	Wing area
ΓW	Wing sweep
ARW	Wing aspect ratio
λW	Wing taper ratio
TCW,tip	Wing tip thickness ratio
TCW,root	Wing root thickness ratio
εW	Wing geometric twist
CW	Wing crank position
λHT	Horizontal tail taper ratio
ARHT	Horizontal tail aspect ratio
ΓHT	Horizontal tail sweep (leading edge)
ARVT	Vertical tail aspect ratio
λVT	Vertical tail taper ratio
ΓVT	Vertical tail sweep (leading edge)
δr	Rudder maximum deflection
δf,TO	Flap deflection for takeoff
δf,LDG	Flap deflection for landing
δs,LDG	Slat deflection for landing
BPR	By-pass ratio
DFAN	Fan diameter
FPR	Fan pressure ratio
OPR	Overall pressure ratio
TIT	Turbine inlet temperature

Table 4: Airplane design parameters.

Description	Unit	LRJA	LRJB	LRJC
SW	m2	180.0	180.0	182.7
ΓW	deg	29.7	26.7	34.8
ARW	-	11.3	11.2	9.2
λW	-	0.202	0.283	0.244
TCW,tip	-	0.077	0.080	0.079
TCW,root	-	0.150	0.184	0.167
εW	deg	-1.0	-3.6	-1.2
CW	-	0.275	0.205	0.273
λHT	-	0.400	0.398	0.396
ARHT	-	6.00	5.99	5.77
ΓHT	deg	35.0	35.0	24.0
ARVT	-	1.00	2.97	2.54
λVT	-	0.201	0.400	0.295
ΓVT	deg	40.0	40.0	30.6
δr	deg	24.9	25.5	27.9
δf,TO	deg	6.4	5.4	27.6
δf,LDG	deg	25.9	32.2	20.8
δs,LDG	deg	15.9	26.9	29.2
BPR	-	6.49	6.43	5.60
DFAN	m	1.856	2.000	1.780
FPR	-	1.74	1.80	1.63
OPR	-	35.0	35.0	25.0
TIT	K	1357	1381	1362
Takeoff thrust	kN/eng	140.3	163.0	144.6
MTOW	kgf	104860	103890	106360
OEW	kgf	55455	54726	56541
Fuel for 3500 nm mission	kg	26085	25850	26507
DOC	US$/nm	18.22	18.69	19.77
Fly-over noise	EPNdB	81.0	75.0	82.5
Sideline noise	EPNdB	87.6	88.5	88.4
Approach noise	EPNdB	89.6	88.3	90.1
LTO NOx	kg	1.528	1.497	0.818

Table 5: Optimization results for the long range jet.

DOC (MRJA), total noise (MRJB) and emissions (MRJC). Results are presented in Table 6:

Figures 15-17 show the optimized MRJ airplanes.

Figures 18-19 show the multi-objective optimization results.

Conclusions

The choice of methodologies proved to be a sound and easy to run on a desktop PC. A single design case took less than two-minutes to run, whereas the multi-objective optimization ran in 7 to 10 days depending on the number of objectives.

The proper integration of the methodologies was evident in the coherence of the resulting designs. A few aspects should be noted for the noise optimized design:

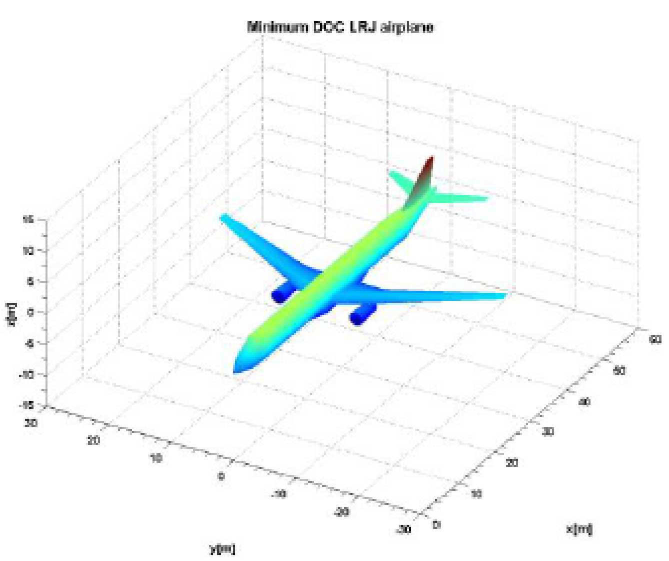

Figure 9: DOC-optimized LRJ.

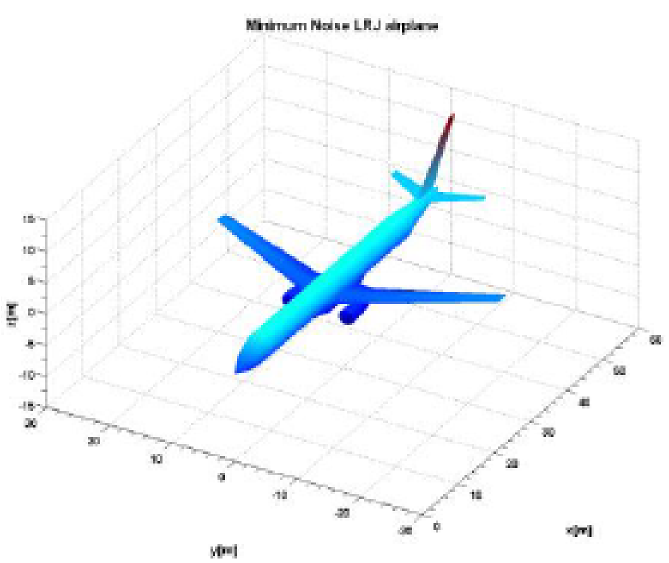

Figure 10: Noise-optimized LRJ.

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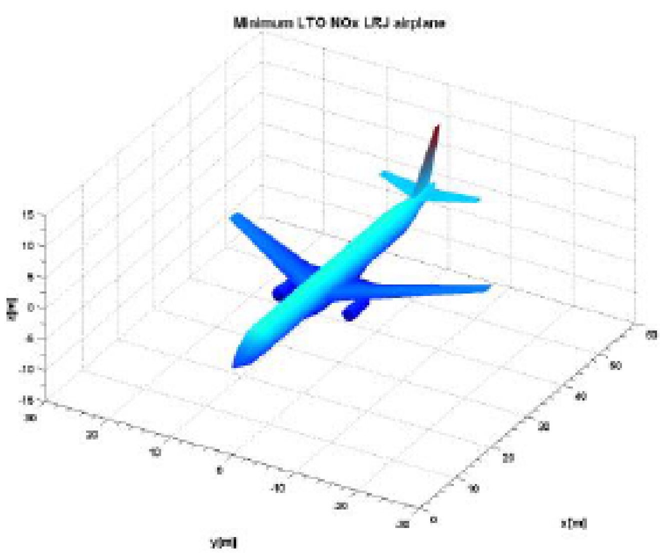

Figure 11: LTO NOX-optimized LRJ.

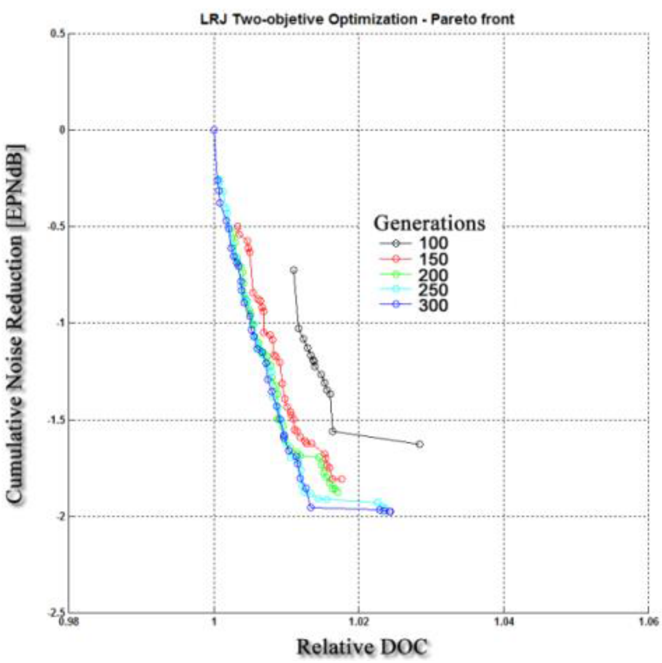

Figure 12: Noise and DOC optimization.

• Heavier empty weight;

• Heavier maximum takeoff weight;

• Larger, more powerful engines;

• Larger, less swept and more elongated wings;

• Takeoff flap setting with a smaller deflection to improve climb-out characteristics;

• Landing flap setting with a larger deflection to reduce approach speed;

• Smaller, less elongated horizontal tail;

• Larger, more elongated vertical tail, with a larger rudder deflection, to account for the higher thrust asymmetry in case of an engine failure.

The NOX-optimized design also confirmed the expected trends:

• Reduced engine size;

• Reduced overall pressure ratio;

• Reduced engine operating temperature;

• Heavier empty weight;

• Heavier takeoff weight;

• Larger, slightly more swept and less elongated wings;

• Smaller flap deflection for takeoff and landing;

• Engines placed farther from fuselage;

• Less tapered, less elongated and less swept horizontal tail;

• More tapered more elongated and less swept vertical tail.

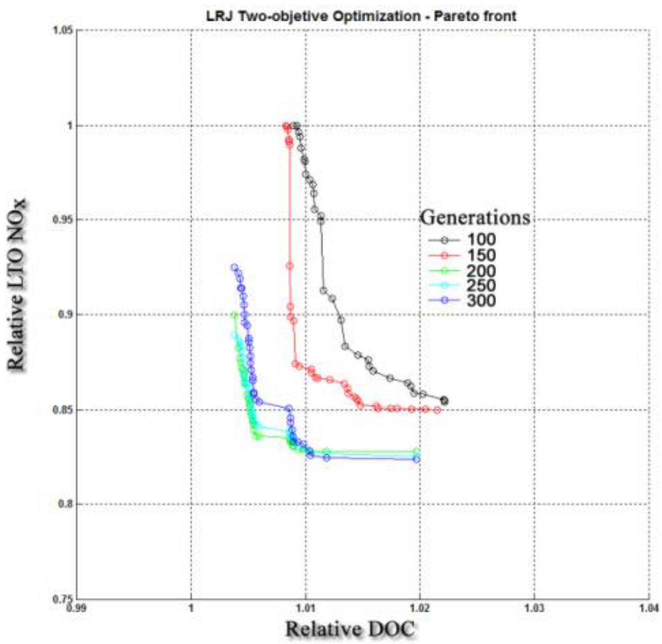

Figure 13: NOX and DOC optimization.

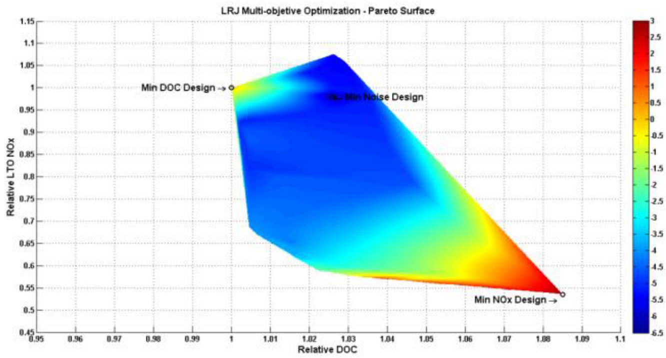

Figure 14: DOC, noise and NOX optimization.

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Description	Unit	MRJA	MRJB	MRJC
SW	m2	80.0	82.6	93.1
ΓW	deg	24.1	21.7	24.6
ARW	-	8.6	11.1	8.4
λW	-	0.203	0.278	0.281
TCW,tip	-	0.067	0.120	0.088
TCW,root	-	0.128	0.199	0.165
εW	deg	-1.0	-3.5	-2.1
CW	-	0.208	0.221	0.300
λHT	-	0.399	0.394	0.283
ARHT	-	6.00	3.35	5.41
ΓHT	deg	35.0	35.0	31.1
ARVT	-	1.02	2.62	2.68
λVT	-	0.209	0.393	0.384
ΓVT	deg	40.0	40.0	36.7
δr	deg	21.0	29.3	21.6
δf,TO	deg	19.4	5.0	10.3
δf,LDG	deg	32.7	38.1	28.6
δs,LDG	deg	21.7	25.9	18.8
BPR	-	5.49	5.50	5.04
DFAN	m	1.228	1.452	1.200
FPR	-	1.77	1.79	1.72
OPR	-	28.6	29.1	20.6
TIT	K	1357	1361	1350
Takeoff thrust	kN/eng	69.6	97.4	68.9
MTOW	kgf	37980	39122	42461
OEW	kgf	15454	16319	18812
Fuel for 2000 nm mission	kg	9426	9703	10550
DOC	US$/nm	8.89	9.83	10.16
Fly-over noise	EPNdB	71.7	68.2	75.6
Sideline noise	EPNdB	84.2	85.0	85.1
Approach noise	EPNdB	86.0	84.1	85.1
LTO NOx	kg	0.469	0.699	0.310

Table 6: Optimization results for the mid-range regional jet.

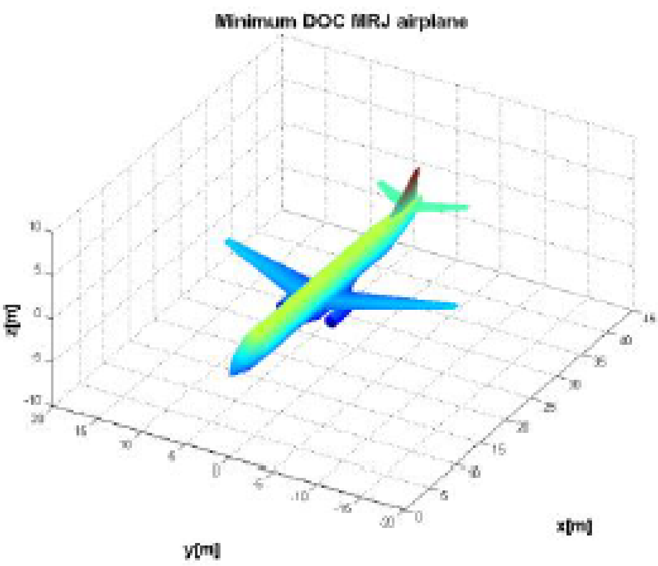

Figure 15: DOC-optimized MRJ.

The choice of optimization technique also proved sound when the results of the multi-objective problem are analyzed. They show a smooth Pareto front (or surface), with a good spread of the resulting points.

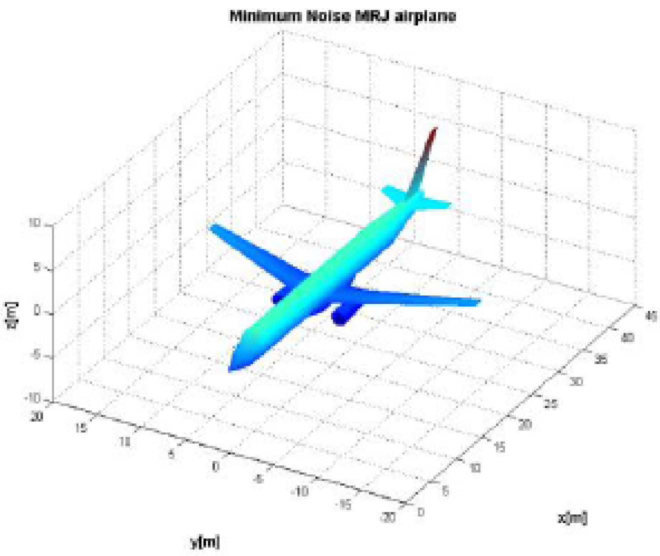

Figure 16: Noise-optimized MRJ.

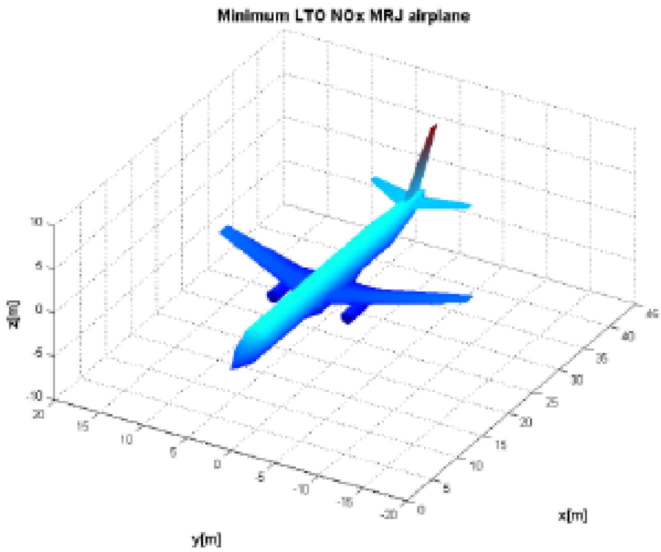

Figure 17: LTO NOX-optimized MRJ.

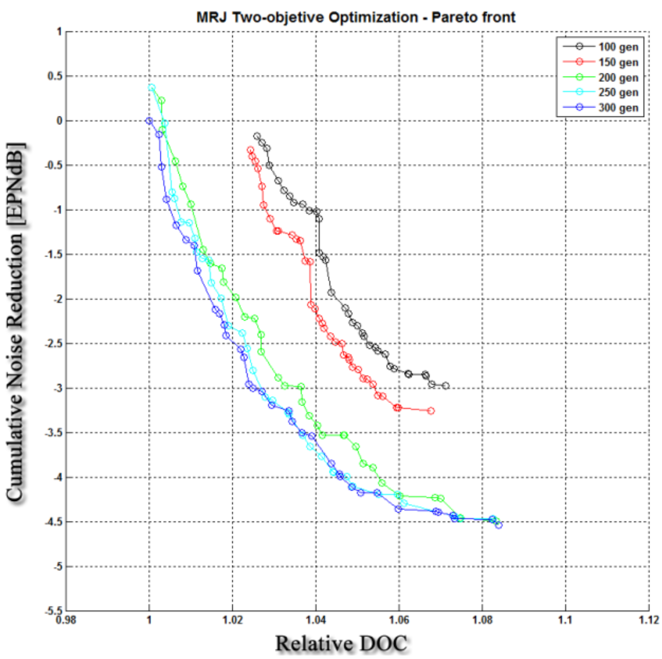

Figure 18: Noise and DOC optimization.

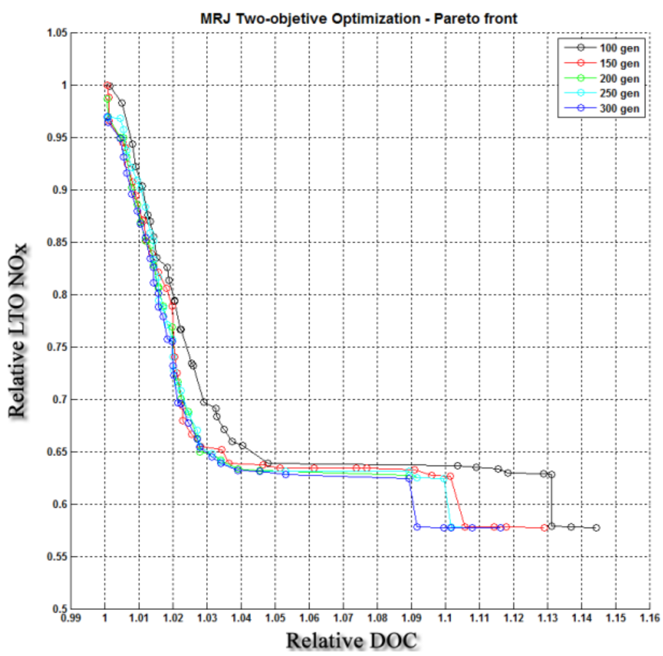

Figure 19: NOX and DOC optimization.

The design frame thus implemented produced coherent results, passing the proposed tests. It may now be used for further studies and researches. It may also be used as the basis for testing and improving new design methodologies.

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