ROMA TRE
UNIVERSITÀ DEGLI STUDI

Faculty of Engineering
Ph.D. Programme in Mechanical and Industrial Engineering

Doctoral thesis

Multidisciplinary conceptual design of eco-friendly commercial aircraft: performance and profitability

Author
Fabio Pisi Vitagliano

. . . .

Supervisor
Prof. Umberto Iemma . . . .

Ph.D. Programme Coordinator
Prof. Edoardo Bemporad . . . .

Rome, June 2016

« *To go outside the mythos is to become insane.* »

Robert M. Pirsig

Acknowledgements

This doctoral thesis deals with airplanes. And it does not.
It deals with optimization problems, environmental issues, financial considerations. And it does not.
It deals with technique. And it deals with art. Which, in the end, is the same.
It deals with people, their souls, their values.
It deals with beauty, politics, quality. It deals with life. Disguised. Like a fairy tale.
Whose moral surfaced after reading and discussing over and over.
Will beauty save the world? Only if we will be able to save beauty.
Thank you Umberto, Francesco, Valerio, Lorenzo.
Thank you Laura, Sebastian.
Thank you Robert, Matteo.
Sir Arthur Conan Doyle stated "My life is spent in one long effort to escape from the commonplaces of existence.".
I reply "My life is spent in one long effort to research for the best Pareto optimal existence".

Contents

List of Figures xi

List of Tables xv

Abstract xviii

Outline of the work xx

I Context 1

1 Introduction 3

1.1 Multi–disciplinarity . . . 3
1.2 Conceptual design, economic and environmental considerations . . . 4
1.3 Optimization problems . . . 6
1.4 Uncertainties . . . 7
1.5 Robust optimization . . . 8
1.6 Accounting Analysis . . . 11
1.7 Financial Analysis . . . 12
1.7.1 Net Present Value . . . 13
1.7.2 Internal Rate of Return . . . 13
1.7.3 Payback period . . . 14

2 The need for the airplane of the future 17

2.1 The airtraffic growth . . . 17
2.2 Global political involvement . . . 19
2.2.1 Reduction at source . . . 20
2.2.2 Land–use planning and management . . . 20

2.2.3 Noise abatement operational procedures 21
2.2.4 Operating restrictions 21
2.3 European political involvement 21
2.4 Economic implications 23
2.5 Innovative configurations 24
2.5.1 Blended–Wing–Body 24
2.5.2 Double bubble plane 25
2.6 Infrastructural impacts 26
2.6.1 Airport capacity 26
2.6.2 Ground operations issues 27
2.6.3 Airport facilities issues 28

II The multi–disciplinary problem **31**

3 The problem definition **33**
3.1 One–airplane analysis 33
3.1.1 Economies of density 33
3.1.2 Economies of capacity utilization 34
3.1.3 Economies of scope 34
3.1.4 Economies of scale 34
3.2 A multi–disciplinary approach 35
3.2.1 The social impact 35
3.2.2 The financial implications 37
3.3 The innovative configurations repercussions on infrastructures 40

4 The problem formulation **49**
4.1 The economic model 49
4.1.1 The accounting model 50
4.1.2 The financial model 53
4.2 Optimization problems 53
4.2.1 The accounting approach 54
4.2.2 The financial approach 56
4.2.3 The financial–environmental approach 64
4.3 The robust optimization problem 74
4.4 Conclusions and future developments 82

III Appendices **87**

A FRIDA **89**

Bibliography **95**

List of Figures

1.1 Balance among environment, aircraft, community acceptance and economic implications in a multi–disciplinary approach. 5
1.2 Multi–objective optimization problems: infeasible region, dominated solutions, utopia point and Pareto front. 7

2.1 Aircraft sideline noise level. 20
2.2 ACARE 2020 Goals [9]. 23
2.3 Blended–wing–body concept. 25
2.4 Double bubble concept [4]. 25

3.1 Ecojet Easyjet open rotor–powered aircraft [34]. 38
3.2 Airline operational costs breakdown. 39

4.1 Single–objective optimization problem convergence - objective function: annual costs. 55
4.2 Single–objective optimization problem convergence - objective function: aircraft price. 55
4.3 Multi–objective optimization solutions and Pareto front - objective functions: mean SEL, fuel burn. 56
4.4 Multi-objective optimization solutions and Pareto front - objective functions: aircraft price, annual costs. 57
4.5 Optimal configurations against the reference wing: minimum annual costs (A), average SEL and fuel burn compromise solution (B), A/C price and annual costs compromise solution (C). 58
4.6 Mission characteristics as a function of the flight duration for the financial approached problem. 59

4.7 Multi–objective optimization aimed to minimize the acquisition price P_{AC} and the annual negative cash flows $NCFs$: normalized solutions (with respect to PSO algorithm first feasible generation) and Pareto front evolution obtained with the PSO and the NSGA-II algorithms. . 60
4.8 Multi–objective optimization aimed to minimize the acquisition price P_{AC} and the annual negative cash flows $NCFs$: Pareto optimal solutions (the generic Pareto optimal solution, shown by the arrow, is the closest to the utopia point) obtained with the PSO and the NSGA-II algorithms. 61
4.9 Multi–objective optimization aimed to minimize the acquisition price P_{AC} and the annual negative cash flows $NCFs$: optimal wing systems. 62
4.10 Multi–objective optimization aimed to minimize the noise level ANE and the fuel consumption W_f: normalized solutions (with respect to PSO algorithm first feasible generation) and Pareto front evolution obtained with the PSO and the NSGA-II algorithms. 63
4.11 Multi–objective optimization aimed to minimize the average noise level ANE and the fuel consumption W_f: Pareto optimal solutions (the generic Pareto optimal solution, shown by the arrow, is the closest to the utopia point) obtained with the PSO and the NSGA-II algorithms. 64
4.12 Multi–objective optimization aimed to minimize the noise level ANE and the fuel consumption W_f: optimal wing systems. 65
4.13 Comparison of performance solutions to financial solutions. 66
4.14 Mission characteristics: geometric altitude h_g and kinematic altitude $h_k = v^2/2g$ as a function of the flight duration for the financial–environmental approached problem. 67
4.15 Mission characteristics: true airspeed v_t and vertical velocity $v_v = v_t sin\gamma$, with γ the ramp angle, as a function of the flight duration for the financial–environmental approached problem. 68
4.16 Feasible solutions (normalized with regard to the values related to a comparable currently flying aircraft) of multi–objective optimization aimed to minimize the acoustic emissions ANE and the fuel consumption W_f. 69
4.17 Pareto front of multi–objective optimization aimed to minimize the acoustic emissions ANE and the fuel consumption W_f. 70
4.18 Feasible solutions (normalized with regard to the values related to a comparable currently flying aircraft) of multi–objective optimization aimed to maximize NPV and minimize fuel consumption W_f. 71
4.19 Pareto front of multi–objective optimization aimed to maximize NPV and minimize fuel consumption W_f. 71
4.20 Feasible solutions (normalized with regard to the values related to a comparable currently flying aircraft) of multi–objective optimization aimed to maximize NPV and minimize acoustic emissions ANE. . . 72

4.21 Pareto front of multi–objective optimization aimed to maximize NPV and minimize acoustic emissions ANE. 72
4.22 Feasible solutions (normalized with regard to the values related to a comparable currently flying aircraft) of multi–objective optimization aimed to maximize NPV and minimize both acoustic emissions ANE and fuel consumption W_f. 73
4.23 Pareto front of multi–objective optimization aimed to maximize NPV and minimize both the acoustic emissions ANE and fuel consumption W_f. 74
4.24 Aircraft path and noise certification points (takeoff–flyover and takeoff–sideline) related to the takeoff procedure. 76
4.25 Aircraft path and noise certification point related to the approach procedure. 76
4.26 Feasible solutions, normalized with regard to a reference configuration, of the robust optimization aimed to maximize the expectation of the Net Present value (NPV) and minimize its standard deviation with regard to the cruise Mach number M_{cr}. 78
4.27 Pareto solutions (mapped) of the robust optimization aimed to maximize the expectation of the Net Present value (NPV) and minimize its standard deviation with respect to the cruise Mach number M_{cr}; the minimum average noise ANE solution is shown by the arrow. . . 79
4.28 Optimal design variables related to the robust optimization problem aimed to maximize the Net Present Value NPV with uncertain cruise Mach number M_{cr}: maximum expected value $E\left[NPV(\mathbf{x},\mathbf{y})\right]$, minimum standard deviation $\sigma\left[NPV(\mathbf{x},\mathbf{y})\right]$, and mininum average noise exposure ANE. 80
4.29 Feasible solutions, normalized with regard to a refernce configuration, of the robust optimization aimed to maximize the expectation of the Net Present value (NPV) and minimize its standard deviation with respect to the inflation rate I_r. 81
4.30 Mapped Pareto solutions of the robust optimization aimed to maximize the expectation of the Net Present value (NPV) and minimize its standard deviation with respect to the inflation rate I_r; the minimum average noise ANE solution is shown by the arrow. 82
4.31 Confidence interval for each solution of Pareto front of the robust optimization, normalized with regard to a refernce configuration, aimed to maximize the expectation of the Net Present value (NPV) and minimize its standard deviation with respect to the inflation rate I_r. 82
4.32 Optimal design variables related to the robust optimization problem aimed to maximize the Net Present Value NPV with uncertain inflation rate I_r: maximum expected value $E\left[NPV(\mathbf{x},\mathbf{y})\right]$, minimum standard deviation $\sigma\left[NPV(\mathbf{x},\mathbf{y})\right]$, and min average noise exposure ANE. 83

A.1 The FRamework for Innovative Design in Aeronautics integrated with models for the economic evaluations estimate: highlighted key modules for optimization campaign of this work. 90

List of Tables

2.1 Aerodrome reference codes. 27
2.2 Minimum runway width for each aerodrome reference code. 27
2.3 Taxiway features. 28
2.4 Apron clearance for each aerodrome reference code. 29
2.5 Aprons classification. 29

3.1 Property and liability rules. 37
3.2 Traditional and innovative configuration airplanes features. 40
3.3 Runways global statistical analysis. 41
3.4 The innovative configurations repercussions on infrastructures. 42
3.5 Analysis of European airports runways size, differentiated for long–haul (L–H) and short–haul (S–H) routes. 43
3.6 Analysis of Asian airports runways size, differentiated for long–haul (L–H) and short–haul (S–H) routes. 44
3.7 Analysis of Oceanian airports runways size, differentiated for long–haul (L–H) and short–haul (S–H) routes. 45
3.8 Analysis of African airports runways size, differentiated for long–haul (L–H) and short–haul (S–H) routes. 46
3.9 Analysis of American airports runways size, differentiated for long–haul (L–H) and short–haul (S–H) routes. 47

4.1 Design variables related to the 164–pax aircraft for the accounting approached problem: reference value, lower bound and upper bound. 54
4.2 Design variables related to the 164–pax aircraft for the financial approached problem: reference value, lower bound and upper bound. . 57
4.3 Results of the optimization analysis aimed at the minimization of the aircraft price P_{AC} and the negative cash flows $NCFs$. 60

4.4 Results of the optimization analysis aimed at the minimization of the average noise level ANE and the fuel consumed W_f. 63
4.5 Optimization problems performed. 66
4.6 Design variables related to the 164–pax aircraft for the financial–environmental approached problem: reference values, lower bounds and upper bounds. 67
4.7 Design variables related to the 164–pax aircraft for the robust optimization problem: reference value, lower bound and upper bound. . . 75
4.8 Optimal design variables related to the robust optimization problem aimed to maximize the Net Present Value NPV with uncertain cruise Mach number M_{cr}: maximum expected value $E\left[NPV(\mathbf{x},\mathbf{y})\right]$, minimum standard deviation $\sigma\left[NPV(\mathbf{x},\mathbf{y})\right]$ and minimum average noise exposure ANE. 79
4.9 Optimal design variables related to the robust optimization problem aimed to maximize the Net Present Value NPV with uncertain inflation rate I_r: maximum expected value $E\left[NPV(\mathbf{x},\mathbf{y})\right]$, minimum standard deviation $\sigma\left[NPV(\mathbf{x},\mathbf{y})\right]$ and minimum average noise exposure ANE). 81

Abstract

This work deals with the conceptual design of environment–friendly airplanes with a focus on both economic, technical and environmental considerations. The ultimate goal of the research is the assessment of the long–term financial implications induced by the highly–innovative, unconventional concepts expected to be introduced in the near future to cope with the environment challenge. Specifically, the present work aims at the identification of a design strategy suitable to ensure the sustainable development of the civil aviation avoiding unaffordable financial penalization for the stakeholders involved.

The main novelty is the analysis of social cost noise fees effectiveness combined with the extension of the economic models embracing a wider group of stakeholders' interests.

The environment challenge and the expected growth of both the market demand and urban areas nearby airport facilities impose a technology breakthrough within the aeronautical industry. Although several innovative configurations of airplanes have been analyzed, none of them has been yet chosen as the most promising candidate and one of the reasons is related to the not yet known economic impacts of these architectures. Negative externalities related to air traffic emissions play a more critical role and their translation into a fair economic value is needed to move forward along a sustainable development. The analysis has been performed within a comprehensive multi–disciplinary framework, adopting all the technical constraints required in aeronautical design. The problem has been explored from a single–airplane approach considering the impact of density, capacity utilization, scope and scale economies and formalized through a multi–objective optimization approach.

Furthermore, most of the innovative solutions under analysis present unconventional characteristics, which involve in the long–run a high level of technical and financial uncertainties, whose quantification and management are key enabling factors for a realistic estimate of new solutions commercial attractiveness.

The comparisons of the Pareto fronts obtained through performance, accounting and financial simulations, show that the model proposed yields highly–efficient, technically sound concepts and they also highlight the need for appropriate noise fees as an instrument to push all the stakeholders towards a radical renewal of the technologies. They therefore encourage the aeronautical industry towards a clear shared strategy in the development of the next generation of innovative eco–friendly configurations.

Outline of the work

The current work begins with an overview of the main concepts (see Chapt. 1) explored throughout the thesis, ranging from multi–disciplinarity to profitability, through optimization and uncertainties. Chapt. 2 deals with the need for this exploration, analysing the trend of the aeronautics industry, political and economic implications in addition to innovative configurations and their impacts. Furthermore, in Chapt. 3, the work defines the multi–disciplinary problem with a specific focus on the social impacts, their financial implications and the repercussions on infrastructures. Finally Chapt. 4 formulates the problem enriching the classic conceptual design with accounting and financial models which are used in several deterministic and stochastic optimization campaigns to identify most suitable configurations.

Part I

Context

CHAPTER 1

Introduction

This chapter explores and describes the main concepts developed throughout the work. A multi–disciplinarity approach is a viable solutions to integrate technical and human topics with the goal of using technology to make our lives more fulfilling. This approach is applied in the conceptual design phase of aircraft which is described with a focus on economic and environmental considerations. Optimization problems are at the basis of conceptual design and they are mathematically described both from a deterministic and stochastic perspective. The latter includes in the analysis the concept of uncertainties and their management. Uncertainties can affect both the variables determined by the designer, and the parameters which are not under its control and the system outputs. As mentioned, traditional conceptual design has been enriched with economic model and here accounting and financial indicators have been described and compared.

1.1 Multi–disciplinarity

The term technic derives from the Greek word $\tau\varepsilon\chi\nu\eta$ (techné). It means art. It also means craftsmanship. For, in the past, there was no split between conceiving and crafting. They were two sides of the same coin [41]. In Latin, the term *technicus* has the same trait. Then, throughout history, art and technic split apart, into a dichotomy still alive. Technic is often linked to work. Also art must be related again to work, in a fusion of the classic, rational, systemic beauty with the romantic, pre-intellectual, instantaneous one. One may argue that the cause of this separation is due to technology. Technology derives from techné and logos and it should deal with the artistic description of an object, however favouring technology against artistic composition, turned technology itself into a mere exhibitionism. Peter Drucker observed that the hardest problems in applying technology are not technical but human ones [50]. In a technological era then, we need to understand what can make our lives more fulfilling in order to use technology to achieve this goal. This way, we could witness the desired reconciliation of classic and romantic beauty. With this purpose, it is therefore essential to approach engineering problems from a multi–disciplinary perspective considering both technical and human issues.

The integration of simulation models from different disciplines is, since long, one of the fields where the challenge to develop tools for analysis and design of the next generation is played. Not surprisingly, “multi–disciplinary”, “integrated modelling” and “optimization” are expressions now part of the common vocabulary, even non–technical ones, to indicate essential features in any long–term planning and development process of complex systems. The need to integrate models and experiences from different disciplines is directly proportional to the interactions tree complexity and depth among components of the system under analysis. This need unavoidably limits the approach, if one wants to ensure the design solution optimality in a wide context. However, the meaning of these expressions has evolved, in response to the evolution of the engineering problems complexity. With this perspective, the solution of a problem is not identifiable through subsequent “mono–disciplinary” analyses, but it has to be sought in the multi–disciplinary and simultaneous balance of all models involved in the analysis. In other words, the solution of a problem must be consistent with all concerned disciplines in order to define “the” most valuable global solution. It is then critical that the multi–disciplinary problem definition embraces features which enhances our life quality.

1.2 Conceptual design, economic and environmental considerations

Sustainable technological development planning and environmental impact is one of the topics where the previous considerations acquire a wide relevance. In this context, the skills needed to face a design process normally belong to disciplines that range across the whole classical knowledge. In the air traffic context, one can observe how the growing need to plan an environmentally sustainable air transport system has requested to integrate, into the design process, disciplines related to aeronautics and environmental impact evaluations. As for noise pollution, for instance, until fifteen years ago, the impact assessment was estimated following preliminary design, while today it is among design constraints since the conceptual stage. Research therefore needs to be a balance among environment, aircraft, community acceptance and economic implications as depicted in Fig. 1.1. In order to achieve the balance point, different features of the aforementioned four components have to be taken into account. As for the environment, resource consumption, chemical pollution and noise emissions are critical elements. About the aircraft, performances, flight mechanics, aeroelasticity, aerodynamics, aeroacustics and structures are key

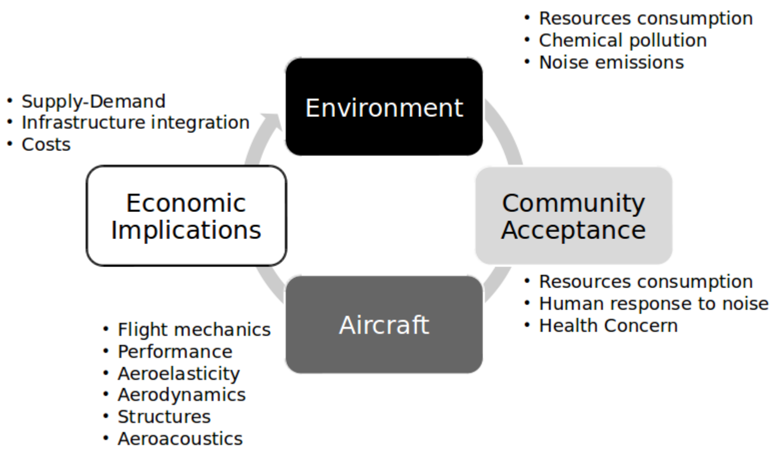


Figure 1.1: Balance among environment, aircraft, community acceptance and economic implications in a multi–disciplinary approach.

factors. Regarding community acceptance resources consumption, human response to noise and health concern while about economic implications supply-demand, infrastructure integration and costs play an essential role. A first approach to the value–based multi–disciplinary conceptual optimization of a commercial airplane was presented by Markish and Willcox [33], where performance, cost and revenue models were integrated to estimate the value of a family of aircraft. In that paper, the analysis is based on the management of the uncertainty level of the future operational scenario, and includes a preliminary exercise on the program value of innovative configurations, more specifically a blended-wing-body (BWB) family. The possibility of including, at the conceptual design level, the environmental footprint of an aircraft as an optimization objective was afterwards discussed in detail [2]. That interesting work describes the comprehensive optimization framework used, and demonstrates, in a multi–objective context, the feasibility of such an approach in substantially decreasing the impact of the civil aviation in terms of noise and emissions. Furthermore it is worth mentioning the article exploring future air–cabins comparing optimisation and win–win scenarios, moving the focus from technical and design considerations to a customer–driven approach, in order to take into account final consumers' needs, and value all stakeholders involved [22]. Another work of high relevance to the objectives of the current research deals with the assessment of the business risk associated to the financial uncertainties [39]. The estimate of the equivalent cost of noise has been thoroughly explored by several authors (see [44, 27, 20]).

1.3 Optimization problems

Optimization is a branch of applied mathematics that studies theory and methods for maximization or minimization of a real–value function on a specified set [1] The generic optimization problem consists then in searching the set of variables $\mathbf{x}$ yielding a minimum of the objective function $J(\mathbf{x}, \mathbf{y})$ subject to the set of parameters $\mathbf{y}$ not controllable by the designer, while all the $N + M$ constraints $g(\mathbf{x})$ and $h(\mathbf{x})$ are satisfied. The generic problem can be formalized as follows

$$\begin{aligned} \min \ [J(\mathbf{x}, \mathbf{y})]\,, &\qquad \mathbf{x} \in \mathcal{D} \text{ and } \mathbf{y} \in \mathcal{B} \\ \text{with bounds } x_n^L \leq x_n \leq x_n^U, &\qquad n = 1, ..., N_x \\ \text{subject to } g_i(\mathbf{x}, \mathbf{y}) \leq 0, &\qquad i = 1, ..., N_g \\ \text{and } h_j(\mathbf{x}, \mathbf{y}) = 0, &\qquad j = 1, ..., N_h \end{aligned} \tag{1.1}$$

being $J(\mathbf{x}, \mathbf{y})$ the *objective function*, with $\mathbf{x}$ the vector containing the N_x *design variables* bounded by x_n^L and x_n^U in the *design space* $\mathcal{D}$, $\mathbf{y}$ the vector containing the N_y *parameters* not controlled by the designer in their domain $\mathcal{B}$, $g_i(\mathbf{x}, \mathbf{y})$ the N_g *inequality constraints* and $h_j(\mathbf{x}, \mathbf{y})$ the N_h *equality constraints*.

A real problem of optimization is often characterized by simultaneous multiple objectives, typically concurrent real–value functions, to be minimized or maximized, and by a number of constraints to satisfy.

The multi–optimization problem can be expressed in the following way

$$\begin{aligned} \text{minimize } \ [J_1(\mathbf{x}, \mathbf{y}), ..., J_k(\mathbf{x}, \mathbf{y}), ..., J_{N_J}(\mathbf{x}, \mathbf{y})]\,, &\qquad k = 1, ..., N_J \text{ and } \mathbf{x} \in \mathcal{D} \text{ and } \mathbf{y} \in \mathcal{B} \\ \text{with bounds } x_n^L \leq x_n \leq x_n^U, &\qquad n = 1, ..., N_x \\ \text{subject to } g_i(\mathbf{x}, \mathbf{y}) \leq 0, &\qquad i = 1, ..., N_g \\ \text{and } h_j(\mathbf{x}, \mathbf{y}) = 0, &\qquad j = 1, ..., N_h \end{aligned} \tag{1.2}$$

being $J_k(\mathbf{x})$ the k^{th} of the vector $\mathbf{J}$ of *objective functions* whose range is $\mathcal{Z}$, with $\mathbf{x}$ the vector containing the N_x *design variables* bounded by x_n^L and x_n^U in the *design space* $\mathcal{D}$, $\mathbf{y}$ the vector containing the N_y *parameters* not controlled by the designer in their domain $\mathcal{B}$, $g_i(\mathbf{x}, \mathbf{y})$ the N_g *inequality constraints* and $h_j(\mathbf{x}, \mathbf{y})$ the N_h *equality constraints*. The set of $\mathbf{x}$ in the n–dimensional design space $\mathcal{D}$ which satisfies the constraints is called the *feasible set*.

Specifically, in multi–objective optimization problems (MOP), typically, a feasible solution minimizing simultaneously all the objective functions does not exist. The solution consists of a set of alternatives, which are Pareto optimal solutions. The optimality criterion lies on the existence of a set of solutions such as it is possible

[1] A maximization problem can always be reformulated as a minimization problem, by minimizing the objective function reciprocal.

to further minimize one objective solely at the expense of one other: such solutions are *non-dominated* (see Fig.1.2). In mathematical terms, a feasible solution $\mathbf{x_1}$ in $\mathcal{D}$, is said to dominate another solution $\mathbf{x_2}$ in $\mathcal{D}$, if

$$\begin{aligned} J_k(x_1) &\leq J_k(x_2), \qquad \text{for all indices } k = 1, ..., N_J \text{ and} \\ J_k(x_1) &< J_k(x_2), \qquad \text{for at least one index } k = 1, ..., N_J \end{aligned} \tag{1.3}$$

A solution $\mathbf{x_1}$ in $\mathcal{D}$ is called Pareto optimal, if no other solution dominates it. The corresponding outcome $J(\mathbf{x}_1)$ lies on the the so–called Pareto front or Pareto boundary which is constituted by the set of all Pareto optimal outcomes. Utopia point is defined as the point characterized by the independent optimization of objective functions.

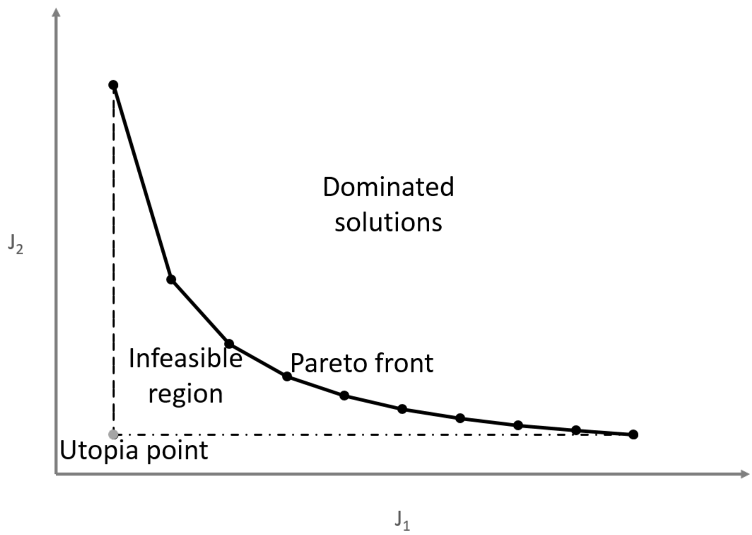


Figure 1.2: Multi–objective optimization problems: infeasible region, dominated solutions, utopia point and Pareto front.

1.4 Uncertainties

Technological goals set over a time frame of more than 30 years imply the arising of uncertainties which may result in a lack of robustness of the final design choice, thus reducing, or even negating, its optimality. The consequent risk therefore is a critical issue to be included in the analysis. Risk analysis is one of the crucial steps in a technological system design whose primary purpose is to quantify, as accurately as possible, a measure of the risk associated with the operation of the system, identifying main dangers and causes of accidents in order to make consequent and effective decisions. The analysis focuses on two different factors: the probability reduction of accidents occurrence and the limitation of any damage caused. The resulting risk is compared to defined acceptance criteria in order to assess the system adequacy to the needs of the community willing to accept the potential associated danger in exchange for the arising benefits.

Often the system cannot be characterized accurately and/or knowledge of involved phenomena is incomplete. The result is an uncertainty related to the model parameters value which is propagated through the model, causing a variability in its output. Consequent uncertainty quantification and characterization is of paramount importance.

Uncertainties may also arise from the complexity of the systems and consequent difficulty in modelling it or from the lack of data. A typical classification split them into two categories: stochastic and epistemic uncertainties. The first type relates to those phenomena whose occurrence is inherently aleatory; by their nature these uncertainties may be described by a probabilistic approach. Epistemic uncertainties relate to an incomplete knowledge of parameters and phenomena. This lack of information may be reflected on one hand on the uncertainty of parameter values and on the other on the uncertainty of the models used for the description of phenomena. The uncertainties that are likely to influence an aircraft innovative design in such a long–term view are mainly of an epistemic nature. Since the long-term view of the project implies sources of uncertainties, related to the operative conditions and economic scenarios, it is crucial that they are taken into account in order to ensure the highest level of confidence and reliability of the emerging design. These aleatory dynamics may affect significantly the financial viability of the optimal design achieved, thus making, in the extreme cases, a technologically "good" aircraft less appealing from the commercial point of view.

1.5 Robust optimization

Deterministic assessments of MCDO are valuable however might be unreliable if operating settings or real–life environment conditions differ than the simulated or estimated ones, or in case of numerical approximations spread in the simulations. Uncertainties can due to unforeseen operating or environmental conditions, *e.g.* the cruise Mach number or the fuel cost. This class of uncertainties are referred to as *Type II variations* [8]. Furthermore deterministic solutions can disclose a notable sensitivity to to even small perturbations in the functions evaluation (both objectives and constraints) for the inaccuracy of either the calculation or the model [5]. Variables, parameters and function evaluations sensitivity might affect the deterministic problem optimal solution validity, turning it into a suboptimal or even infeasible solution [3].

One might suppose that an optimization problem is not connected with the robustness by definition [32]. However, *robust* solutions of a MCDO problem can be found, turning it into a MCRDO (Multi–objective Conceptual Robust Design

Optimization) problem, reformulating the standard deterministic problem considering the aforementioned issues. Recently, since a *robust* solution may yield to a cost–effective and enduring product, the uncertainty management has been playing a more critical role in the design process.

The first approach to broaden the design choices to stochastic processes is based on a three–stage design and has been developed by Taguchi [47]. Differently than the standard deterministic optimization, the noise factors which are not under the designer control, determine variations on performance and are taken into consideration through appropriate signal–to–noise measures: objective functions standard deviation minimization yields to a robust design in a strict sense, since it minimizes the risk to achieve a value different than the expected one. Another attempt, which is extremely conservative, is the *minmax*–approach [48]: it aims to minimize the objective functions in the worst–case scenario so that designer expectations are met in the analyzed case and exceeded in all the others, An additional approach evaluates the optimization problem probabilistic constraints [49, 14, 45, 1]. It is noted that the objective function expected value minimization with regard to the uncertain parameters stochastic variation yields the optimal designer choice: the Bayesian approach to the designer decision–making problem [48, 11] improves substantially the final design robustness to the operating conditions perturbations. Following the Bayesian perspective, the objective function expected value minimization can be achieved with the simultaneous objective function standard deviation minimization with respect to the relevant variables or parameters.

The uncertainties effects evaluation expressed through the expected value, the standard deviation and the probability distributions is known as *uncertainty quantification* (UQ).

The mathematical approach previously discussed (see Eq. 1.2) is then integrated with the introduction of uncertainties.

$$\begin{aligned}
\text{minimize } \left[J_1(\mathbf{x},\mathbf{y}),...,J_k(\mathbf{x},\mathbf{y}),...,J_{N_J}(\mathbf{x},\mathbf{y})\right], &\qquad k=1,...,N_J \text{ and } \mathbf{x}\in\mathcal{D} \text{ and } \mathbf{y}\in\mathcal{B}\\
\text{with bounds } x_n^L \le x_n \le x_n^U, &\qquad n=1,...,N_x\\
\text{subject to } g_i(\mathbf{x},\mathbf{y}) \le 0, &\qquad i=1,...,N_g\\
\text{and } h_j(\mathbf{x},\mathbf{y}) = 0, &\qquad j=1,...,N_h
\end{aligned} \tag{1.4}$$

being $J_k(\mathbf{x})$ the k^{th} element of the vector $\mathbf{J}$ of *objective functions* whose range is $\mathcal{Z}$, with $\mathbf{x}$ the vector containing the N_x *design variables* bounded by x_n^L and x_n^U in the *design space* $\mathcal{D}$, $\mathbf{y}$ the vector containing the N_y *parameters* not controlled by the designer in their domain $\mathcal{B}$, $g_i(\mathbf{x},\mathbf{y})$ the N_g *inequality constraints* and $h_j(\mathbf{x},\mathbf{y})$ the N_h *equality constraints.* The set of $\mathbf{x}$ in the n–dimensional design space $\mathcal{D}$ which satisfies the constraints is called the *feasible set.* The constrained problem can be reformulated as an unconstrained one, introducing a a pseudo objective function $J_k(\mathbf{x},\mathbf{y})$, evaluated with the use of an external penalty function (proportional to the square of the ratio of the violated constraint value to a reference value). Since the design variables $\mathbf{x}$, the parameters $\mathbf{y}$ and the functions evaluation can be subject to perturbations, the solution is subject too. In order to determine a *robust* solution the problem can be expressed differently. First, let's analyse the design variables $\mathbf{x}$ uncertainties dependence for manufacturing tolerances. Be $\hat{\mathbf{x}}$ the decision vector, *i.e.* the designer choice, and $\mathbf{u} \in U$ the error related to this choice. Be $\mathbf{u}$ a stochastic process, depending on the choice $\hat{\mathbf{x}}$, whose probability density function is $p(\mathbf{u})$ (therefore $\int_U p(\mathbf{u})d\mathbf{u} = 1$). The expected value $E[\mathbf{x}]$ is

$$E[\mathbf{x}] := \mu(\hat{\mathbf{x}} + \mathbf{u}) = \int_U (\hat{\mathbf{x}} + \mathbf{u})p(\mathbf{u})d\mathbf{u} \tag{1.5}$$

If $\int_U up(\mathbf{u})d\mathbf{u} = 0$, *i.e.* if the stochastic process has zero expectation, then $E[\mathbf{x}] = \hat{\mathbf{x}}$

Parameters vector $\mathbf{y}$ assembles both operating and environmental conditions and if subject to uncertainties they are not related to the decision vector $\hat{\mathbf{x}}$. For this reason, differently than design variable vector $\mathbf{x}$ uncertainties, it is not appropriate to consider them as errors and it is convenient to define the parameters vector $\mathbf{y}$ as intrinsically aleatory and therefore it can be described through its probabilistic distribution, *i.e*

$$E[\hat{\mathbf{y}}] := \mu(\hat{\mathbf{y}}) = \int_Y \mathbf{y}p(\mathbf{y})d\mathbf{y} \tag{1.6}$$

System output uncertainties are connected to objective functions and constraints evaluations. They can be due to numerical approximations or models inaccuracies in the problem physics description, which lead to a stochastic error $\mathbf{w} \in W$.

Be $\hat{\mathbf{x}}$ a deterministic designer choice such that $\hat{\mathbf{f}} := \mathbf{f}(\hat{\mathbf{x}}, \mathbf{y})$. The expected value of $\hat{\mathbf{f}}$ therefore is

$$E[\mathbf{f}] := \mu(\hat{\mathbf{f}} + \mathbf{w}) = \int_W (\hat{\mathbf{f}} + \mathbf{w})p(\mathbf{w})d\mathbf{w} \tag{1.7}$$

being $\mathbf{f} := [J_1, \dots, J_{N_J}, g_1, \dots, g_{N_g}, h_1, \dots, h_{N_h}]^T$ the vector composed of both the objective functions and the constraints and $p(\mathbf{w})$ the design–point–dependent probability density function.

Through Eqs. 1.5, 1.6 and 1.7, the expected value $E[\mathbf{f}]$ can be defined as follows

$$E[\mathbf{f}] := \mu(\mathbf{f}) = \int_U \int_Y \int_W [\mathbf{f}(\hat{\mathbf{x}} + \mathbf{u}, \mathbf{y}) + \mathbf{w}]\, p(\mathbf{u}, \mathbf{y}, \mathbf{w})d\mathbf{u}d\mathbf{y}d\mathbf{w} \tag{1.8}$$

being $p(\mathbf{u}, \mathbf{y}, \mathbf{w})$ a joint probability density function related to $\mathbf{u}, \mathbf{y}$ and $\mathbf{w}$. It is worth highlighting that the $\mathbf{f}$ expectation depends exclusively on $\hat{\mathbf{x}}$, which is to say it is a function only of the designer choice. The standard deviation of $\mathbf{f}$ with respect to the variation of $\mathbf{u}, \mathbf{y}$ and $\mathbf{w}$ can be formulated as follows

$$\sigma[\mathbf{f}] := \sqrt{\int_U \int_Y \int_W \left\{[\mathbf{f}(\hat{\mathbf{x}} + \mathbf{u}, \mathbf{y}) + \mathbf{w}] - \hat{\mathbf{f}}(\hat{\mathbf{x}})\right\}^2 p(\mathbf{u}, \mathbf{y}, \mathbf{w})d\mathbf{u}d\mathbf{y}d\mathbf{w}} \tag{1.9}$$

and it is function of the only designer choice, too. The Uncertainty Quantification (UQ) is determined as the calculation of the integrals in Eqs. 1.8 and 1.9.

The optimization problem reformulation leads to the consequent new one which can be approached following different strategies. The *minmax*–approach, the most conservative method, is based on minimization of the objective $J_k(\mathbf{x}, \mathbf{y})$ in the worst case scenario [48]. An alternative, option consists in optimizing $J_k(\mathbf{x}, \mathbf{y})$ assessing probabilistic constraints [49, 14, 45, 1]. Furthermore, the standard deviation minimization of $\mathbf{f}$ ensures a robust design in a strict sense [47]. On the other hand, the $J_k(\mathbf{x}, \mathbf{y})$ expected value minimization, with regard to the $\mathbf{y}$ stochastic variation, which, determining a system performances loss, can be considered as a risk, yields the optimal solution. In other terms, this mathematical formulation, based on the Bayesian approach [48, 11], shifts the focus on the expected value of the chosen objective function, influenced by uncertainties. The minimization of the merit factor leads to the solution that minimizes the risks associated with the design choice.

Under the hypothesis that the uncertainties both on the design variable vector $\mathbf{x}$ and in the system output are controllable, only the uncertainty related to the environmental and operating conditions requires to be included in the analysis. The aforementioned Bayesan approach can be integrated with the $J_k(\mathbf{x}, \mathbf{y})$ standard deviation minimization, so the Eq. 1.4 becomes:

$$\begin{aligned} \text{minimize} \qquad & E\left[J_k(\mathbf{x}, \mathbf{y})\right], \sigma\left[J_k(\mathbf{x}, \mathbf{y})\right] && k = 1, ..., N_J \\ \text{with } & x_n^L \leq x_n \leq x_n^U, && n = 1, ..., N_x \text{ and } \mathbf{x} \in \mathcal{D} \text{ and } \mathbf{y} \in \mathcal{B} \\ \text{subject to } & \sup\left\{g_i(\mathbf{x}, \hat{\mathbf{y}})\right\} \leq 0, && i = 1, ..., N_g \\ \text{and } & \mu\left[h_j(\mathbf{x}, \hat{\mathbf{y}})\right] = 0, && j = 1, ..., N_h \end{aligned} \tag{1.10}$$

and the resulting system provides a $2 \times N_j$–dimensional optimization problem.

1.6 Accounting Analysis

Capital investment decisions involve an initial disbursement and future benefits and cover a significant timeframe between the first expense and its recover. In order to enrich conceptual design with economic considerations, marketability of an airplane configuration has to be investigated and integrated within the very first stage.

One possible strategy is to perform an accounting analysis to be included in the design process.

Accounting analysis is a valuation of a business, sub-business, or project profitability. A company's profitability level is based on the profit and loss statement, which records the company's operation results. In order to conduct a decision–making study, it is appropriate to leverage final considerations on contributions of management accounting, extending, the latter over the following three areas:

1. Strategic management

2. Performance management
3. Risk management

Management accounting provides managers of a company with confidential information with a forward–looking focus, computed according to the needs of managers themselves.

In order to calculate profitability, decision–makers can rely, among the others, on the following ratios. Return on Equity (ROE) is calculated as follows:

$$ROE = \frac{NetIncome}{Equity} \tag{1.11}$$

It expresses corporation's profitability, measuring the earnings generated with the money invested by the shareholders.

Furthermore, Return on Asset (ROA) is computed as follows:

$$ROA = \frac{NetIncome}{TotalAssets} \tag{1.12}$$

It is an indicator of profitability of a company expressing how efficient management is at using its assets to generate profit.

It is worth highlighting that the previous indexes focus on the whole corporation profitability. Moreover they provide decision–makers with limited information about the firm's prospects in an absolute sense since their remarks on performance are to be compared to a reference point from other time periods or similar firms.

On the other hand, in order to identify the value of specific project, management can leverage on Average Accounting Return (ARR) which is calculated as follows:

$$ARR = \frac{AverageEBIT}{AverageInvestment} \tag{1.13}$$

where $EBIT$ stands for Earnings Before Interest and Taxes but after depreciation and amortization.

It measures the worth of a project over its useful life expressing the operating profit generated through the initial investment recorded in the Balance Sheet. Main drawback of this ratio is linked to the average values used for its calculation: following this method, one does not take into account the distribution of $EBIT$ over the investment life which means time value of money is ignored. In order to overcome this limitation a financial approach is recommended.

1.7 Financial Analysis

Investment decisions can be based according to several approaches: one can consider net present value (NPV), internal rate of return (IRR) or payback period. A brief description of these indexes follows.

1.7.1 Net Present Value

Cash flows represent the amount of money flowing into and out of a business. They can be both positive and negative, meaning they are respectively inflows and outflows. Net cash flows are the algebraic sum of all flows. The time value of money synthesizes the concept that money currently available has a value which is greater than the same amount of money in the future, since it is characterized by the capacity of earning due to its investment possibilities. Net Present Value (NPV) is the value of net cash flows expressed in present currency. Discounting is the process to convert cash receivable in the future, in the value at present time.

$$PV = \frac{FV_j}{(1+r)^j} \tag{1.14}$$

being PV the present value, FV_j the future value at year j and r the discount rate.

Therefore NPV is calculated discounting all the future cash flows in order to convert them in present value and then adding these terms up [13].

$$NPV = \sum_{j=0}^{N} \frac{CF_j}{(1+r)^j} \tag{1.15}$$

where r is the discount rate, N represents the number of years of investment life and CF are the Cash Flows, both positive (PCF) and negative ones (NCF).

NPV can be used when two or more mutually alternative investments are under analysis: the one having the greatest NPV is the preferred one. This decision–making process is valid even though all potential investments require different initial disbursement. It is worth noting that risk is not related with the required capital but it is expressed through the discount rate; the higher the discount rate is, the riskier the investment is.

1.7.2 Internal Rate of Return

The Internal Rate of Return (IRR) represents the interest rate earned on an investment throughout its life. Mathematically it can be calculated as the discount rate r in Eq. 1.15 which makes NPV vanish.

$$\sum_{j=0}^{N} \frac{CF_j}{(1+IRR)^j} = 0 \tag{1.16}$$

being N the number of years of investment life and CF the Cash Flows. It is worth highlighting that IRR, being a rate, is an indicator of yield of the investment, while NPV expresses the magnitude of an investment. For this reason IRR is an appropriate index to compare investments requiring the same initial disbursement. Differently, one investment could be preferred for having a greater IRR but its overall impact on the value of the company would be minor. In case only one investment is under analysis, it is viable if it is greater than the cost of capital, that is to say the cost, in terms of interests and sale of shares, the company faces to raise the needed capital.

1.7.3 Payback period

Payback period is the time required to recover the initial disbursement of an investment through the subsequent cash flows. Despite this simple definition, it is affected by a few inconveniences. First of all, it is calculated adding up cash flows of different years, without considering the time value of money. Furthermore it does not take into account the risk of the investment nor it considers whether the magnitude of recovering cash flows lies mostly in the first part or last part of the period. These drawbacks could be fixed adding up discounted cash flows giving rise to the adjusted payback period. However this index does not value cash flows occurring after the payback period. It is often misused as an indicator of the risk, while the latter cannot be only related to the time needed to recover the initial investment, when it should be associated to the investment type. It is a frequently used method for its simplicity however for its inaccuracy decision makers opt for the previous indexes.

CHAPTER 2

The need for the airplane of the future

The identification of a design strategy suitable to ensure the sustainable development of the civil aviation avoiding unaffordable financial penalization for the stakeholders involved has turned into a must–do. Indeed, according to all analysts, a substantial growth in air traffic demand is expected in Europe in all possible socio–political scenarios. EUROCONTROL has proposed four different scenarios [15] whose numbers of flights reveal that a doubling of the air traffic in the European skies is a more than a plausible forecast. In such a context, the environmental targets can be accomplished only through a substantial reduction of the emissions of noise and nitrogen oxides, indicated by ACARE (Advisory Council for Aeronautic Research and Innovation in Europe). Unfortunately, technical advancements are becoming more and more difficult, as the conventional technologies are reaching a saturation point. On the other hand, innovative configurations might require critical improvements of current infrastructures.

Any further evolutionary improvement is becoming more costly and time consuming, thus making the introduction of breakthrough concepts a mandatory enabling factor to face the environmental challenge in a constantly growing market.

2.1 The airtraffic growth

In the next 25 years, a relevant growth in air traffic is likely to occur. EUROCONTROL, the European Organisation for the Safety of Air Navigation is an intergovernmental organisation with 41 Member States within the European continent, aiming to improve the air traffic management in Europe. More specifically they support their Member States to manage air traffic operations in Europe in a safe, efficient and eco–friendly way. EUROCONTROL delivered a detailed forecast of air transportation both in a short and long–run perspective. Majority of world GDP is expected to derive from areas other than the European one, therefore the depth and frequency of relations between Europe and these areas play obviously a critical role in the expansion of this industry. An inward or outward European political orientation will consequently impact the air traffic movements increase.

EUROCONTROL developed a 20–year forecast with the aim of a deeper comprehension of the elements determining air traffic and future risks. Initially, the following six scenarios had been taken into account.

Scenario A: Global Growth (Technological Growth). The first scenario is characterized by a substantial economic growth, in globalized and interconnected world, with a strong focus on a sustainable development thanks to enhanced technologies.

Scenario B: Business as usual. The second scenario is based on an average economic growth and it is expected to face limited change from current situation. Therefore tendencies are not affected by any variation.

Scenario C: Regulated Growth. This scenario foresees a limited economic growth in a general context of balance among environmental, societal and economic needs, in order to manage sustainability issues. It is considered as the "most–likely".

Scenario C': Happy Localism. This scenario has been conceived as a different future starting from a hypothesis of limited grow. It envisions weak economies within the EU which stresses and promotes the importance of a sustainable development through continental policies. It also foresees a limited globalization which then favours internal trade within the EU and therefore more continental air traffic in a point–to–point approach. This scenario has then a strong focus on a local development. It is, as the name suggests, based on previous scenario and it combines features of other ones, *i.e.* high fuel prices and low business air traffic of scenario D.

Scenario D: Fragmenting World. Scenario D lies on the assumption of decreased international trade and transportation for an increase of conflicts and then security menace which implies higher fuel prices.

Scenario E: Resource Limits. This scenario considers the quantitative consequences on European traffic of peak oil production envisioned to be achieved in 2020 which yields to a limited access to resources.

These six scenarios have then been reduced to four, dropping B and E. Scenario B has been discarded since different business analysts have a different perspective on the meaning of business–as–usual. More important, determining the future mainly through past trends can be inaccurate. It is like driving a car only looking at the rear mirror and the aim of long–run forecasts is to challenge this assumption. Scenario E has been abandoned since the main assumption of oil production peak, still a valuable option, has not been considered a high–priority situation to be deeper analysed.

Each scenario is characterized by a different air traffic growth. In scenario C, the most–likely, the annual traffic increase is 1.8% on average, bringing to 14.4 million flights in Europe in 2015, *i.e.* 1.5 times the number of flights in 2012. In 2025 this grow decreases for the market maturation and the airports capacity constraints. In scenario C', the same growth trend is followed by a reduced growth rate, for the limited economic development and higher fuel prices. In 2025 the growth is further reduced and therefore in 2035, 0.6 times less movements compared to scenario C would occur. Scenario A, being characterized by a significant economic growth, a low fuel price, shows the highest increase of movements: 17.3 million flights in 2035 in Europe which is to say 1.8 times the 2012 traffic levels. In other terms, an annual growth of 2.6%. Again market maturation and airport capacity limits cause a growth declining in 2020. Scenario D is characterized by high fuel prices, limited economic growth related with a reduced extra–European trade. These elements hinder the traffic growth both at a continental and global levels, bringing to 11.2 million flights in Europe in 2035, corresponding to an annual traffic increase of 0.7% on average. It is worth mentioning that according to scenario D, the total number of flights in 2035 is exceeded by the number of flights in 2019 expected in the most likely scenario.

2.2 Global political involvement

The International Civil Aviation Organization (ICAO) is an agency of the United Nations in charge of developing the principles and techniques of international air navigation, of route and airport and promote planning and development of international air transport in order to foster a safe and ordered evolution. Since urban areas are expanding close to airport facilities, strongly impacting the life quality of the communities who inhabit these neighbourhood, ICAO launched in 2001 and reaffirmed in 2007 the "balanced approach" to aircraft noise management.

In 2001, the ICAO Assembly first introduced the concept of a "balanced approach" to aircraft noise management. The rationale of this approach lies on the following considerations: aircraft noise problems have limited airport operations and expansions and uncoordinated actions to handle aircraft noise could be an obstacle to the aviation contribution to economic development. It stresses the need for objective evaluation criteria, a collaborative approach, transparency, dissemination, and exchange of information.

The balance approach consists of the identification of a noise problem at a specified location (typically an airport) and then of the analysis of the possible mitigation strategies along four paths [24]:

1. reduction at source (quieter aircraft)
2. land–use planning and management
3. noise abatement operational procedures
4. operating restrictions

The goal is addressing the noise problem in the most (cost–)effective manner.

2.2.1 Reduction at source

In the last 40 years, ICAO has emphasized the importance of noise reduction at source. In fact, aircraft and helicopters, nowadays are manufactured according to noise certification standards ruled by the ICAO council. However the analysis of the noise reduction trend reveals a substantial saturation of the available technologies as shown in Fig. 2.1

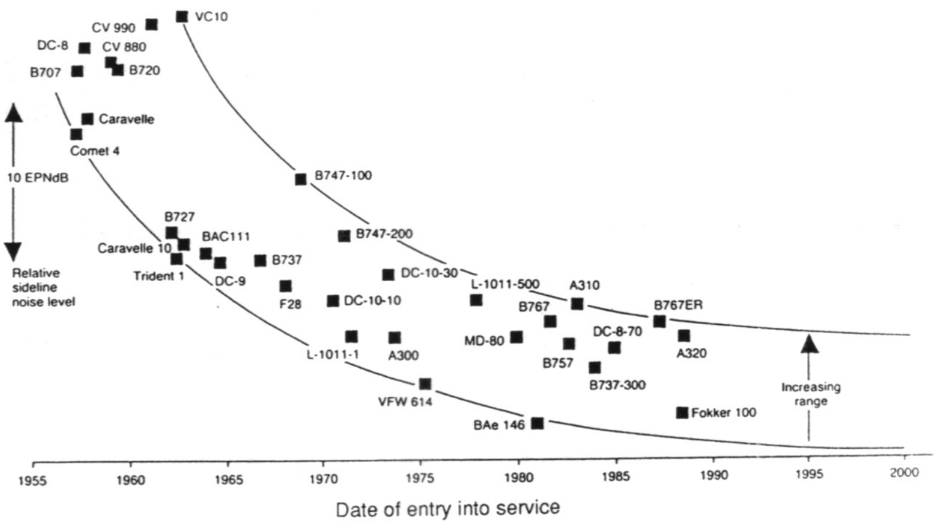


Figure 2.1: Aircraft sideline noise level.

2.2.2 Land–use planning and management

Land–use planning often leads to land–use regulations, also known as zoning, but they are not one and the same. As a tool for implementing land–use plans, zoning regulates the types of activities that can be accommodated on a given piece of land, the amount of space devoted to those activities and the ways that buildings may be placed and shaped. Planning of land–use is of course definitely based on environmental sustainability. However, an appropriate land–use allows to better manage the current situation but it is unlikely to lead to major future developments.

2.2.3 Noise abatement operational procedures

Take–off and landing are the most critical phases of the flight. Pilots and ATM must strictly fulfil well–defined operative constraints to ensure the maximum level of safety. In addition, passengers comfort is also a critical aspect in commercial aircraft, and sharp manoeuvres must be avoided in normal operation. As for take–off, one procedure to reduce noise is called the "close–in". Aim of this procedure is noise reduction nearby airport facilities. It is constituted of a thrust cutback at or above 800 ft and of a flaps/slats retraction delay at the maximum altitude of 3000 ft. An alternative procedure is called the "distant". Differently than the previous one, goal of this procedure is noise reduction at a greater distance from airport facilities. It involves flap/slat retraction at 800 ft, with a positive rate of climb, then an acceleration the zero flaps safe manoeuvring speed increased by 15 knots with a concurrent thrust reduction. There are possible approach strategies that can reduce the noise close to the touchdown. A possible strategy is to guarantee a higher fly–over by forcing the aircraft to have a steeper final descent. An experiment conducted in Toulouse–Blagnac brought to an observation of noise reductions. Despite the gain achieved, this approach was rejected because it may be detrimental to flight safety. The final phase of the flight is much more constrained, and the degrees of freedom to reduce the noise impact are limited since the ILS (instrument landing system) forces the same rate of descent for all the aircraft, regardless of their relative noise impact, typically to 3°. The fundamental rule is: procedure must never prevail over safety aspects. Another option is the Continuous Descent Approach (CDA). Basic assumption of the CDA is the minimum or no recourse to level flight segments below a certain altitude (typically 7000 ft). Use of CDA in London–Heathrow (33% of daytime operations) revealed a noise gain of more than 5 dB(A) at 8-11 NM from the airport. Potential problems of this approach are related with reduced reliability of ILS interception at high altitude and possible traffic stacking.

2.2.4 Operating restrictions

Noise issues have driven some countries, especially developed ones, to reduce, up to outlaw, operations of specific airplanes characterized by high level of sound emissions, at noise–sensitive airports. However, these operating restrictions can have meaningful impacts from an economic viewpoint on airlines having their hubs in these countries and on air carriers operating from and to these airports. Many airports are close at night–time however there are several exceptions among which it is worth mentioning Dubai and Cologne–Bonn on top of cargo airports.

2.3 European political involvement

The Advisory Council for Aviation Research and innovation in Europe (ACARE) was settled in June 2001 and is composed of over 40 member organisations including governmental, private organizations, research institutes and academia. ACARE is an agency dealing with the improvement of the competitive situation of the European Union in aeronautics and air transport. In this sphere, it constitutes a network for strategic research in order to satisfy society and environmental needs. With the purpose of progressing along this way, ACARE developed a plan defining a strategy to be implemented over a 20 and 50–year time–frame. The aviation sector attracts great interest since it has been characterized by a strong focus on innovation: current aircraft burn 70% less fuel, are 75% quieter compared to the first jet airliners, on a passenger per kilometre basis. ACARE developed a Strategic Research Agenda (SRA) in order to help achieve the goals of Vision 2020 and Vision 2050. Targets have been set covering five different aspects:

1. Meeting societal & market needs

2. Maintaining and extending industrial leadership

3. Protecting the environment and the energy supply

4. Ensuring safety and security

5. Prioritising research, testing capabilities & education

Within this scenario, ACARE, consistently with point 3, has launched the Community objectives for noise mitigation. ACARE set challenging goals for 2020 relative to the year 2000 which look difficult to be achieved and in order to continue beyond 2020, ACARE developed a new program, called Flightpath 2050 which sets a reduction, relative to 2000 levels, of 75% in CO_2 emissions, of 90% in NO_X emissions and of 65% in perceived noise by 2050. Since conventional technologies has approached a saturation point, technical improvements are becoming more difficult and therefore further evolutionary enhancements are more costly and time consuming. For this reason breakthrough concepts introduction is a mandatory enabling factor to face the environmental challenge in a constantly growing market, as highlighted by ACARE itself and depicted in Fig. 2.2

This situation is making the ecological footprint a key feature within the transport system development. In this context, in the last decade, the European Community has consistently fostered scientific projects in order to develop solutions to reduce chemical and acoustical emissions. Consequently, chemical and acoustic pollution, impacting life quality of inhabitants of these areas, stirred political, economic and social interests Within this context, it is understandable why the European Community allocated funds to scientific projects focusing on novel technologies and procedures to handle this issue.

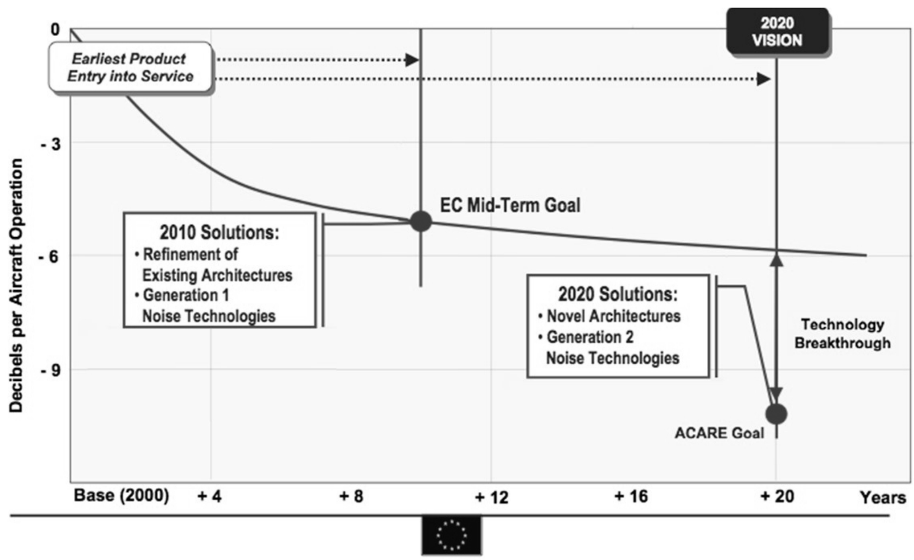


Figure 2.2: ACARE 2020 Goals [9].

2.4 Economic implications

In order to foster a high level of commitment from both airline companies and manufacturers sides, ICAO in addition to all the efforts and actions to achieve noise reduction at source, recognizes the importance and effectiveness of noise fees. Noise fees have been designed and ruled as charges which are levies conceived to pay back the investments in facilities and services. ICAO recognized the need, for several airports, for additional measures to prevent or alleviate noise, and the consequential expenses incurred into for the implementation of these measures, at the member States discretion, can be charged to the users. States are flexible to determine the method of collection and calculation which has to be agreed through consultation with ICAO Council, in accordance with the following principles. Noise charges should:

1. be applied only at airports characterized by noise problems and only to recover the investments to mitigate the aforementioned problems

2. be collected with landing fee, and be designed consistently with the noise certification provisions

3. be defined aligned with equality between users in order not to discriminate certain aircraft users with disproportionally high amounts

It is worth mentioning then that not all the airports apply noise fees, not only since a clear need has to be highlighted but also for they are collected to recover costs to implement measures to alleviate noise emissions. This implies that airports need to include in their organisations a team assigned to this task which therefore requires to manage an economic–organisational issue. In case collected charges are not allocated to noise mitigation measures, ICAO can ask airports to return them to airline companies.

Noise fees are calculated based on effective perceived noise level. Aircraft are grouped per noise emissions and then charges per grouped are determined. Groups can be defined by airports or by ICAO according to to average noise at 3 certification points. Furthermore, extra charges are applied per night time operations.

Currently, noise fees are charged in most of major airports; they are playing a more relevant role and consequently noisy fleets are turning into a meaningful expense. It is an option that in the future, regulation could switch from noise fees to noise taxes, with the not negligible implication for airlines to be charged for the ownership of noisy aircraft, and not any more for their actual operation, however a detailed analysis of this hypothesis from the legal and economic point of view goes beyond the purpose of this work. On the other hand, economic management of noise will be further explored in the following chapter.

2.5 Innovative configurations

During the last decade, several unconventional configurations have been introduced, each one characterized by specific revolutionary solutions, among which the author describes the following two in order to introduce and depict the level of innovation.

2.5.1 Blended–Wing–Body

A blended–wing–body (BWB) is an airplane made with no clear separation between wings, and main body. Airbus and NASA are co–operating to research about the commercial launch of this configuration which, among other benefits, would yield a maximum take–of weight (MTOW) reduction of up–to 18% and a decrease of quantity of fuel burnt per seat–nautical mile of 32% with regard to Boeing conventional configurations. The BWB configuration meaningfully reduces wet surface, which decreases drag. Moreover, it also determines a wing root area thickening, which brings to a more efficient structure compared to a conventional craft.

From an initial study of a single 800–passenger aircraft, a family of airplanes ranging from 250 to 450 seats have been defined, designing common interchangeable spare parts, therefore reducing manufacturing costs. Composite materials adoption will further decrease its weight and thus its fuel consumption. Another advantage is related to a limited noise pollution thanks to the position of engines, placed on top of the central body which shields sound emissions. On the other hand, a few drawbacks have to be analysed, yet, like evacuation problems in case of emergency and passengers perceived safety for the presence of windows only close to the peripheral seats. The last one could be mitigated, installing video cameras broadcasting external environment on displays installed within the central body.

Figure 2.3: Blended–wing–body concept.

2.5.2 Double bubble plane

Double bubble configuration is an aircraft which incorporates two fuselages arranged side–by–side, linked by an outside housing. The Massachusetts Institute of Technology (MIT) in collaboration with NASA is researching to define such an innovative configuration airplane which would consume 70% less than corresponding conventional aircraft, thus reducing chemical emissions. The engines are placed at the rear of the fuselage, instead of under the wing, in order to benefit from boundary layer ingestion (BLI) which is based on a slower moving air entering the engines from the fuselage wake, resulting in a reduced fuel consumption per thrust. The drawback lies on reduced speeds and stress increase on the engine. A family of aircraft is object of the research, including D8.5 conceived to replace short–haul planes and D13. and D15.1 both ideated to cover long–haul routes.

Figure 2.4: Double bubble concept [4].

2.6 Infrastructural impacts

The introduction of innovative configuration in commercial aviation requires an in–the–round analysis which embraces aspects from manifold disciplines, including impacts on current infrastructures.

2.6.1 Airport capacity

An air traffic increase in Europe will imply busier airports. In 2035, more than 150,000 departures a year in the most–likely scenario will be managed by 20 airports; this level of traffic is currently handled only by 8 airports in Europe. Some faster–growing airports in Southern and Eastern Europe will join the top 25.

Different airports have their own peculiar strength within the European network: some are dedicated to definite markets, attracting specific customer segments (*e.g.* airports supporting low–cost airline companies in their point–to–point strategy, serving short–haul trips, or central airports mainly dedicated to business travels) others invite passengers to enlarge their area of travel or are used as hubs by major airlines. Eastern Europe countries are predicted to grow more quickly, therefore airports in this area are forecast to join the top 25 in Europe and to compete with current crowded airports, as for departures. Many airports in Europe are expected to reach their full capacity by 2035 depending on their growth rate, however Turkish and Ukrainian airports are believed to be among the busiest [15]. Moreover, traffic will be further concentrated in top 10 airports: in 2012 they accounted for 23% of departures, in 2035 they are supposed to account for 31% in the most–likely scenario. One of the main hurdle for air traffic growth lies on airports capacity to handle increasing number of flights even though the traffic decline experienced in 2009–2012 and in 2013 has postponed the alert on this topic, conceding some additional years to react and adapt. Specifically with a slow recovery of growth and return to 2008 air traffic situation now forecast for 2016, airport congestion is likely to be a limited problem for the next few years. In the short–run, according to 2013 forecast, 0.14 million departures are expected not to be accommodated in 2019, while in the long–term, airports will be busier and not always able to respond to traffic increase. One of the main reasons is related to current traffic reduction due to difficult economic situation since it yields a revenues decrease for airports which limits financial possibilities of expansion plans. This is extremely important if one considers that innovative configurations, as explained in the following sections, might require severe infrastructure adjustments and upgrades. In a holistic perspective, a critical improvement might undermine the whole development and success of future aircraft. Of course, enhancements might be charged to airlines or passengers, however the lack of initial capital could anyway slow the process.

2.6.2 Ground operations issues

ICAO has classified airports defining a reference code based on performance characteristics and dimensions of airplanes intended to operate at the aerodrome. Element 1 is a number related with the aircraft reference field length while element 2 is a letter depending on the aeroplane wing span and outer main gear wheel span. The code number for element 1 is determined according to Tab. 2.1, column 1, and it is established upon the highest value of the reference field lengths of aircraft intended for the airport. The code letter for element 2 is determined according to Tab. 2.1, column 3: it is established upon the greatest wing span, or the greatest outer main gear wheel span, whatever factor is more demanding, of aircraft intended for the airport.

Code Element 1		**Code Element 2**		
Code no	Airplane reference field length	Code letter	Wing Span	Outer main gear wheel span
1	<800m	A	<15m	<4.5m
2	≥800m and <1200m	B	≥15m and <24m	≥4.5m and <6m
3	≥1200m and <1800m	C	≥24m and <36m	≥6m and <9m
4	≥1800m	D	≥36m and <52m	≥9m and <14m
		E	≥52m and <65m	≥9m and <14m
		F	≥65m and <80m	≥14m and <16m

Table 2.1: Aerodrome reference codes.

Furthermore, ICAO provides indication of minimum runway width depending on the reference code previously described.

Code no	**Code Letter**					
	A	B	C	D	E	F
1	18m	18m	23m			
2	23m	23m	30m			
3	30m	30m	30m	45m		
4			45m	45m	45m	60m

Table 2.2: Minimum runway width for each aerodrome reference code.

ICAO also determines characteristics of taxiways in order to ensure safety operations, according to code letter (see Tab. 2.3). Moreover, bends can be critical and for this reason the intersection angle of a rapid exit taxiway with the runway has to extend between 25°and 45°, preferably 30°.

Code letter	**Strip**	**Minimum width**	**Maximum transverse slope**	**Maximum longitudinal slope**
A	16.25m	7.5m	2%	3%
B	21.5m	10.5m	2%	3%
C	26m	15m	1.5%	1.5%
D	40.5m	18m	1.5%	1.5%
E	47.5m	23m	1.5%	1.5%
F	57.5m	25m	1.5%	1.5%

Table 2.3: Taxiway features.

Innovative configurations could be limited to a reduced number of airports or require to handle the need for extension of current facilities based on their performance characteristics and dimensions. These factors might be included as constraints in the design of future configurations, and/or a thorough analysis of impacts on infrastructure has to be performed.

2.6.3 Airport facilities issues

A jetway is a closed mobile connector linking plane and gate allowing embarkation / disembarkation of all passengers (including the ones with mobility problems) in a short time. Currently, a ramp is equipped with two jetways which can be used simultaneously, if required by the aircraft configuration, in order to accelerate operations. Considering height, capacity and, above all, the current fuselage access, innovative configurations could be incompatible with present jetways and require infrastructure enhancements.

ICAO has also defined the parameters for the classification of aprons. They are the areas where passengers boarding / disembarking, cargo loading and unloading, and aircraft servicing (refueling, cleaning, loading of supplies, waste discharge, controls and regular maintenance) occur. Regardless of the configuration and classification, aprons need to be designed in order that slope does not allow the stagnation of water, while minimum distance between the aircraft and any other object, such as the terminal building, or another plane, depends on the airplane class as shown in the Tab. 2.4. Moreover, aprons have been classified according to their size as expressed in Tab. 2.5.

Aprons can also be located close to terminals and at a nose–in aircraft stand, clearances can be reduced for code letter D, E or F, to 4.5 m between the terminal, including any fixed passenger bridge, and the aircraft nose, and to 3 m over any portion of the stand provided with azimuth guidance by a visual docking guidance system.

Code letter	**Clearance**
A	3m
B	3m
C	4.5m
D	7.5m
E	7.5m
F	7.5m

Table 2.4: Apron clearance for each aerodrome reference code.

Apron code	**Length**	**Width**
1	80.5m	80m
2	71.5m	67m
3	65m	63m
4	57.5m	53m
5	54.5m	44m
6	46.5m	44m
7	44.5m	40m
8	34.5m	37m

Table 2.5: Aprons classification.

Therefore, new configurations aircraft could require a thorough analysis since, in two consecutive aprons, close to terminals, two innovative airplane could not fit with a strong impact from a technical, operational and economic viewpoint. This potential issue will be explored in Sect. 3.3.

Part II

The multi–disciplinary problem

CHAPTER 3

The problem definition

In order to study innovative configurations, the analysis is based on a single airplane approach, regardless of fleet size, leveraging on economies of densities, scope and capacity utilization of aeronautical industry. The problem is manifold, embracing different dimensions ranging from environment, to aircraft, through finance and community acceptance. A multi–disciplinary approach is therefore appropriate in order to achieve the equilibrium point and a great focus is on financial and social topics.

3.1 One–airplane analysis

Airline companies fleet size is obviously a critical factor on profitability. It is intuitive that the higher the number of aircraft is, the greater revenues are (until market saturation point is reached) and the lower costs per flight are. Consistently, one might argue that in an economic–ecological analysis, emphasis has to be put on this element. However, studying the economic relevance from an operational perspective requires an additional investigation about the relationship between fleet size and economic analysis.

3.1.1 Economies of density

A company benefits from density economies when 1% percent increase in all outputs, holding network size, production technology, and input prices constant, determine a company's costs increase by less than 1%, then air transportation firms can benefit from economies of density, if a one 1% increase in miles flown, is affected by a rise of costs by less than 1%. Of course, since distances are fixed an increase in miles flown implies, at least, an additional mission over a define route. Considering all the costs not directly related with the flight, *i.e.* ticketing, sales and promotion, airline companies can benefit from economies of density. On the other hand, direct cost items *i.e.* airport charges, fuel, passenger services are directly proportional with number flights. In any case, it is clear that the network size has no relationship with economies of density by definition and therefore, the analysis based on a single–airplane study is consistent with them.

3.1.2 Economies of capacity utilization

Economies of density is a spatial concept, while economies of capacity utilization may be aspatial. If the percentage of used capacity increases by 1%, holding network size, production technology, and input prices constant, and costs increase by less than 1% a company benefits from economies of utilization.

As for airline companies, capacity refers to level of occupancy of their aircraft and if it increases, several costs item *i.e* air navigation fees, maintenance, station and ground are marginally or not impacted at all. However, if full capacity is approached, costs may occur in terms of missed revenues. For this reason airline companies tend to have a very high occupancy rate which ranges, on average about 80% [16]. In any case, economies of capacity utilization are by definition independent from size of capacity, therefore a single–airplane analysis is not conflicting.

3.1.3 Economies of scope

A company generally produces a large number of distinct products from a common production facility and, in this case, common costs occur. When an extra product is produced in a shared facility, it determines a cost increase of C_S. When an extra product is produced in a dedicated facility it determines of cost increase of C_D. If $C_S < C_D$, then a company benefits from economies of scope. That can happen when the new product can be produced leveraging on some inputs whose costs have already been incurred into and are not incremental. Economies of scope are related to the cost characteristic that a single firm multi–product technology is less costly than a single product multi–firm technology. In other terms, it is less expensive sharing facilities and related costs rather than dedicating a facility to each product. This analysis evaluates the additional costs for enlarging the product line. As for air traffic industry, airline companies can benefit from economies of scope, when they include a new route to their offers, whose starting or ending airport is shared with another of their routes. In this case, fixed airport costs do not increase proportionally. However, this characteristic is strictly related to an additional product, that is to say to an additional mission, and not to the fleet size.

3.1.4 Economies of scale

Economies of scale exist when an increase in the size of the company determines a reduction of its products unitary costs. They occur, therefore when a 1% increase in output and size of network yields a cost rise by less than 1% with production technology and input prices held constant. In other words, in the long–term, companies can change the size of their networks and economies of scale measures the relationship between average cost and network size. In case of presence of meaningful scale economies, a reduced number of players would yield higher efficiency in a competitive market. Since airline companies run comparable business, whose output is flying aircraft supported by several back–office functions, *i.e.* administration, human resource management and finance, mergers can severely reduce these costs. For this reason, we witnessed to several mergers and among the others it is worth mentioning British Airways–Iberia and United Airlines–Continental both in 2010. In an economic analysis therefore, the size of fleet plays a critical role, however, as aforementioned, the economies of scale impact only back–office functions while operating activities related with the airline companies core–business are not affected. For this reason a one–aircraft approach is effective as far as the economic analysis focus on the operations and not on other functions. Since the airplane configuration has a strong influence on operations and very limited or absent on back–office activities, it is appropriate not to include scale economies in this work and to focus on a single airplane approach regardless of fleet size.

3.2 A multi–disciplinary approach

3.2.1 The social impact

The current aeronautical market scenario is making the ecological footprint a feature of paramount relevance for the sustainable development of the transportation system. In this context, in the last decade, the European Community has consistently fostered scientific projects in order to develop solutions to reduce chemical and acoustical emissions. Consequently, chemical and acoustic pollution, impacting life quality of inhabitants of these areas, stirred political, economic and social interests Within this context, it is understandable why the European Community allocated funds to scientific projects focusing on novel technologies and procedures to handle this issue.

In economics, an externality is a consequence of a business activity experienced by a party different than the one involved in the activity itself, therefore negative externalities are the “costs” affecting this party. Currently, according to the International Civil Aviation Organization policies [25], airline companies are charged with noise fees based on flight time and the class of the airplane. These incomes are supposed to be re–invested in the implementation of strategies and infrastructural improvements aimed at community noise abatement. It is worth noting that these charges are applied as air navigation fees when a flight is operated. This choice aims to internalize a negative externality, in fact the consequence due to the business activity has an economic impact on the party being the source of the inconvenience. Innovative configurations are then required to be financially sustainable as well as socially sustainable. As for management of social costs deriving from negative externalities, it is worth mentioning the article written by Calabresi and Melamed [6] who proposed four kind of rules to discipline inconveniences. First, they discuss in detail the concept of entitlement, in order to clearly identify, in a conflicting situation, which part is entitled to prevail and then whether the entitlement is alienable in a voluntary transaction or, in the worst case, in a collective decision forced by the court. In the first couple of options the injurer cannot produce the inconvenience and in rule 1 the victim can obtain an injunction to stop it, while in rule 2 the injurer is allowed to continue if it pays damages, established by the court, to the victim. In the second couple of options, the injurer has the right to continue its action and in rule 3 the victim has no right to obtain an injunction or a sum of money, while in rule 4 the victim can obtain the injurer stops if the former pays the latter damages due to the business interruption. Rule 1 and rule 3 are called property rules, since they have the characteristic that an entitlement can be transferred by a subject to another only with the consent of the entitled. In fact, in case of rule 1 the injurer can continue its action only if it achieves an agreement with the victim. Vice versa, rule 3 implies that victim can obtain the injurer stops only after an agreement signed by both parties. Rule 2 and rule 4 are called liability rules and they are characterized by the possibility to take an entitlement from the owner without his consent, but the infringer must pay a compensation. In fact, in case of rule 2, the injurer is forced to pay damages in order to continue its action, while rule 4 implies the victim is forced to pay damages to make the injurer stops. In a situation where transaction costs prevent a contract between the involved parties, liability rules are preferred, since in order to improve efficiency, it is necessary to consider the existence of a rule that does not ask for consent in order to allow a transfer of an entitlement. Several approaches can be followed to determine the amount of the compensation and in the author's opinion it is worth mentioning the work written by Pigou [40]. An industrialist pursues its marginal private interest, regardless of social costs. If the latter exceeds the former one, the industrialist over produces the product. In order to handle this over–production, a tax to be charged to the injurer is recommended [40], whose amount equalises the marginal social cost, this way the offender pays for the externality it creates. Therefore, if the compensation equals the damage for the entitled, efficiency is satisfied because the entitlement moves from a subject who values it less to a subject who values it more. The aforementioned four cases are resumed in Tab. 3.1.

The discussion on how to deal with acoustic emissions is still open. One possible option is to switch from noise fees to noise taxes, with the not negligible implication for airline companies to be charged for the ownership of noisy aircraft, and not any more for their actual operation. A detailed analysis of this hypothesis from the legal and economic point of view goes beyond the purpose of this work.

This legal aforementioned detailed study should consider several operational complications among which a critical one is the identification of the subject and the country supposed to be collecting the cash flows deriving from these taxes.

Initial Entitlement	Injunction & Property Rule	Damages & Liability Rule
Sufferer	Rule 1: The injurer cannot produce the inconvenience and the sufferer can obtain an injunction to stop it	Rule 2: The injurer is not allowed to produce the inconvenience unless they pay the sufferer damages
Injurer	Rule 3: The injurer can produce the inconvenience without paying the sufferer any damage	Rule 4: The injurer has the right to produce the inconvenience unless the sufferer pays the injurer damages

Table 3.1: Property and liability rules.

These speculations, regardless of their development, testify the existence of a strong economic interest among airline companies and, on top of the expansion of urban areas and the growth of air traffic, show that social and political concerns can have a severe impact on noise fees determination.

3.2.2 The financial implications

Financial implications from the viewpoint of manufacturer have been deeply explored and it is worth mentioning the excellent analysis proposed by Markish and Willcox [33]. Therefore design and manufacturing costs have been widely studied and modelled. Nevertheless, marketability of a product strongly depends on the demand side, too.

Innovative configurations of airplanes have been widely investigated during the last two decades and the majority of the technical issues have been identified. The solution strategies for some of them have been determined, whereas for others the aeronautical research community is spending substantial efforts, with continuous advancements. In any case, the undoubted existence of these technical aspects cannot be considered anymore a justification of the lack of a common strategies in the identification of the next generation of commercial aircraft. So why must we expect to keep watching tube–and–wings configurations flying in our skies at least for other 25/30 years? Most likely because manufacturers have not yet converged onto a common strategy for the development of the next generation of airliners. Why? Is this delay only driven by technical reasons? Unlikely. A not negligible cause can lie on the not completely disclosed economic impact of these unconventional concepts. The pervasive effect of an unconventional concept on the entire logistic/infrastructural framework imposes the life–cycle costs analysis to be addressed by all the stakeholders in a synergistic fashion, and integrated as early as possible in the design process in a renewed multi–disciplinary approach. It is therefore clear that in order to develop a cost–effective analysis it is key that economic considerations impacting the whole design process are included from the conceptual design phase.

Previous works have explored the value–based perspective, and Markish and Willcox [33] linked financial considerations to performance factors and also included the uncertainty analysis applying an approach developed in the finance environment to innovative configurations. Antoine and Kroo [2] introduced the environmental impacts of aircraft within the conceptual design frame, in a multi–objective approach, as an objective function to be minimised. Furthermore, the interdependencies between acquisition cost and negative cash flows for low–noise aircraft from an airline perspective has been investigated [30].

In this work, analysing the market from a different perspective which embraces several stakeholders considerations, including the airline company's one is proposed. On one hand, even though in the aeronautical industry, according to Porter's five forces analysis [42], suppliers have the strongest negotiation power, airline companies started providing manufacturers with their proposals for the future planes. Examples include but are not limited to Easyjet which in 2007 show their support to an open rotor–powered to solve environmental issue (see Fig. 3.1). On the other hand, airline companies constitute the joining link between manufacturers and airports.

Figure 3.1: Ecojet Easyjet open rotor–powered aircraft [34].

What does an airline company need in order to decide whether to invest in a new airplane? Several approaches can be identified from an accounting and financial perspective, as explored in Sects. 1.6, 1.7. Whatever viewpoint is chosen the initial investment has to be assessed. Moreover if the accounting approach is preferred, revenues and operating costs have to be calculated, while in the financial one, positive and negative cash flows throughout the airplane's life and discount rate have to be estimated. Positive cash flows are obviously related to revenues, while negative ones are associated with operating costs. Revenues are related to the number of passengers and ticket prices. Both variables are determined by laws of supply and demand in the transportation industry and are affected by uncertainties due to technical innovation, especially in the long term view. According to IATA [16], airways companies operating cost structure follows in Fig. 3.2. In this analysis, top three direct cost categories have been considered (fuel, aircraft ownership, maintenance) since they account for 53% of operational costs and 77% of direct operational costs. In addition, airport charges, even if their incidence is limited (5%), have been comprised since they include noise fees which are expected to become more impacting in the future.

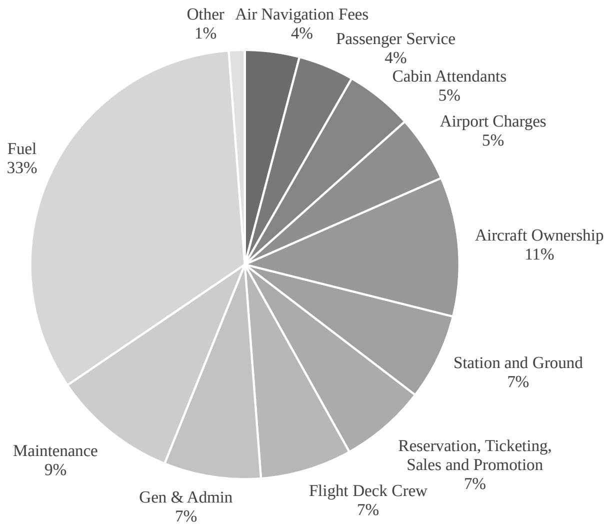


Figure 3.2: Airline operational costs breakdown.

In the last quarter of century, life–cycle costs have been linked to two main stages: design and operational ones [33]. These cost categories have been associated to the fuel–weight and empty–weight of the plane. However, from an airline perspective it is critical to determine the acquisition price P_{AC} and, since the commercial planes market is regulated by the laws of supply and demand, price is not determined by the cost of design. Of course, from a manufacturer viewpoint, selling price is its source of revenues which has to recover manufacturing costs, including its design ones. This implies that acquisition price is limited but not determined by the cost of design and it is defined by the value delivered and perceived by the customer, which strongly depends on the performance of the aircraft. In order to include the added–value, a relevant previous work [33] has considered that an operating costs increase was offset by a proportional selling price decrease and vice versa, in a zero–sum approach. A different cost analysis approach is proposed, in order to determine the most valuable solutions.

Configuration	Type	Aircraft	Seats	Wing span [m]	Length [m]	Range [km]
BWB	Short–haul	5-250-G	250	60.72	39.50	N.A.
Conventional	Short–haul	A320	150-180	35.80	37.57	6,100
Double bubble	Short–haul	D8.5	180	51.82	35.36	5,556
BWB	Long–haul	5-450-G	450	67.67	46.33	N.A.
Conventional	Long–haul	A350	366-440	64.75	73.78	14,800
Conventional	Long–haul	A380	544-853	79.75	72.72	15,200
Double bubble	Long–haul	D13.1	500	64.92	59.74	14,075
Double bubble	Long–haul	D15.1	500	68.88	52.73	14,075
Double bubble	Long–haul	D17.1	226	58.52	58.52	14,816

Table 3.2: Traditional and innovative configuration airplanes features.

3.3 The innovative configurations repercussions on infrastructures

Innovative configurations have been described in Sect. 2.5 and in order to analyse their repercussions on infrastructures, the developed projects characteristics are summarized in Tab. 3.2. More in details the following BWB configurations refer to a collaboration between Boeing and NASA while Double bubble airplanes to a cooperation of NASA and MIT.

In order to explore concerns related to runways and to analyze the suitability of current airports with regard to innovative configurations, a thorough analysis has been performed: per every continent, twenty airport samples have been selected, ten of which are dedicated to long–haul flights and the remaining ones to short–haul flights, so that, totally, one–hundred airports have been included (see Tabs. 3.5, 3.6, 3.7, 3.8, 3.9). Furthermore, based on the previous analysis, mode and mean values of runways have been computed (see Tab. 3.3).

Ground operation issues are potentially due to runways, taxiways and aprons. The short–haul BWB configuration configuration, 5-250-G, has a 60.72 m wing span while a double bubble D8.5 has a 51.82 m one which require aerodromes whose letter codes are respectively D and E according to Tab. 3.1, while current short–haul airplane generally requires a C airport. Since short–haul runways average width is 43 m, the size of these configurations might be an issue. It is worth noting, however, that one of the main reasons of width constraints is related to the risk that engines could be affected by debris placed outside of the runways. As shown in Fig. 2.3 and Fig. 2.4, engines in innovative configurations are located at the rear of the fuselage. For this reason, according to current regulations runways width might be an issue however a legislation review could consider the possibility to loosen this constraint. As for long–haul innovative configurations, their width ranges from 64.92 m for

	Primary Runway		Secondary Runway	
	Width [m]	**Length [m]**	**Width [m]**	**Length [m]**
Long–haul runways mean value	53	3,618	50	2,709
Short–haul runways mean value	43	2,341	34	1,317
Long–haul runways mode value	60	4,000	45	1,524
Short–haul runways mode value	45	2,000	45	N.A.

Table 3.3: Runways global statistical analysis.

D13.1 to 68.88 m for D15.1 passing through 66.67 m for BWB 5-450-G. Average runway width size is 53 m, however mode is 60 m and required airport are generally E–classed. Aircraft whose wing span exceeds 65 m requires an F airport and this would be the case for 5–450–G and D15.1, however the excess is limited and, again, engines location could determine a review of the current legislation which would not impose any runway enlargement. The same reasoning could apply for taxiways. 90–degree turns are the most critical for the risk that engines could be affected by debris. Again engine positions could determine a loosening of regulations. Throughout decades of improvements and enhancements, aprons have been changed and modernized, in order to adapt their sizes according to continuously updated airplanes. These repeated evolutions yielded to aprons characterized by different sizes. The introduction of innovative configurations, especially in the case of short–haul aircraft, require large size aprons, making unusable the small ones. Areas currently dedicated to aprons would therefore be able to handle less airplanes and therefore, considering the air traffic increase, would not have sufficient capacity to manage innovative aircraft. This limit could require to reconsider the entire airport operational area, especially for short–haul innovative aircraft whose wing span ranges from 150% to 170% of traditional airplane one.

Furthermore, since number of flyers of innovative configuration airplanes is comparable to traditional ones, airport facilities providing services to passengers are not supposed to be critical. The only attention point is related to 5–250–G BWB configuration, having a capacity 40% larger than short–haul traditional airplanes which could affect service travel quality in small–sized airports. Check–in desks, toilets, security controls, lounges, waiting areas capacity would keep being satisfactory. The situation would be different, in case, in order to handle a continuously growing air traffic, innovative aircraft were designed to transport a larger number of passengers, in order to reduce the risk of congestion of airports. It is worth mentioning that

Airplane		**Runway**	**Taxiway**	**Apron**	**Services**
BWB	5–250–G	😐	😐	☹	😐
BWB	5–450–G	😐	😐	☺	☺
Double bubble	D8.5	😐	😐	☹	☺
Double bubble	D13.1	☺	☺	☺	☺
Double bubble	D15.1	😐	😐	☺	☺
Double bubble	D17.1	☺	☺	☺	☺

Table 3.4: The innovative configurations repercussions on infrastructures.

airport managers are already accustomed to planning airport extensions according to airline industry evolution. The impact analysis is synthesized in the Tab. 3.4.

			Primary Runway		Secondary Runway		
Type	**Airport (IATA)**	**Country**	**W [m]**	**L [m]**	**W [m]**	**L [m]**	**Jet–ways**
L–H	Amsterdam Schiphol (AMS)	Netherlands	60	3800	45	2014	Yes
L–H	Athens Eleftherios Venizelos (ATH)	Greece	45	4000	45	3800	Yes
L–H	Frankfurt sur Mein (FRA)	Germany	60	4000	45	2800	Yes
L–H	Lisbon (LIS)	Portugal	45	3805	45	2804	Yes
L–H	London Heathrow (LHR)	UK	50	3902	50	3660	Yes
L–H	Madrid Barajas (MAD)	Spain	60	4169	60	3500	Yes
L–H	Milan Malpensa (MPX)	Italy	60	3920	60	3920	Yes
L–H	Moscow (VKO)	Russia	60	3060	60	3000	Yes
L–H	Paris Charles de Gaulle (CDG)	France	45	4200	60	2700	Yes
L–H	Rome Fiumicino (FCO)	Italy	60	3900	45	3309	Yes
S–H	Alicante Elche (ALC)	Spain	45	3000	NA	NA	Yes
S–H	Billund (BLL)	Denmark	45	3100	NA	NA	Yes
S–H	Birmingham (BHX)	UK	45	2599	NA	NA	Yes
S–H	Burgas (BOJ)	Lithuania	45	3200	NA	NA	No
S–H	Düsseldorf Weeze (NRN)	Germany	45	2440	NA	NA	No
S–H	Eindhoven (EIN)	Netherlands	45	3000	NA	NA	No
S–H	Ibiza (IBZ)	Spain	45	2800	NA	NA	Yes
S–H	León (LEN)	France	45	3000	NA	NA	No
S–H	Milan Linate (LIN)	Italy	60	2440	23	620	Yes
S–H	Mykonos (JMK)	Greece	30	1903	NA	NA	No

Table 3.5: Analysis of European airports runways size, differentiated for long–haul (L–H) and short–haul (S–H) routes.

			Primary Runway		Secondary Runway		
Type	**Airport (IATA)**	**Country**	**W [m]**	**L [m]**	**W [m]**	**L [m]**	**Jet–ways**
L–H	Abu Dhabi (AUH)	UAE	60	4100	60	4095	Yes
L–H	Chhatrapati Shivaji (BOM)	India	60	3448	45	2871	Yes
L–H	Chubu Centrair (NGO)	Japan	60	3500	NA	NA	Yes
L–H	Dubai (DXB)	UAE	60	4000	60	4000	Yes
L–H	Hong Kong (HKG)	China	60	3800	60	3800	Yes
L–H	Seul Incheon (ICN)	South Korea	60	4000	60	3750	Yes
L–H	Singapore Changi (SIN)	Singapore	60	4000	60	4000	Yes
L–H	Taiwan Taoyuan (TPE)	Taiwan	60	3800	60	3660	Yes
L–H	Tokyo Haneda (HND)	Japan	60	3360	60	2500	Yes
L–H	Ulan Bator Gengis Khan (ULN)	Mongolia	45	3100	50	2000	Yes
S–H	Bagdogra (IXB)	India	45	2754	NA	NA	No
S–H	Beihai Fucheng (BHY)	China	45	3200	NA	NA	Yes
S–H	Dabolim (GOI)	India	45	2390	NA	NA	Yes
S–H	Dušanbe (DYU)	Tajikistan	45	3112	NA	NA	Yes
S–H	Izumo (IZO)	Japan	45	2000	NA	NA	Yes
S–H	Khon Kaen (KKC)	Thailand	45	3050	NA	NA	Yes
S–H	Qinhuangdao Shanhaiguan (SHP)	China	50	2440	NA	NA	No
S–H	Takamatsu (TAK)	Japan	60	2500	NA	NA	Yes
S–H	Ulsan (USN)	South Korea	45	2000	NA	NA	Yes
S–H	Wadi al–Dawasir (WAE)	Saudi Arabia	45	3050	NA	NA	No

Table 3.6: Analysis of Asian airports runways size, differentiated for long–haul (L–H) and short–haul (S–H) routes.

			Primary Runway		Secondary Runway		
Type	**Airport (IATA)**	**Country**	**W [m]**	**L [m]**	**W [m]**	**L [m]**	**Jet–ways**
L–H	Adelaide (ADL)	Australia	45	3100	45	1652	Yes
L–H	Auckland (AKL)	New Zealand	45	3653	45	3108	Yes
L–H	Canberra (CBR)	Australia	45	3273	45	1679	Yes
L–H	Christchurch (CHC)	New Zealand	45	3288	45	1703	Yes
L–H	Darwin (DRW)	Australia	60	3354	30	1524	Yes
L–H	Hobart (HBA)	Tasmania–Australia	45	2251	NA	NA	No
L–H	Honiara (HIR)	Salomon Islands	45	2200	NA	NA	No
L–H	Jacksons (POM)	Papua New Guinea	45	2750	NA	NA	Yes
L–H	Melbourne (MEL)	Australia	60	3657	45	2286	Yes
L–H	Sydney Kingsford Smith (SYD)	Australia	45	3962	45	2438	Yes
S–H	Devonport (DPO)	Tasmania–Australia	45	1838	NA	NA	No
S–H	Dunedin (DUD)	New Zealand	45	1900	NA	NA	Yes
S–H	Gold Coast (OOL)	Australia	45	2492	23	582	No
S–H	Gove (GOV)	Australia	45	2208	NA	NA	No
S–H	Kalgoorlie Boulder (KGI)	Australia	45	2000	18	1200	No
S–H	Kavieng (KVG)	Papua New Guinea	30	1704	NA	NA	No
S–H	Mackay (MKY)	Australia	45	1981	30	1344	No
S–H	Madang (MAG)	Papua New Guinea	30	1690	NA	NA	No
S–H	Palmerston North (PMR)	New Zealand	45	1902	NA	NA	No
S–H	Wagga Wagga (WGA)	Australia	45	1768	NA	NA	No

Table 3.7: Analysis of Oceanian airports runways size, differentiated for long–haul (L–H) and short–haul (S–H) routes.

			Primary Runway		Secondary Runway		
Type	**Airport (IATA)**	**Country**	**W [m]**	**L [m]**	**W [m]**	**L [m]**	**Jet–ways**
L–H	Antananarive Ivato (TNR)	Madagascar	45	3100	NA	NA	No
L–H	Cape Town (CPT)	South Africa	60	3201	45	1701	Yes
L–H	Henrique de Carvalho (VHC)	Angola	45	3402	NA	NA	No
L–H	Hosea Kutako (WDH)	Namibia	45	4532	30	1524	No
L–H	Kigali Gregoire (KGL)	Rwanda	45	3500	NA	NA	No
L–H	King Shaka (DUR)	South Africa	60	3700	NA	NA	No
L–H	Johannesburg O.R.Tambo (JNB)	South Africa	60	4418	60	3389	Yes
L–H	Marrakech Menara (RAK)	Morocco	45	3100	NA	NA	No
L–H	Marsa Alam (RMF)	Egypt	45	3000	NA	NA	No
L–H	Moi (MBA)	Kenya	45	3350	30	1363	Yes
S–H	Axum Airport (AXU)	Ethiopia	45	2400	NA	NA	No
S–H	Bahir Dar Airport (BJR)	Ethiopia	45	3000	NA	NA	No
S–H	Cotonou Cadjehoun (COO)	Benin	45	2400	NA	NA	No
S–H	East London (ELS)	South Africa	45	1939	45	1585	No
S–H	George Airport (GRJ)	South Africa	45	2000	NA	NA	No
S–H	Jijel Ferhat Abbas (GJL)	Algeria	45	2400	NA	NA	No
S–H	Mfuwe (MFU)	Zambia	30	2200	NA	NA	No
S–H	Nampula (APL)	Mozambique	45	2000	NA	NA	No
S–H	Pietermaritzburg (PZB)	South Africa	30	1537	NA	NA	No
S–H	Selebi Phikwe (PKW)	Botswana	30	1780	NA	NA	No

Table 3.8: Analysis of African airports runways size, differentiated for long–haul (L–H) and short–haul (S–H) routes.

			Primary Runway		Secondary Runway		
Type	**Airport (IATA)**	**Country**	**W [m]**	**L [m]**	**W [m]**	**L [m]**	**Jet–ways**
L–H	Buenos Aires Ministro Pistarini (EZE)	Argentina	60	3300	45	3105	Yes
L–H	Calgary McCall Field (YYC)	Canada	60	4267	45	1890	Yes
L–H	Cancún (CUN)	Mexico	60	3500	45	2400	Yes
L–H	Chicago O'Hare (ORD)	USA	45	3962	45	2286	Yes
L–H	Hartsfield–Jackson Atlanta (ATL)	USA	45	3776	45	2743	Yes
L–H	José Martí (HAV)	Cuba	45	4000	NA	NA	Yes
L–H	New York John F. Kennedy (JFK)	USA	60	4423	60	2560	Yes
L–H	Rio de Janeiro Galeão (GIG)	Brazil	45	4000	45	3180	Yes
L–H	San Francisco (SFO)	USA	60	3618	60	2636	Yes
L–H	Toronto Pearson (YYZ)	Canada	60	3389	60	2743	Yes
S–H	Balmaceda Airport (BBA)	Chile	45	2501	NA	NA	Yes
S–H	Colima (CLQ)	Mexico	45	2300	NA	NA	No
S–H	Columbia Metropolitan (CAE)	USA	45	2622	45	2439	Yes
S–H	Comodoro Pedro Zanni Airport (PEH)	Argentina	30	1500	NA	NA	No
S–H	Earlton (YXR)	Canada	45	1828	NA	NA	No
S–H	Guillermo León Valencia (PPN)	Colombia	30	2080	NA	NA	No
S–H	Mobile Regional Airport (MOB)	USA	45	2591	45	1334	Yes
S–H	Palmas B. L. Rodrigues (PMW)	Brazil	45	2500	NA	NA	Yes
S–H	Roatán J.M. Gálvez (RTB)	Honduras	45	2090	NA	NA	No
S–H	San Paolo Congonhas (CGH)	Brazil	45	1940	45	1435	Yes

Table 3.9: Analysis of American airports runways size, differentiated for long–haul (L–H) and short–haul (S–H) routes.

CHAPTER 4

The problem formulation

For the current economic, political, environmental and technical scenario, breakthrough concepts introduction is an essential element to deal with the environmental challenge in a constantly growing market. A viable approach to address this issue consists of the integration of updated economic models in the conceptual multi–disciplinary design, adopting a multi–objective approach to include all involved stakeholders' interests. In order to achieve this goal, several optimization campaigns have been performed from an accounting, financial and financial-environmental viewpoint. Two gradient–free methods have been employed to execute the optimization problems which have been carried out within the framework `FRIDA` - FRamework for Innovative Design in Aeronautics (for details see the Appendix). The first is the Particle Swarm Optimization (PSO) [[31]], as deterministic implementation (MODPSO) developed by the *Resistance & Optimization team* of the CNR–INSEAN [7], the second one is a Multi–Objective Genetic Algorithm (MOGA) and the adopted algorithm is based on the `NSGA-II`, exhaustively described by [10].

4.1 The economic model

The decision on innovative airplane configurations introduction embraces several stakeholders' interests, which have to be wholly considered in the research of a point of equilibrium among the four following systems: environment, aircraft, economy and community acceptance. In order to include benefits and drawbacks of the different stakeholders involved, it is valuable to develop an aircraft conceptual design which incorporates both technical and economic features. The latter, from the manufacturer's perspective, have been investigated and design and manufacturing costs have been modelled [33]. On one hand, according to Porter's five forces analysis [42], within the aeronautical industry, suppliers have a strong bargaining power, on the other hand airline companies already engaged manufactures in discussions about future planes, and they can be also considered the contact point between the travellers, the manufacturers, the environment, and the infrastructure. As described in Sects. 1.6 and 1.7 different indexes can be identified for profitability analysis. If a decision–maker opts for an accounting approach, consequently she focuses on the Accounting Return Rate ARR, and revenues deriving from ticket sales and operating costs including amortization and depreciation have to be considered. If she decides to perform a financial analysis, the Net Present Value NPV has to be calculated. For the sake of simplicity, assuming the revenues and costs have their corresponding cash inflows and outflows in the same accounting period, the only difference lies on depreciation and amortization which, being non–cash expenses, affect only the accounting analysis.

4.1.1 The accounting model

In order to determine the most profitable aircraft, among different alternative options, a decision–maker has to calculate the Accounting Return Rate ARR. As expressed in Eq. 4.1 ARR is defined as follows

$$ARR = \frac{AverageEBIT}{AverageInvestment} \tag{4.1}$$

$EBIT$ can be expressed as:

$$EBIT = R - OC \tag{4.2}$$

being R revenues and OC operating costs.

Revenues are related to the sale of tickets and are defined as follows:

$$R = N_s \cdot p_s \cdot N_M \cdot O_r \tag{4.3}$$

being N_s the number of seats, p_s the average price per seat, N_M the number of flights per year and O_r the occupancy rate.

Among all operating costs, for the sake of simplicity, the most relevant direct operating costs [16], have been selected and considered constant throughout the aircraft life. They comprise fuel, maintenance costs and depreciation since they account for 53% of operational costs and 77% of direct operational costs. In addition, airport charges, even if their incidence is limited (5%), have been comprised since they include noise fees which are expected to become more impacting in the future.

The average investment is related to the acquisition price of the aircraft. In the last 25 years, design and operational costs have been considered the two components defining the life–cycle costs. From an airline perspective the initial investment equals the acquisition price which is not determined by the design costs. Of course, from a manufacturer viewpoint the airliner acquisition price is its source of revenues which has to exceed manufacturing costs, including design ones, however being the commercial planes market regulated by the laws of supply and demand, acquisition price is not determined by costs but by the value perceived by the purchaser. The features bringing value to airline companies has been analyzed, considering that a variation in operating costs would be offset by a change in selling price in a zero–sum approach [33]. Indeed, in this work, acquisition price has been related to elements determining profits which are driven by aeronautical performance and internal airplane characteristics, passengers comfort and seats features. Maximum speed and balanced field length BFL define the first set whereas the second one is composed of seats number, width and pitch of seats. The aircraft price can be calculated through the following empirical formula [17]:

$$\frac{P_{AC}}{N_s} = 126.708 - 1.007 \cdot N_s + 0.481 \cdot V_{max} + 0.11 \cdot P_s \cdot W_s - 0.025 \cdot BFL \quad (4.4)$$

being N_s the number of seats, V_{max} the maximum aircraft speed, P_s the seat pitch (*i.e.* the space between two consecutive rows of seats), W_s the seat width and BFL the balanced field length.

Fuel, accounting for 33% of operational costs (see [16]) is the most impacting cost item. It has been calculated as follows

$$C_F = M \cdot N_M \cdot P_F \cdot K_F \quad (4.5)$$

being M is the distance covered in an average mission, N_M the average annual flights number, P_F the fuel price, K_F the consumption of the aircraft.

The second–most impacting cost item is maintenance cost which accounts for 9% of operational costs [16]. It has been historically calculated as directly proportional to the acquisition price, for the high cost of a technological product would require expensive spare parts and more specialized workforce. This approach has been followed, being aware an opposite perspective is respectable, based on the assumption that benefits deriving from low manufacturing costs could be charged within the selling price by the manufacturer as an additional value delivered to the purchaser.

In order to move toward the aforementioned equilibrium point among environment, aircraft, finance and community, negative externalities have been included in this analysis.

As described in Sect. 3.2.1, Calabresi and Melamed detailed four options to discipline inconveniences [6].

Air traffic causes chemical and acoustical pollution over a large community inhabiting areas nearby airport facilities. This scenario clearly involves a significant number of people, therefore transaction costs could prevent the possibility for the parties to achieve a deal. More complicated is the discussion on the initial entitlement assignment. On one hand, in case citizens moved to these areas after the settlement of the airport, managers of the latter could affirm that they started their operations with no harm for any community. A similar case has been analysed in 1972 by the Arizona state supreme court: Del Webb, an Arizona real–estate developer, was working on a retirement community development, and sued Spur Industries, a pre–existing feedlot owner since its activities determined a nuisance to the retirement community. Analysing all the elements, and considering that only Del Webb and not Spur Industries could have predicted the nuisance problem, the court ruled that Spur Industries would be obligated to move, but that Del Webb had to reimburse Spur Industries. From this perspective, airport structures could defend their positions if not in conditions to foresee any inconvenience at the beginning of their operations. However considering the evolution of airline industry, it is difficult to state that communities living in those areas were in condition to foresee the air traffic growth. Moreover one might argue that inhabitants have their rights to live in the area without being damaged by pollution causes by airport facilities. As a support of this position, it is worth citing article IV of Declaration of the Rights of Man and the Citizen, which states the following: "Liberty consists of doing anything which does not harm others: thus, the exercise of the natural rights of each man has only those borders which assure other members of the society the enjoyment of these same rights. These borders can be determined only by the law." [38]. Consequently rule 2 looks the more appropriate.

Noise pollution has a critical impact on the inhabitants of boroughs nearby airport facilities causing a properties value decrease which is affected by both internal features and external factors. Schipper deeply analysed hedonic pricing methods [44], including willingness to pay and then Grampella et al. developed a method to calculate the properties loss of value [20] as follows

$$C_N = 437 \cdot 2^{\frac{ANE-95.2}{2}} \cdot N_M \tag{4.6}$$

being N_M the average annual flights number and ANE the Average Noise Exposure that is to say the SEL average value measured in approach, flyover and lateral points as defined by ICAO certification.

Moreover depreciation is calculated according the linear method, as follows:

$$D = \frac{P_{AC}}{N_Y} \tag{4.7}$$

being P_{AC} the aircraft acquisition price and N_Y the years number of airplane useful life.

Finally Operating Costs are defined as:

$$OC = C_F + C_M + C_N + D \tag{4.8}$$

being C_F the fuel cost, C_M the maintenance one and C_N, the monetary impact of sound emissions, D depreciation.

4.1.2 The financial model

In order to identify the best investment within a pool of potential mutually exclusive ones, a company has to compute the Net Present Value NPV of each one. As indicated in Eq. 4.9, NPV is calculated as follows:

$$NPV = \sum_{j=0}^{N} \frac{CF_j}{(1+r)^j} \tag{4.9}$$

where r is the discount rate, N represents the number of years of investment life and CF are the Cash Flows, both positive (PCF) and negative flows (NCF).

$$CF_j = PCF_j - NCF_j \quad j = 0, ..., N \tag{4.10}$$

Negative cash flows, for the sake of simplicity, include the most relevant direct operating costs [16], fuel and maintenance costs, and social costs related to noise pollution, in addition to the acquisition price.

Outflows at year 0 are therefore equal to the acquisition price of the plane as calculated in Eq. 4.4, whereas at year 1 they correspond to the aforementioned direct operating costs, and then they are increased by the inflation rate.

Therefore, negative cash flows are calculated as follows:

$$NCF_j = \begin{cases} P_{AC} & j = 0 \\ (C_F + C_M + C_N) \cdot (1 + I_r)^{(j-1)} & j = 1, ..., N \end{cases} \tag{4.11}$$

being C_F the fuel cost, C_M the maintenance one and C_N, the monetary impact of sound emissions, as defined in 4.1.1, I_r the inflation rate.

Inflows are related to revenues, and have been computed as follows

$$PCF_j = N_s \cdot p_s \cdot N_M \cdot O_r \cdot (1 + I_r)^{(j-1)} \quad j = 1, ..., N \tag{4.12}$$

being N_s the number of seats, p_s the average price per seat, N_M the number of flights per year, O_r the occupancy rate and I_r the inflation rate.

4.2 Optimization problems

In order to identify the most valuable configuration from an airline company viewpoint, the research has been narrowed down on a specific airplane class (single–aisle or twin–aisle jet) on a consistent average mission (short–haul, medium–haul and long–haul flight) and on an average number of missions.

The generic optimization problem consists in searching the set of variables $\mathbf{x}$ yielding a minimum of the objective function $J(\mathbf{x})$, while all the $N + M$ constraints $g(\mathbf{x})$ and $h(\mathbf{x})$ are satisfied, and formalized as in Eq. 1.2.

4.2.1 The accounting approach

The first set of optimization problems has been designed in order to determine the optimal wing system through the minimization of the costs faced by the airlines. Specifically a 164-passengers class aircraft travelling a fixed short–range mission of about 670 kms was analyzed. The design variables and their bounds are summarized in Tab. 4.1.

Design Variable	Reference	Lower Bound	Upper Bound
Half–span [m]	17.05	10.00	35.00
Root Chord [m]	5.100	4.000	10.00
Tip Chord [m]	1.600	1.000	4.000
Thickness Ratio (root)	0.152	0.050	0.200
Thickness Ratio (tip)	0.108	0.050	0.200

Table 4.1: Design variables related to the 164–pax aircraft for the accounting approached problem: reference value, lower bound and upper bound.

The characteristics of the take-off are modeled on the NADP–ICAO A1 procedure, whereas the final approach is compliant with most regulations, i.e. imposed descent of 3°. The fuselage angle–of–attack is such as to provide the vertical equilibrium, and the high-lift devices settings during both take–off and approach procedures ensure the stall prevention. Note that the modification of the wing aerodynamic characteristics due to the change in the geometry is offset by the imposition of the following constraints

$$
\begin{aligned}
g_1(\mathbf{x}) &= \frac{\alpha}{\alpha_{max}} - 1 \leq 0 \\
g_2(\mathbf{x}) &= \frac{N1}{N1_{os}} - 1 \leq 0 \\
g_3(\mathbf{x}) &= 1 - \frac{N1_i}{N1} \leq 0
\end{aligned}
\tag{4.13}
$$

where α_{max} is the stall angle, $N1_{os}$ the engine over-speed, $N1_i$ the engine rotational speed in idle condition. It is worth noting that a pseudo–objective function, including the inequality constraints, is defined in order to achieve the solution of the corresponding unconstrained minimization problem: the constraints treatment is addressed through the penalty function method.

Two single–objective problems have been studied whose objective functions are annual costs incurred into by an airline as defined in Eq. 4.8 and aircraft price (see Eq. 4.4). Solutions of these problems look to converge within 1,500 objective function evaluations as shown in Figs. 4.1 and 4.2.

The first multi–optimization problem is a classic performance analysis whose objective functions are fuel burn and average SEL. One can observe the solutions with respect to generations' progress and the Pareto frontier in Fig 4.3.

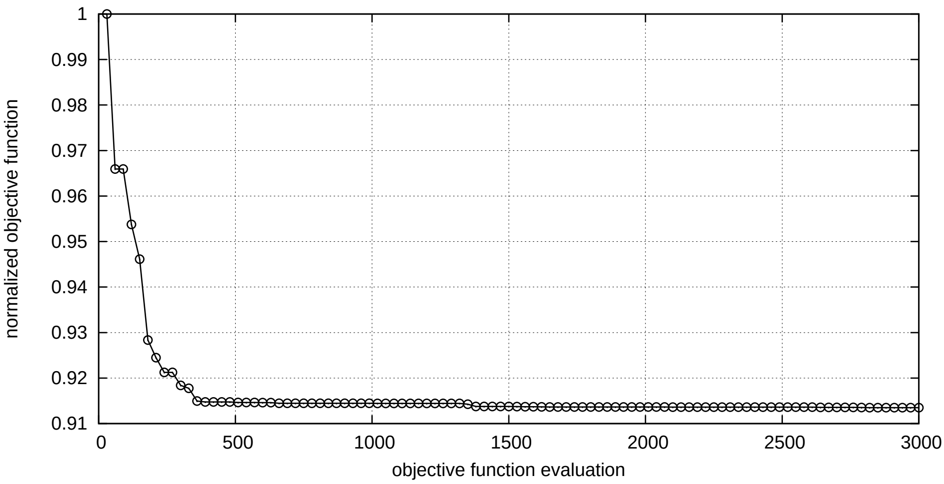


Figure 4.1: Single–objective optimization problem convergence - objective function: annual costs.

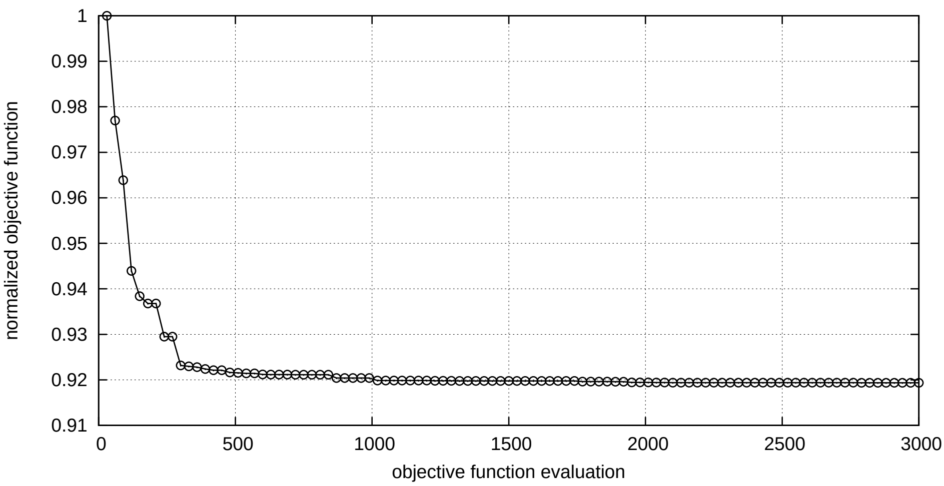


Figure 4.2: Single–objective optimization problem convergence - objective function: aircraft price.

Wing configuration related to a compromise solution belonging to the Pareto set is represented in Fig. 4.5(B). The second optimization problem analyses the impact on aircraft configurations due to accounting consideration; objective functions are therefore aircraft price and annual costs.

Annual costs minimization brings to A wing configuration as indicated in Fig. 4.5. As expected, the consequent price and annual costs compromise configuration (C) deriving from the last multi–objective problem differs from the previous ones (A and B). This testifies that annual costs minimization is a compromise between fuel and noise costs minimization. However, since the aircraft price is a financial item while annual costs are accounting items and that depreciation determines a

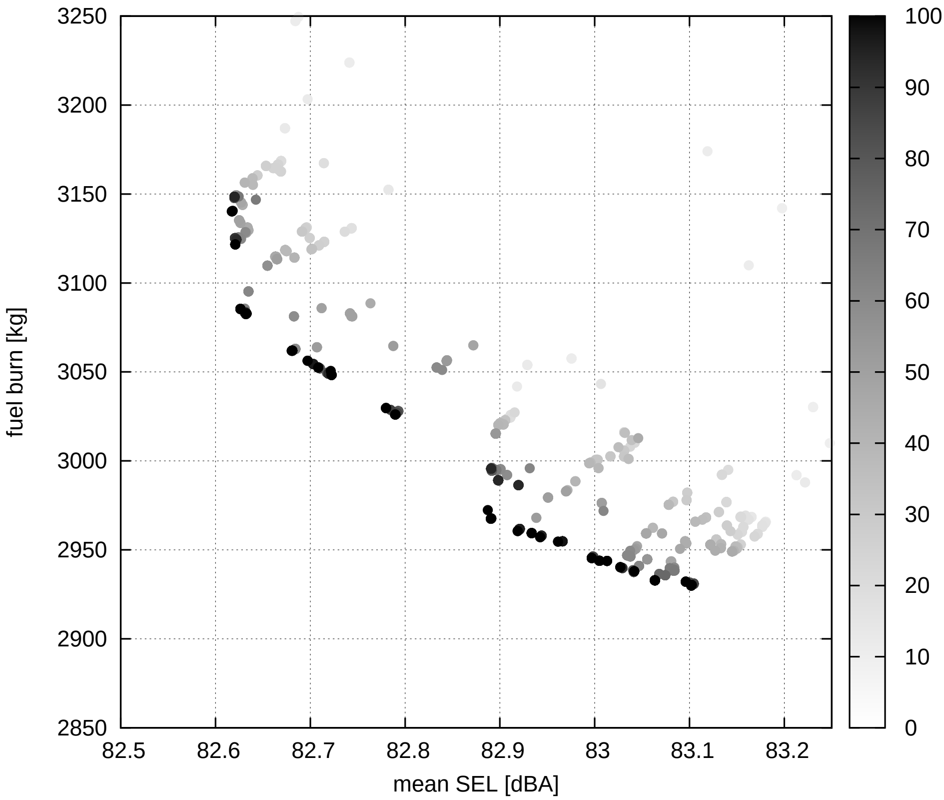


Figure 4.3: Multi–objective optimization solutions and Pareto front - objective functions: mean SEL, fuel burn.

strong dependency of annual costs from aircraft price, being the former directly proportional to the latter, the problem could be ill-posed.

4.2.2 The financial approach

Hinging on the outcome of the first set of optimization problems a second one, based on a financial approach fixing the inconvenience previously identified and refining the economic model, has been performed. The outcome of the study is the identification of the he optimal wing system of a single–aisle aircraft while the goal is the determination, according to the cost modelling described above, of the influence of the acquisition price P_{AC} on the negative cash–flows $NCFs$, chosen as objective functions:

$$\begin{aligned} J_1(\mathbf{x}) &= P_{AC} \\ J_2(\mathbf{x}) &= NCFs \end{aligned} \tag{4.14}$$

In Tab. 4.2 the optimization variables can be found. They deal with the wing shape, as for span, chords and thickness ratio. The tail geometry and the fuselage

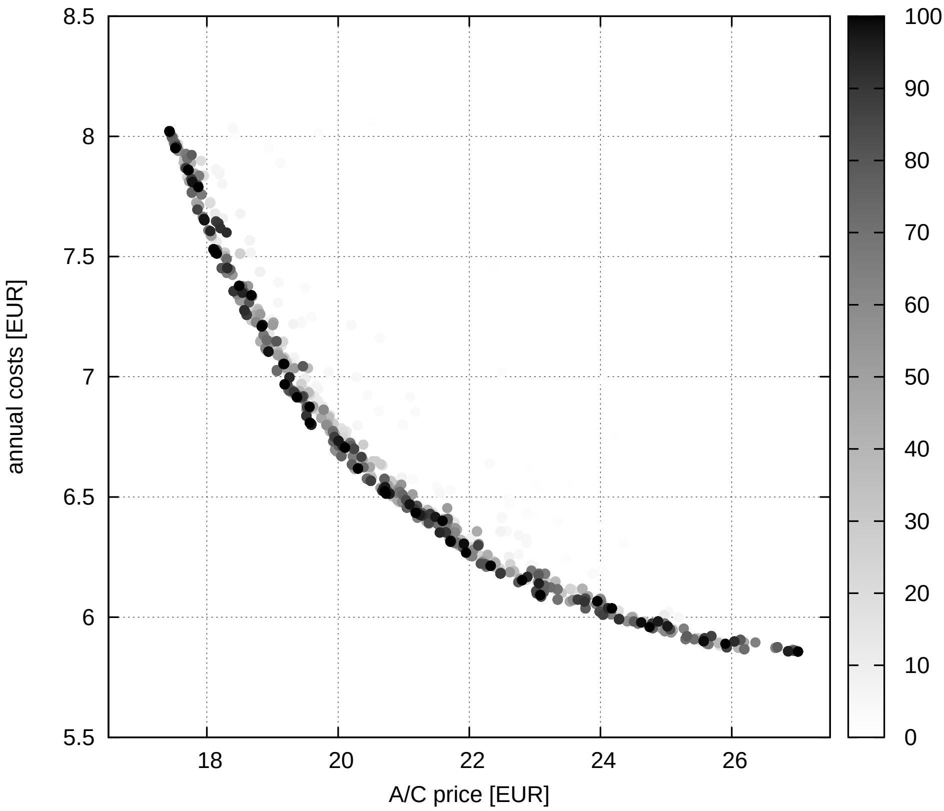


Figure 4.4: Multi-objective optimization solutions and Pareto front - objective functions: aircraft price, annual costs.

size are not object of the optimization and the latter has been fixed consistently with the aircraft class (164–pax)

Design Variable	Reference	Lower Bound	Upper Bound
Half–span [m]	17.05	10.00	35.00
Root Chord [m]	5.100	4.000	10.00
Tip Chord [m]	1.600	1.000	4.000
Thickness Ratio (root)	0.152	0.050	0.200
Thickness Ratio (tip)	0.108	0.050	0.200

Table 4.2: Design variables related to the 164–pax aircraft for the financial approached problem: reference value, lower bound and upper bound.

In Fig. 4.6 the mission profile can be found. It has been modelled based on 100–minutes flight, a typical European air travel: the cruise altitude is 10.000 metres and the cruise Mach number is around 0.77; moreover both the take–off and approach procedures are compliant with current regulations.

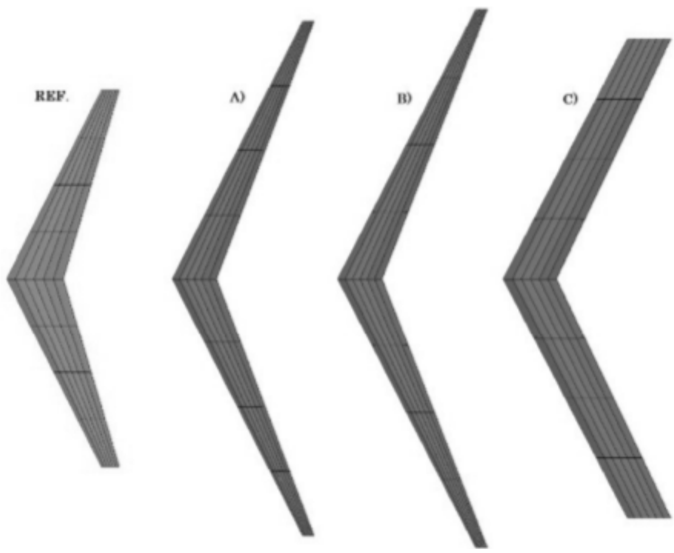


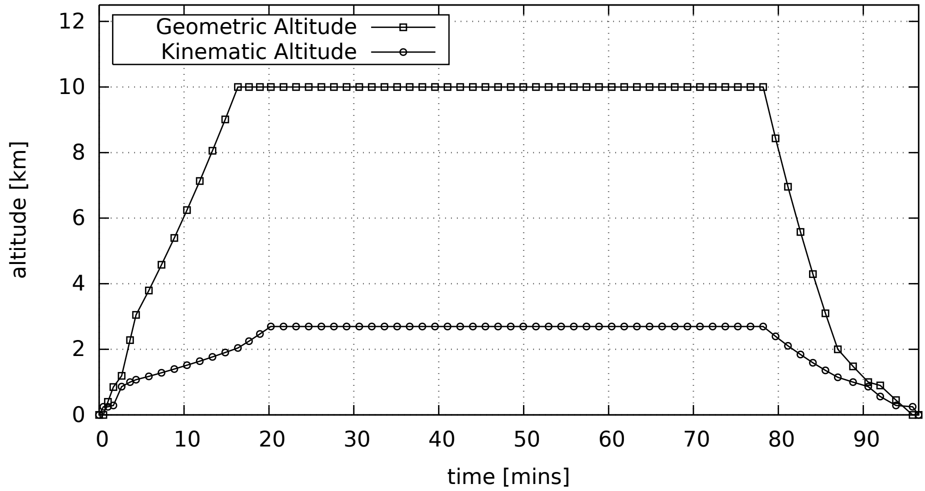
Figure 4.5: Optimal configurations against the reference wing: minimum annual costs (A), average SEL and fuel burn compromise solution (B), A/C price and annual costs compromise solution (C).

The high–lift devices of the reference configuration (see Tab. 4.2) and fuselage angle of attack are set so that both the vertical equilibrium and the stall prevention are simultaneously ensured during the entire mission. Moreover the engines operate at points which guarantee that overspeed is never exceeded and rotational speed never drops beyond the *idle* condition. In addition, since the wing geometry changes determine aerodynamic, structural and inertial aircraft characteristics modifications, during the optimization the following constraints must be imposed:

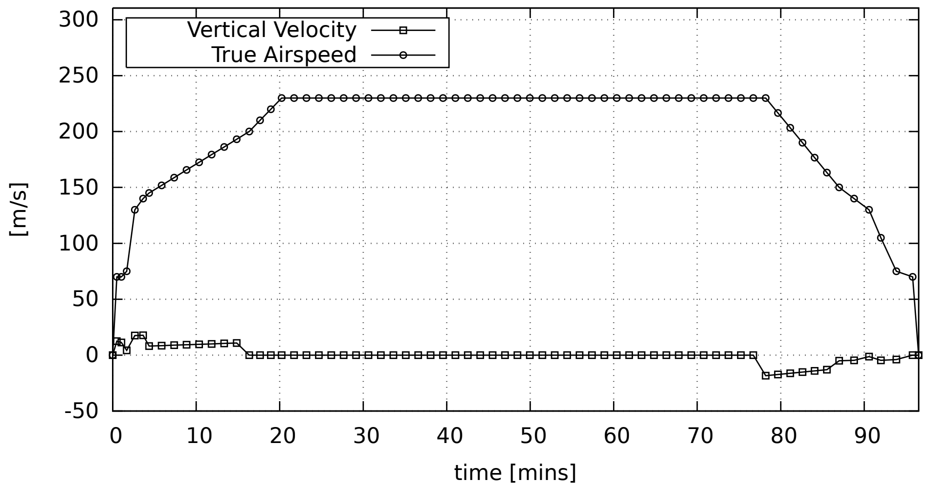
$$
\begin{aligned}
g_1(\mathbf{x}) &= \frac{\alpha}{\alpha_{max}} - 1 \leq 0 \\
g_2(\mathbf{x}) &= \frac{N1}{N1_{os}} - 1 \leq 0 \\
g_3(\mathbf{x}) &= 1 - \frac{N1_i}{N1} \leq 0 \\
g_4(\mathbf{x}) &= \frac{v}{v_{max}} - 1 \leq 0 \\
g_5(\mathbf{x}) &= \frac{\sigma}{\sigma_{max}} - 1 \leq 0
\end{aligned}
\tag{4.15}
$$

being α_{max} the stall angle (function of the high–lift devices settings), $N1_{os}$ and $N1_i$ respectively the engine overspeed and *idle* condition (in revolutions per minute), $v_{max} = \min\left[v_f, v_{NE}\right]$ the maximum acceptable velocity (with v_f the flutter velocity and v_{NE} the *never–exceed* velocity, according to the Federal Acquisition Regulation regulations), σ_{max} the maximum normal stress at the wing root.

In order to include the optimization constraints, a pseudo objective function is



(a) Geometric altitude h_g and kinematic altitude $h_k = v^2/2g$.



(b) True airspeed v_t and vertical velocity $v_v = v_t sin\gamma$, with γ the ramp angle.

Figure 4.6: Mission characteristics as a function of the flight duration for the financial approached problem.

defined based on an external penalty function. The one adopted in this campaign is a quadratic penalty function calculated as proportional to the square of the ratio of the violated constraint value with regard to a reference value.

1000 iterations and 50 particles for the PSO, and 50 individuals over 1000 generations for the MOGA (50000 objective function evaluations for both the algorithms) have been adopted to carry out the minimization problems. Fig. 4.7 and Fig. 4.8 respectively represent the Pareto front evolution through iterations and the optimal Pareto solutions.

Out of all Pareto optimal solutions, the one minimizing the acquisition price

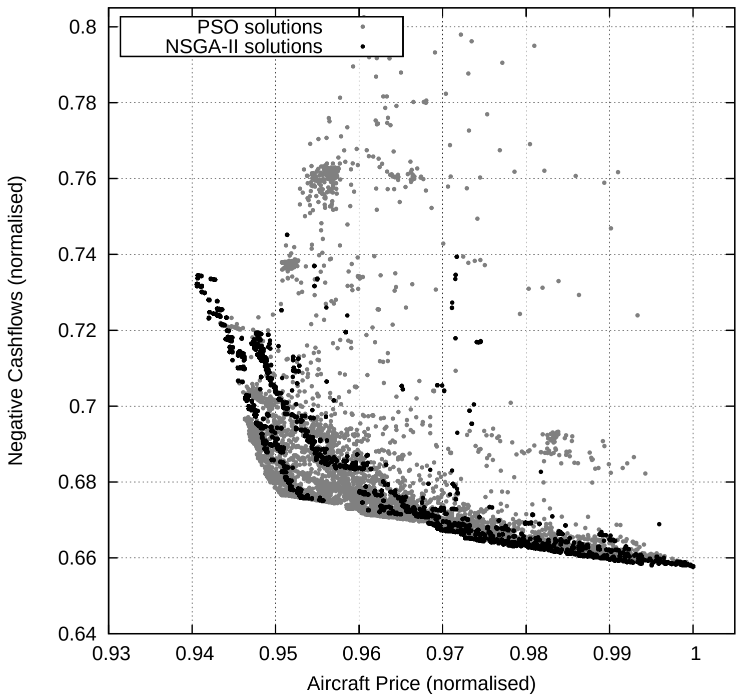


Figure 4.7: Multi–objective optimization aimed to minimize the acquisition price P_{AC} and the annual negative cash flows $NCFs$: normalized solutions (with respect to PSO algorithm first feasible generation) and Pareto front evolution obtained with the PSO and the NSGA-II algorithms.

P_{AC}, the one minimizing negative cash flows $NCFs$, and generic trade–off one have been selected and shown in Fig. 4.8. The associated wing configurations geometric variables have been disclosed in Tab. 4.3.

Design Variable	min[P_{AC}]	min[$NCFs$]	generic OPT
Half–span [m]	16.77	21.31	17.52
Root Chord [m]	5.64	4.036	4.153
Tip Chord [m]	1.817	1.038	2.581
Thickness Ratio (root)	0.074	0.068	0.075
Thickness Ratio (tip)	0.112	0.052	0.077

Table 4.3: Results of the optimization analysis aimed at the minimization of the aircraft price P_{AC} and the negative cash flows $NCFs$.

The minimum price solution being characterized by a greater reference surface and a smaller aspect ratio (see Fig. 4.9) is affected by a greater induced drag contribution and is therefore less performing in terms of fuel consumption. In addition, because of a greater wet surface, acoustic emissions are more impacting. One might

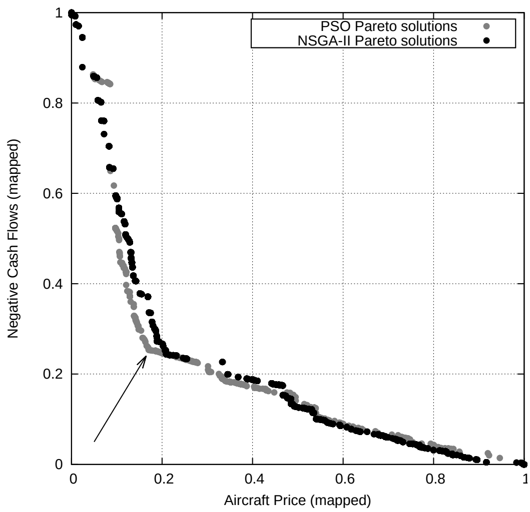


Figure 4.8: Multi–objective optimization aimed to minimize the acquisition price P_{AC} and the annual negative cash flows $NCFs$: Pareto optimal solutions (the generic Pareto optimal solution, shown by the arrow, is the closest to the utopia point) obtained with the `PSO` and the `NSGA-II` algorithms.

argue that this configuration is less efficient, therefore not appropriate for an airline company, however, being positioned on the Pareto Front, it is an optimal solution to be taken into consideration by airways corporations.

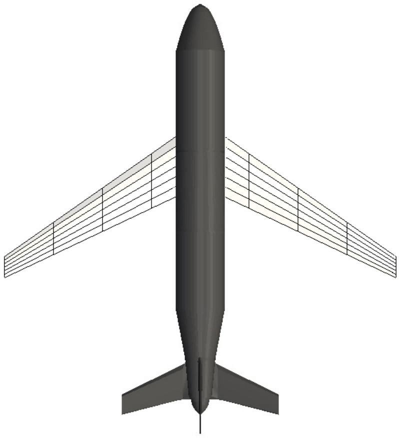
While conceptual design approach traditionally concentrates on performance features, the one proposed in this work is integrated with financial considerations, therefore the connection between airline company financial connotations and aircraft performance can play a critical role in the enhancement of this study and consequently an additional multi–objective optimization analysis has been performed. It aims to minimize the average noise exposure level ANE (see Eq. 4.6) and the fuel burnt W_f over the mission, *i.e.* the objective functions are

$$\begin{aligned} J_1(\mathbf{x}) &= ANE \\ J_2(\mathbf{x}) &= W_f \end{aligned} \tag{4.16}$$

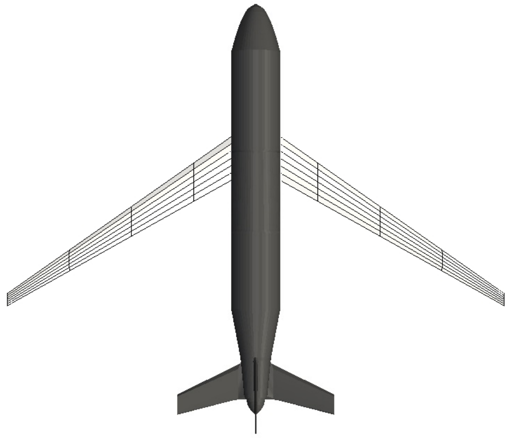
and the constraints are the same defined in Eq. 4.15. The same minimization algorithms and the same number of objective function evaluations have been employed, which for the sake of convenience are reminded hereby: 1000 iterations and 50 particles for the PSO and 50 individuals over 1000 generations for the MOGA.

Tab. 4.4 shows the wing configuration characteristics through the problem design variables, related to the average noise level ANE and fuel consumed W_f minimum solutions. Fig. 4.10 depicts the normalised solutions and the Pareto front evolution and Fig. 4.11 shows the optimal Pareto solutions.

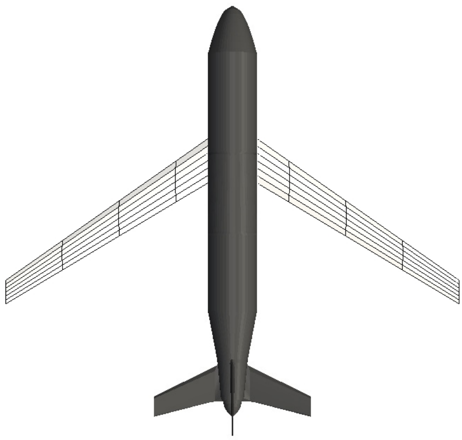
The results reveal that the Pareto front solutions yield to a configuration consistent with the Fig. 4.9(b), which means that the design choices which determine an



(a) Minimum aircraft acquisition price P_{AC}.



(b) Minimum airline negative cash flows $NCFs$.



(c) Trade–off solution (the closest one to the utopia point).

Figure 4.9: Multi–objective optimization aimed to minimize the acquisition price P_{AC} and the annual negative cash flows $NCFs$: optimal wing systems.

abatement of acoustical emissions are similar to the ones which ensure the annual negative cash flows minimum for an airline.

In order to highlight the connections between the two optimization problems, the Paretial optimal solutions in the performance space $(ANE - W_f)$ have been represented in the financial space $(P_{AC}-NCFs)$ and they are located in proximity of its Pareto front. On the other hand, financial optimal solutions have been depicted in the financial space and they lie within the range of the performance problem, not on the front, as shown in Fig. 4.13. This discloses that a conceptual design, based only on technical–performance considerations, could yield to an unsustainable

Design Variable	min[ANE]	min[W_f]	generic OPT
Half–span [m]	23.39	23.34	23.37
Root Chord [m]	4.001	4.213	4.002
Tip Chord [m]	1.002	1.001	1.001
Thickness Ratio (root)	0.058	0.051	0.057
Thickness Ratio (tip)	0.073	0.058	0.072

Table 4.4: Results of the optimization analysis aimed at the minimization of the average noise level ANE and the fuel consumed W_f.

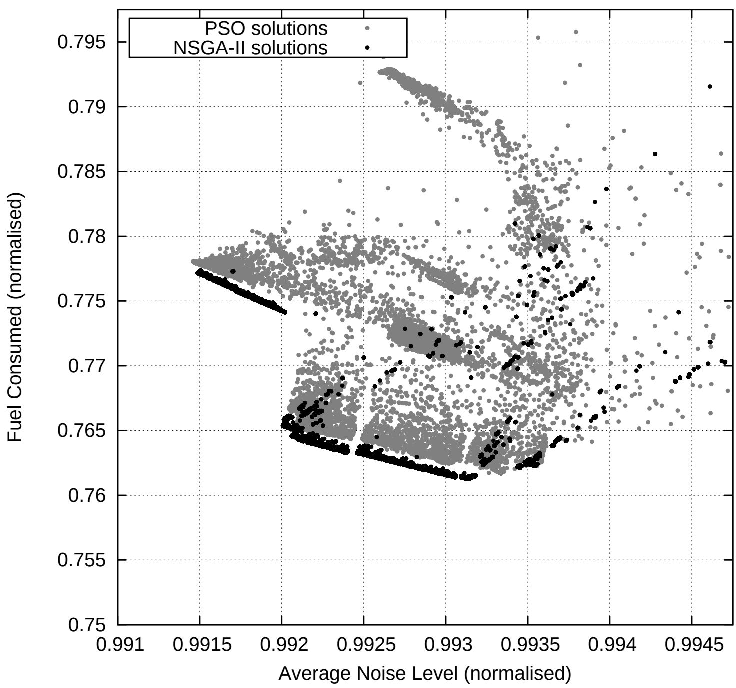


Figure 4.10: Multi–objective optimization aimed to minimize the noise level ANE and the fuel consumption W_f: normalized solutions (with respect to PSO algorithm first feasible generation) and Pareto front evolution obtained with the PSO and the NSGA-II algorithms.

economic output.

Finally, it is key to recognize that cost minimization is absolutely critical to all companies, however value maximization is essential, since higher costs can determine higher revenues. For this reason, after fixing the inconvenience deriving from the accounting approach, it is relevant to enhance the financial analysis including both positive and negative cash flows, so that final value can be calculated.

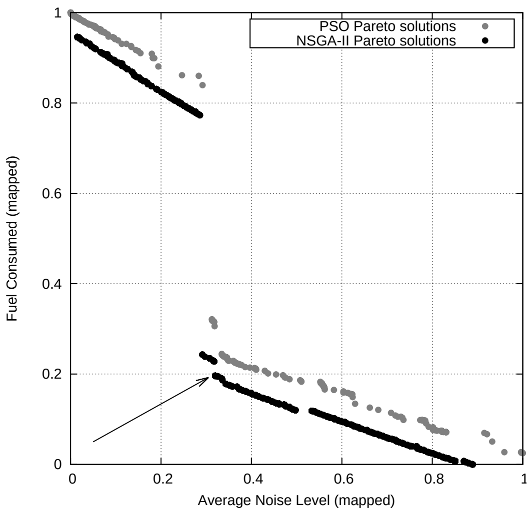


Figure 4.11: Multi–objective optimization aimed to minimize the average noise level ANE and the fuel consumption W_f: Pareto optimal solutions (the generic Pareto optimal solution, shown by the arrow, is the closest to the utopia point) obtained with the `PSO` and the `NSGA-II` algorithms.

4.2.3 The financial–environmental approach

The considerations of the previous set have been used as a starting point for an additional multi–optimization campaign with the aim of identifying the trade–off solution which considers performance, environmental and financial considerations.

A typical performance optimization problem (OPT–0) embraces consumed fuel quantity W_f and average acoustic emissions at certification points ANE as objective functions and another function NPV for an airline company has been taken as merit factor $\Psi(x)$, in order to choose the appropriate solution along the Pareto frontier.

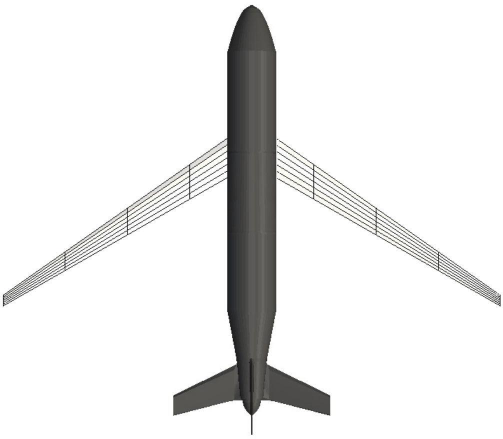
$$\begin{aligned} J_1(\mathbf{x}) &= ANE \\ J_2(\mathbf{x}) &= W_f \end{aligned} \tag{4.17}$$

For an airline company, the main goal is value maximization, *i.e.* NPV maximization which can occur outside of performance–oriented problem Pareto front. For this reason, the analysis has been extended with two additional optimization problems: the first one (OPT–1) objective functions are W_f and NPV

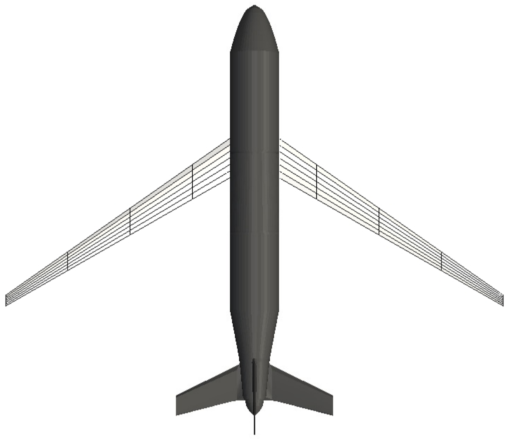
$$\begin{aligned} J_1(\mathbf{x}) &= W_f \\ J_2(\mathbf{x}) &= NPV \end{aligned} \tag{4.18}$$

and ANE is the merit factor $\Psi(x)$. In the second one (OPT–2) NPV and ANE are objective functions and W_f is the merit factor $\Psi(x)$.

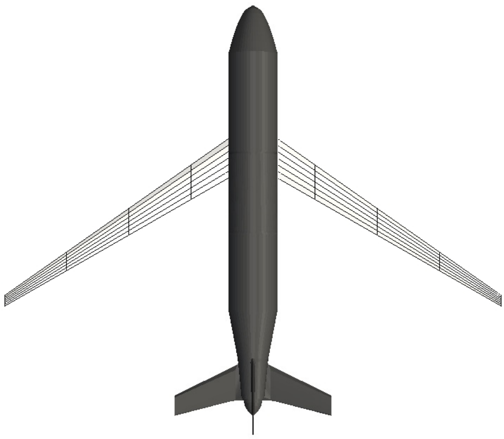
$$\begin{aligned} J_1(\mathbf{x}) &= NPV \\ J_2(\mathbf{x}) &= ANE \end{aligned} \tag{4.19}$$



(a) Minimum noise level ANE.



(b) Minimum fuel consumption W_f.



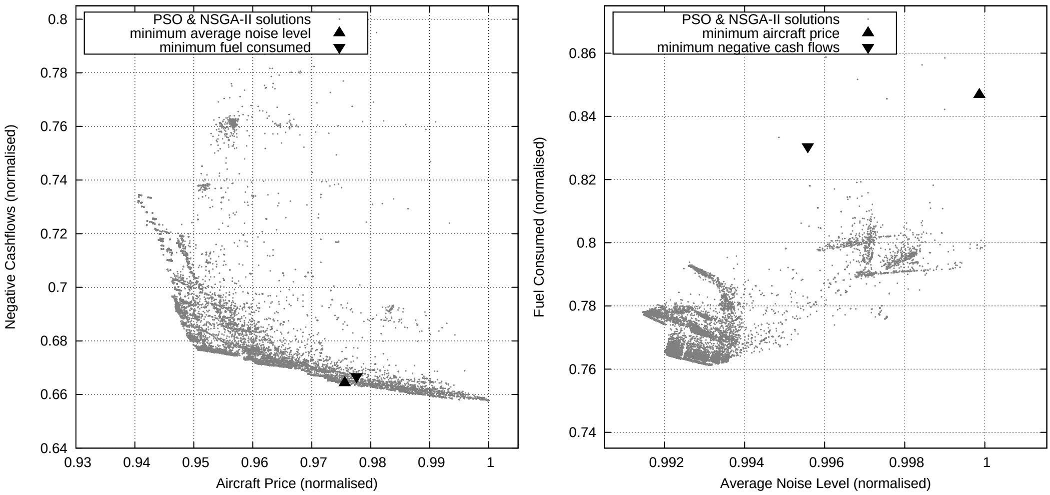
(c) Trade–off solution (the closest one to the utopia point).

Figure 4.12: Multi–objective optimization aimed to minimize the noise level ANE and the fuel consumption W_f: optimal wing systems.

Finally, in order to investigate the connection between the initial investment, its profitability and performance features, it has been investigated a three–dimensional optimization problem (OPT–3) whose objective functions are NPV, ANE and W_f while the merit factor $\Psi(x)$ is the aircraft price P_{AC} (see the Eq. 4.4):

$$\begin{aligned} J_1(\mathbf{x}) &= ANE \\ J_2(\mathbf{x}) &= W_f \\ J_3(\mathbf{x}) &= NPV \end{aligned} \tag{4.20}$$

In Tab. 4.5 a summary of the performed optimization problems can be found. The design space is 11–dimensional and has been set in a way which allows the wing



(a) Minimum average noise level ANE and minimum fuel consumed W_f solutions in the financial problem normalized space ($P_{AC} - NCFs$).

(b) Minimum aircraft price P_{AC} and minimum airline negative cash flows $NCFs$ solutions in the performance problem normalized space ($ANE - W_f$).

Figure 4.13: Comparison of performance solutions to financial solutions.

	OPT–0	**OPT–1**	**OPT–2**	**OPT–3**
ANE [dBA]	$J_1(x)$	$\Psi(x)$	$J_2(x)$	$J_1(x)$
W_f [kg]	$J_2(x)$	$J_1(x)$	$\Psi(x)$	$J_2(x)$
NPV [M$]	$\Psi(x)$	$J_2(x)$	$J_1(x)$	$J_3(x)$
P_{AC} [M$]	–	–	–	$\Psi(x)$

Table 4.5: Optimization problems performed.

configuration to be substantially modified throughout the process. More specifically, the optimization variables, summarized in Tab. 4.6, refer to the wing as for chords, attack angle, thickness ratio at root and tip, span, sweep angle, dihedral angle and flap geometry.

The 164–pax aircraft class determine the fuselage size and the tail geometry is assumed fixed. The mission profile has been conceived according to classic European air route: duration is 100 minutes, the cruise altitude is 10.000 metres and the cruise Mach number is proximately 0.77. The take–off and approach procedures have been designed in accordance with regulations. Fig. 4.14 shows geometric and kinematic altitudes while Fig. 4.15 depicts true airspeed and vertical velocity.

In these optimization problems as well, the reference configuration high–lift devices and the fuselage angle of attack are set so that, throughout the entire mission, the stall is prevented (see Tab. 4.6); furthermore, the engines operate at conditions

Design Variable	Reference	Lower Bound	Upper Bound
Half–span [m]	17.30	12.50	25.00
Root Chord [m]	5.410	4.000	8.000
Tip Chord [m]	1.410	1.000	2.000
Root Thickness Ratio	0.150	0.100	0.200
Tip Thickness Ratio	0.108	0.075	0.150
Root Attack Angle [deg]	3.000	2.000	4.000
Tip Attack Angle [deg]	1.500	0.000	2.000
Sweep Angle [deg]	25.00	20.00	30.00
Dihedral Angle [deg]	5.000	2.500	7.500
Flap Span Ratio	0.680	0.600	0.800
Flap Chord Ratio	0.110	0.050	0.200

Table 4.6: Design variables related to the 164–pax aircraft for the financial–environmental approached problem: reference values, lower bounds and upper bounds.

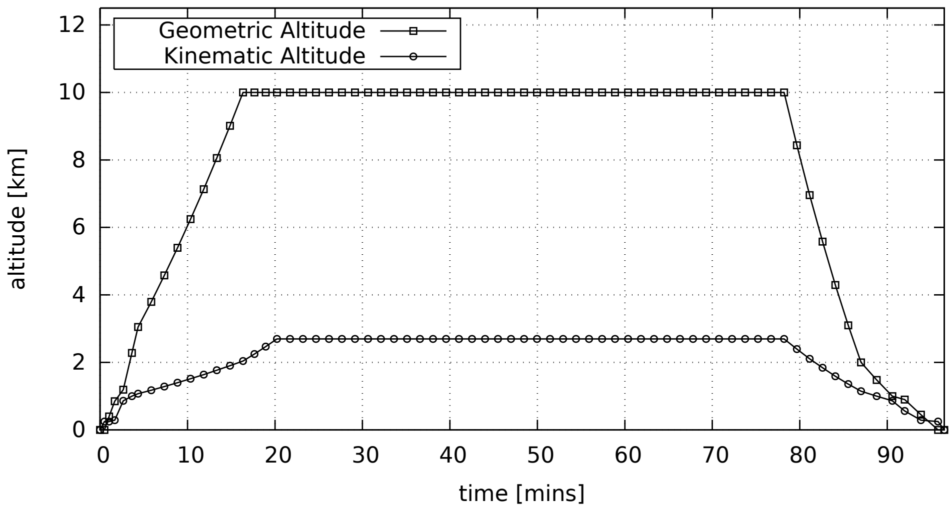


Figure 4.14: Mission characteristics: geometric altitude h_g and kinematic altitude $h_k = v^2/2g$ as a function of the flight duration for the financial–environmental approached problem.

which avoid both the overspeed is exceeded and the rotational speed falls beyond the *idle* condition. Besides, aerodynamic, structural and inertial characteristics of the aircraft are subject to change for the wing geometry variations and therefore

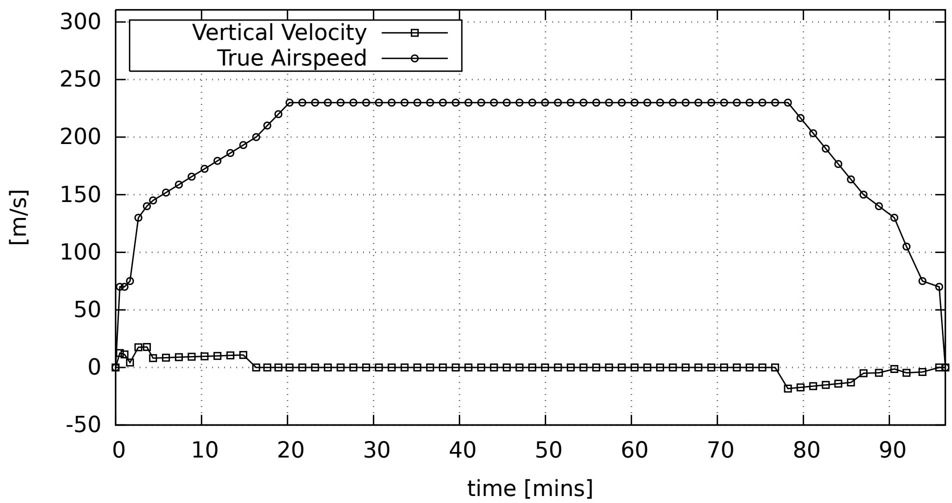


Figure 4.15: Mission characteristics: true airspeed v_t and vertical velocity $v_v = v_t sin\gamma$, with γ the ramp angle, as a function of the flight duration for the financial–environmental approached problem.

the constraints are integrated with the following ones:

$$
\begin{aligned}
g_1(\mathbf{x}) &= \frac{\alpha}{\alpha_{max}} - 1 < 0 \\
g_2(\mathbf{x}) &= \frac{N_1}{N1_{os}} - 1 < 0 \\
g_3(\mathbf{x}) &= 1 - \frac{N1_i}{N_1} < 0 \\
g_4(\mathbf{x}) &= \frac{v}{v_{max}} - 1 < 0 \\
g_5(\mathbf{x}) &= \frac{\sigma}{\sigma_{max}} - 1 < 0 \\
g_6(\mathbf{x}) &= \frac{\tau}{\tau_{max}} - 1 < 0 \\
g_7(\mathbf{x}) &= \frac{EPNL_{T^f}}{EPNL^c_{T^F}} - 1 < 0 \\
g_8(\mathbf{x}) &= \frac{EPNL_{T^s}}{EPNL^c_{T^S}} - 1 < 0 \\
g_9(\mathbf{x}) &= \frac{EPNL_A}{EPNL^c_A} - 1 < 0
\end{aligned}
\tag{4.21}
$$

being α_{max} the stall angle (function of the high–lift devices settings), $N1_{os}$ and $N1_i$ respectively the engine overspeed and *idle* condition (in revolutions per minute), $v_{max} = \min\left[v_f, v_{NE}\right]$ the maximum acceptable velocity (with v_f the flutter velocity and v_{NE} the *never–exceed* velocity, according to the Federal Acquisition Regulation regulations), σ_{max} the maximum normal stress at the wing root, the subscripts T^f, T^s and A denote respectively the take–off flyover, the take–off sideline and the approach certification points whereas the superscript c is related to the values of the noise certification requirements.[1]

These constrained optimizations problems as well have been replaced by other ones, which include pseudo–objective functions incorporating the constraints through a quadratic penalty function. In addition, they have been solved making use of 300 iterations and 110 particles, *i.e.* 33.000 objective function evaluations. Feasible solutions and Pareto fronts of all the explored optimization analyses have been identified and represented. Frontiers have been normalized with respect to the values of a comparable currently operating aircraft. Fig. 4.16 shows the optimization problem OPT–0 feasible solutions (see Tab. 4.5) whose goal is consumed fuel W_f and acoustic emissions ANE minimization and Fig. 4.17 depicts its normalized Pareto front.

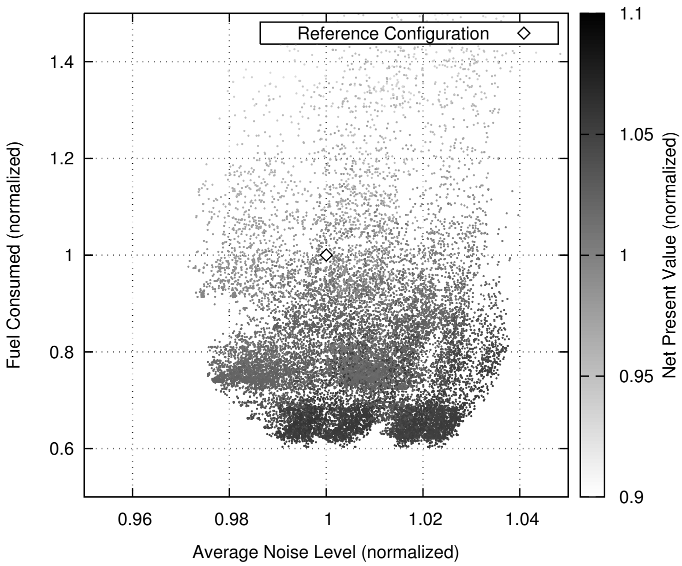


Figure 4.16: Feasible solutions (normalized with regard to the values related to a comparable currently flying aircraft) of multi–objective optimization aimed to minimize the acoustic emissions ANE and the fuel consumption W_f.

The solution on the Pareto frontier characterized by the the maximum NPV could represent the best compromise dealing with the economic interests of an airline company. It is noted that it is in proximity of the solution whose distance from utopia point is the minimum one.

On the other hand, airways companies strive to influence the market in order to have introduced airplane configurations maximizing their NPV and the corre-

[1]The values of the noise certification requirements are obtained, in this work, as average values of the certification sheets related to the specific aircraft class.

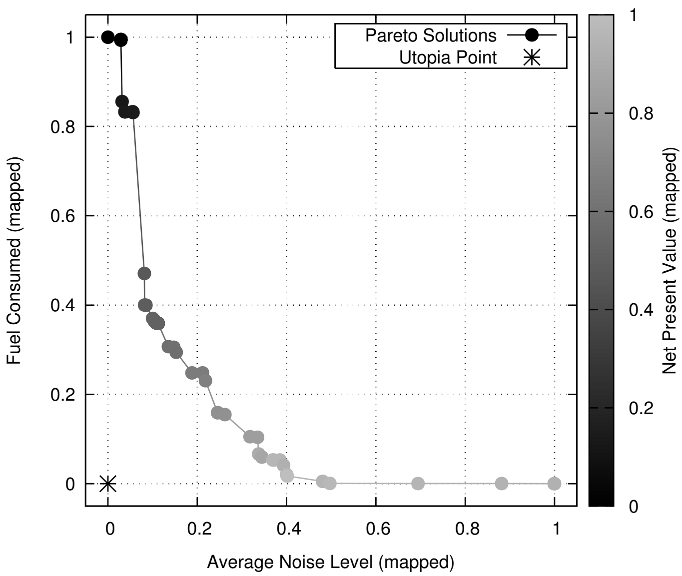


Figure 4.17: Pareto front of multi–objective optimization aimed to minimize the acoustic emissions ANE and the fuel consumption W_f.

sponding solution might not lie on the Pareto front of the W_f, ANE space. What is, then, the link between airline profitability and aircraft performance features? The case OPT–1 (see Tab. 4.5) explores the connection between the fuel burnt W_f and the investment profitability NPV: Fig. 4.18 and Fig. 4.19 show respectively feasible solutions and Pareto front of this optimization problem. The front shape reveals that NPV and W_f are objective functions moderately concurrent. Furthermore, one can note that feasible solutions show that a fuel consumption decrease is associated to an NPV increase, up to a threshold. This is aligned with the cost breakdown [16] which exposes that fuel cost accounts for 1/3 of total annual costs, being then the most impacting cash outflow item. It is also consistent with the actions airline companies implement with the goal of a fuel consumption reduction. The problem OPT–2 (see Tab. 4.5) investigates the relation between the investment profitability NPV and the acoustic emissions ANE: Figs. 4.20 and 4.21 represent respectively feasible solutions and normalized Pareto front.

Differently than before, the Pareto front shape reveals that NPV and ANE are highly concurrent objective functions which yield to the conclusion that airline companies are not motivated to reduce noise emissions unless other forces intervene, like market dynamics for instance related to consumers' interest toward ecological solutions, or regulatory authority which might reduce the limit of ANE or charge the quantity exceeding an established level. Furthermore, it is worth highlighting that feasible solutions representation reveal the presence of a threshold delimiting an area where noise costs have an extremely limited influence on NPV. This area shows that NPV does not exceed 105% of NPV of the reference configurations

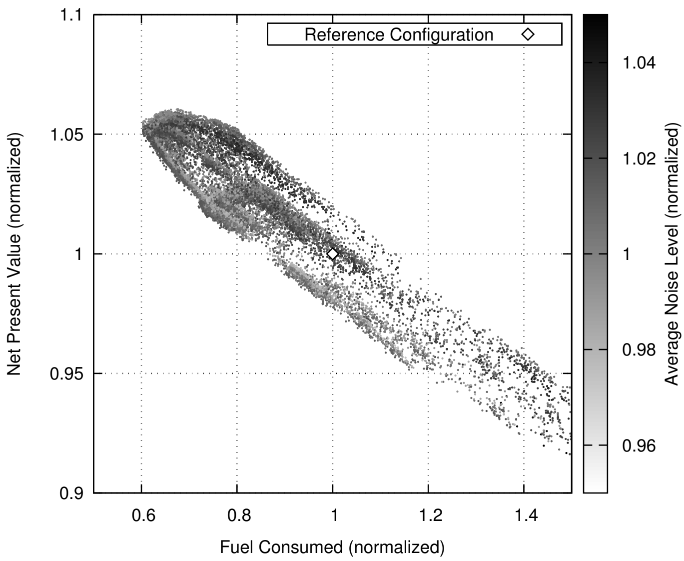


Figure 4.18: Feasible solutions (normalized with regard to the values related to a comparable currently flying aircraft) of multi–objective optimization aimed to maximize NPV and minimize fuel consumption W_f.

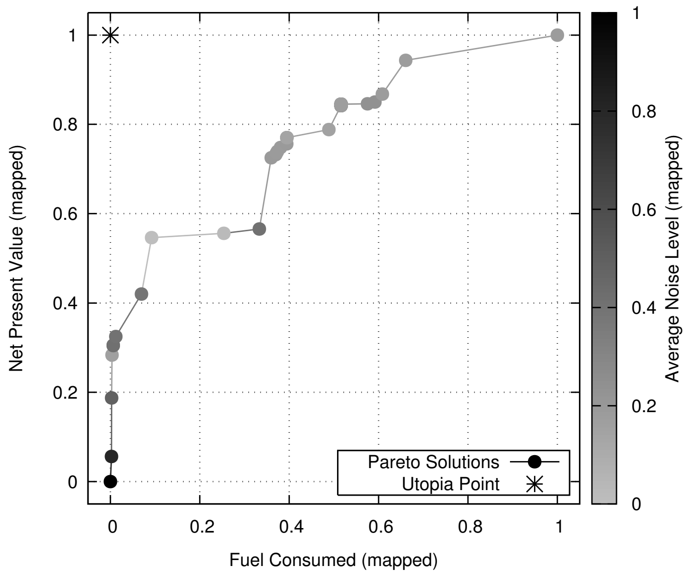


Figure 4.19: Pareto front of multi–objective optimization aimed to maximize NPV and minimize fuel consumption W_f.

and ANE spans between 99% and 103% of reference emissions. This reinforces and integrates the previous consideration: airline companies have no financial interest to reduce their noise emissions and if a decrease is desirable and required, noise charges need to be more significant. This outcome can be achieved through different

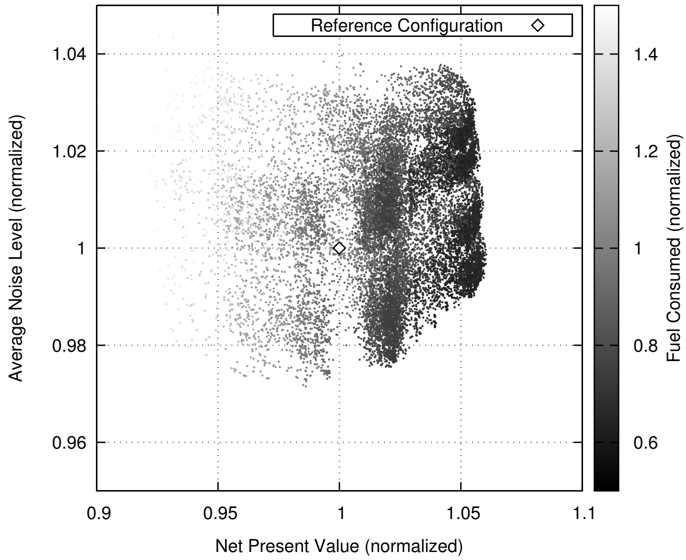


Figure 4.20: Feasible solutions (normalized with regard to the values related to a comparable currently flying aircraft) of multi–objective optimization aimed to maximize NPV and minimize acoustic emissions ANE.

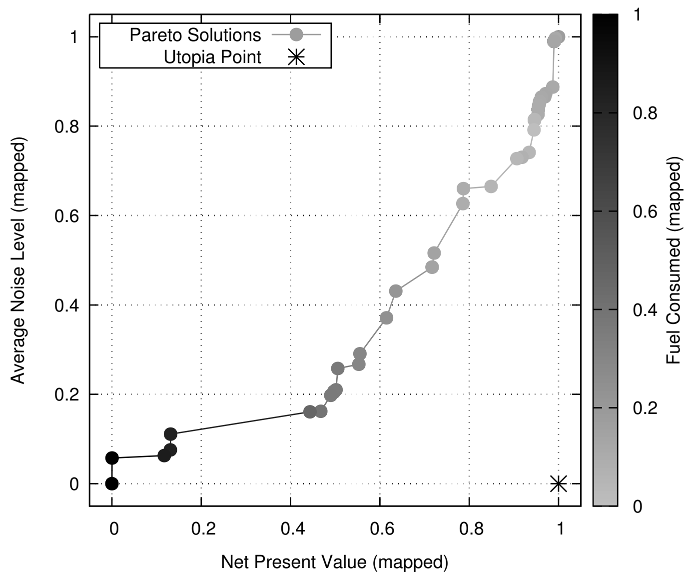


Figure 4.21: Pareto front of multi–objective optimization aimed to maximize NPV and minimize acoustic emissions ANE.

options. It is worth mentioning two among the most common. Airways companies exceeding an ANE maximum value established by law can be charged an extra fee. Alternatively "noise certificates" could be established. Virtuous companies whose ANE values are below the limit could market a quantity of certificates determined by the difference between the limit itself and their noise emissions, while "noisy" airways companies should acquire a quantity of certificates to compensate their exceeding quota. Notwithstanding, a deep business law analysis of these approached go beyond the purpose of this work.

In order to include in a more complete analysis, both performance and financial factors, a three–dimensional multi–objective optimization problem has been explored (OPT–3, see Tab. 4.5). Objective functions are acoustic emissions ANE, fuel consumption W_f and Net Present Value NPV. Fig. 4.22 depicts the feasible solutions whereas Fig. 4.23 shows the Pareto front.

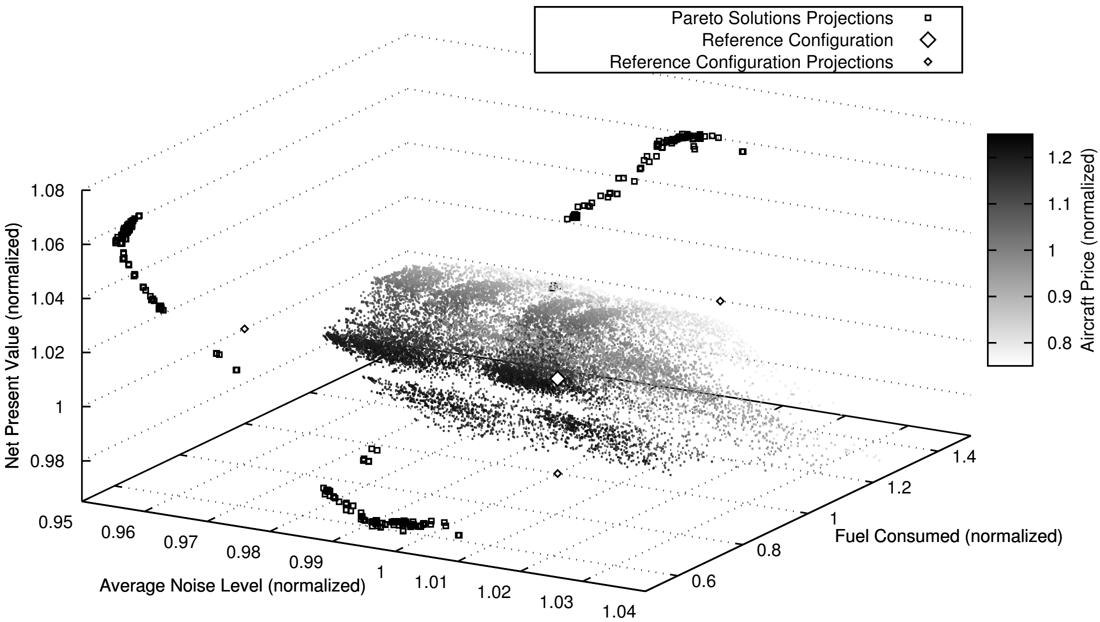


Figure 4.22: Feasible solutions (normalized with regard to the values related to a comparable currently flying aircraft) of multi–objective optimization aimed to maximize NPV and minimize both acoustic emissions ANE and fuel consumption W_f.

Financial resources are obviously finite therefore, the initial investment is a crucial factor to be taken into account. The study of the three–dimensional problem reveals that the higher values of NPV are characterized by high airplane costs which is consistent with the manufacturers goal to monetize the value they create for their customers, the airways companies. This is also in agreement with the capital–intensive characteristics of the industry. The analysis also shows that maximum NPV is achieved at a point where fuel consumption is low and average emissions level is at an average value equal to 99% of the reference acoustic pollution. This viewpoint, then, allows to observe that airlines have an economic interest to maintain the current noise level and it strengthens the previous observation about the need for critical noise fees to achieve a reduction of acoustic emissions.

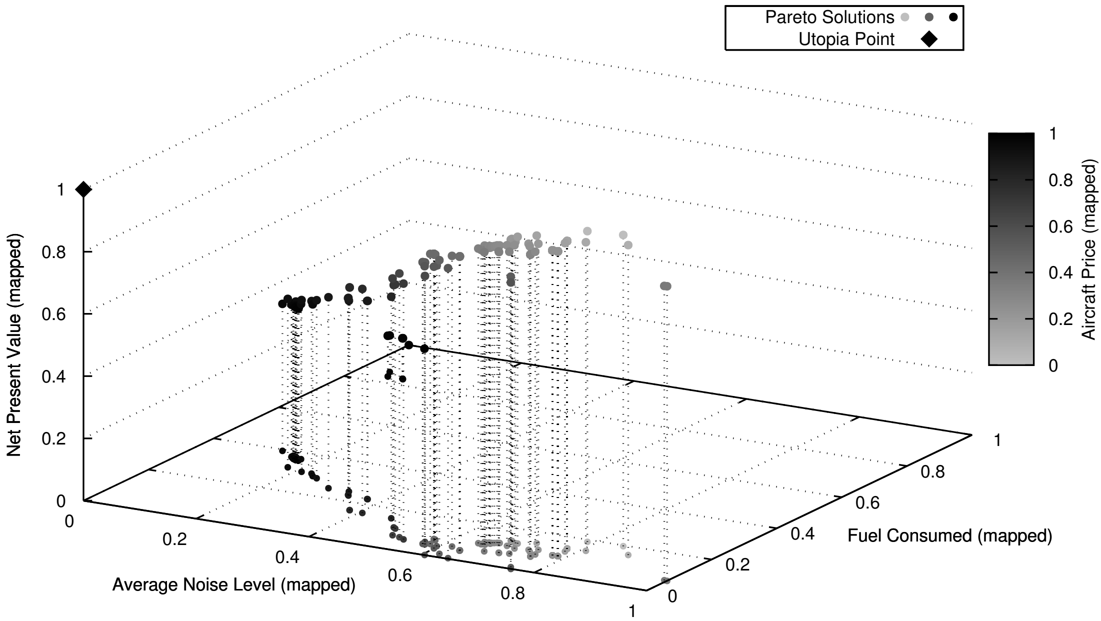


Figure 4.23: Pareto front of multi–objective optimization aimed to maximize NPV and minimize both the acoustic emissions ANE and fuel consumption W_f.

4.3 The robust optimization problem

The analysis developed in the previous sections explores the conceptual design from a deterministic viewpoint. The robust optimization of a single–aisle aircraft wing system is therefore analyzed with the aim of exploring the impacts on uncertainty due to operational and financial factors on an airline profitability. More specifically, the cruise Mach number (a typical performance operational parameter) and the inflation rate (a financial–based environmental parameter) are taken into consideration, being critical in cash flows distribution. The most valuable configuration identification from an airways company perspective is meaningfully affected by uncertain environmental circumstances since operating conditions different than the design conditions can undermine the long–term profitability. With the aim of mitigating financial risks, then, a robust approach to conceptual design is advisable. This approach is declined, in the current work, in the airline initial investment profitability maximization (mathematically represented by the NPV), in a risk management scenario *i.e.* handling uncertainties on parameters not controlled by the designer. As described in Sect. 1.5, the robust optimization problem is based on the study of the expected value $E[f_i]$ and standard deviation $\sigma[f_i]$ of the function f_i of interest. In this work, the focus is on the net present value of an airline company, *i.e.* $f_1 = NPV$, therefore the objective functions, according to Eq. 1.10, are the following ones

$$J_1(\mathbf{x},\mathbf{y}) = E\left[NPV(\mathbf{x},\mathbf{y})\right]$$
$$J_2(\mathbf{x},\mathbf{y}) = \sigma\left[NPV(\mathbf{x},\mathbf{y})\right] \tag{4.22}$$

with $J_1(\mathbf{x},\mathbf{y})$ to be maximized and $J_2(\mathbf{x},\mathbf{y})$ to be minimized. Furthermore a third objective function Ψ, has been defined as merit factor, in order to identify a criterion to determine the most suitable solutions among the ones on the Pareto front.

$$\Psi(\mathbf{x},\mathbf{y}) = ANE \tag{4.23}$$

This add–on allows to take in to account the needs of community living in areas nearby airport facilities in addition to airline company's interests. Two different stochastic scenarios have been analysed and both might largely impact cash flows distribution. In the first one the cruise Mach number M_{cr} is affected by uncertainties and this influences the fuel burnt quantity, that is to say cash outflows. In the second one, an uncertain inflation rate I_r impacts cash flows distribution over the aircraft useful life. According to historical data analysis, the uncertain parameters probabilistic distribution has been approximated through discrete *beta*–distribution functions [21]. In this problem, as well, the wing shape in terms of span, chords, thickness ratio, both root and tip angle of incidence, dihedral and sweep angles are the optimization variables and have been summarized in Tab. 4.7. The fuselage size is still determined according to the aircraft class (164–pax) and the tail geometry is assumed as fixed.

Design Variable	**Reference**	**Lower Bound**	**Upper Bound**
Half–span [m]	17.05	10.00	35.00
Root Chord [m]	5.100	4.000	10.00
Tip Chord [m]	1.600	1.000	4.000
Thickness Ratio (root)	0.152	0.050	0.200
Thickness Ratio (tip)	0.108	0.050	0.200
Angle of Incidence (root) [deg]	5.000	2.000	8.000
Angle of Incidence (tip) [deg]	0.000	-2.000	2.000
Sweep [deg]	25.00	20.00	30.00
Dihedral [deg]	5.000	2.500	7.500

Table 4.7: Design variables related to the 164–pax aircraft for the robust optimization problem: reference value, lower bound and upper bound.

A 100–minutes flight, a typical European air travel, has been selected to define the mission profile. Therefore the cruise altitude is 10.000 metres, the cruise Mach number is 0.77 (design condition if the parameter is affected by uncertainty). Both the take–off and approach procedures are compliant with current regulations: the

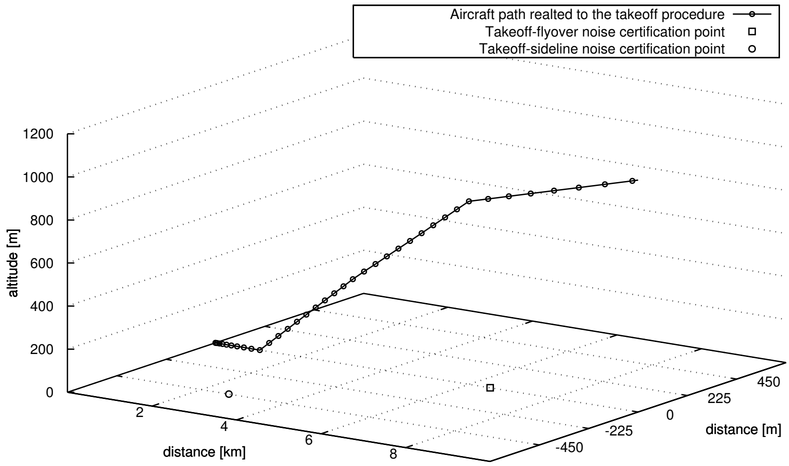


Figure 4.24: Aircraft path and noise certification points (takeoff–flyover and takeoff–sideline) related to the takeoff procedure.

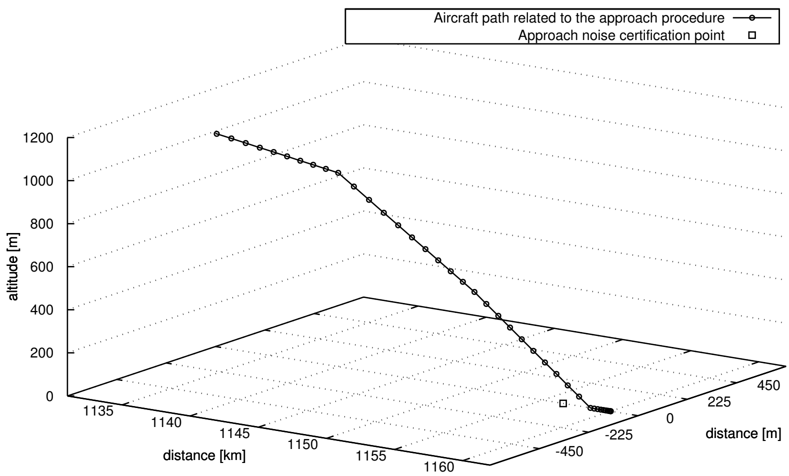


Figure 4.25: Aircraft path and noise certification point related to the approach procedure.

noise certification points, defined by ICAO certification, are represented in Figs. 4.24 and 4.25.

The vertical equilibrium and the stall prevention of the reference configuration are ensured throughout the mission by the high–lift devices settings and the fuselage angle of attack. As in previous problems, engines operates at conditions which guarantee the *overspeed* is never exceeded and the rotational speed never drops beyond the *idle* condition. In addition, aircraft configuration aerodynamic, structural and inertial characteristics are subject to change for the modifications of the geometry of the wing and consequently, the following constraints have been imposed in the optimization

$$
\begin{aligned}
g_1(\mathbf{x}) &= \frac{\alpha}{\alpha_{max}} - 1 \leq 0 \\
g_2(\mathbf{x}) &= \frac{N1}{N1_{os}} - 1 \leq 0 \\
g_3(\mathbf{x}) &= 1 - \frac{N1_i}{N1} \leq 0 \\
g_4(\mathbf{x}) &= \frac{v}{v_{max}} - 1 \leq 0 \\
g_5(\mathbf{x}) &= \frac{\sigma}{\sigma_{max}} - 1 \leq 0 \\
g_6(\mathbf{x}) &= \frac{\tau}{\tau_{max}} - 1 \leq 0
\end{aligned}
\tag{4.24}
$$

being α_{max} the stall angle (function of the high–lift devices settings), $N1_{os}$ and $N1_i$ respectively the engine overspeed and *idle* condition (in revolutions per minute), $v_{max} = \min\left[v_f, v_{NE}\right]$ the maximum acceptable velocity (with v_f the flutter velocity and v_{NE} the *never–exceed* velocity, in compliance with the Federal Acquisition Regulations), σ_{max} and τ_{max} the maximum normal and shear stress at the root of the wing. In addition, since the aircraft must be certified with regard to the noise emissions, additional constraints were also imposed

$$
\begin{aligned}
g_7(\mathbf{x}) &= \frac{EPNL_{T^f}}{EPNL^c_{T^F}} - 1 < 0 \\
g_8(\mathbf{x}) &= \frac{EPNL_{T^s}}{EPNL^c_{T^S}} - 1 < 0 \\
g_9(\mathbf{x}) &= \frac{EPNL_A}{EPNL^c_A} - 1 < 0
\end{aligned}
\tag{4.25}
$$

where the subscripts T^f, T^s and A denote respectively the take–off flyover, the take–off sideline and the approach certification points whereas the superscript c is related to the values of the noise certification requirements: it is important to highlight that the values of the noise certification requirements are obtained as average values of the certification sheets related to the specific aircraft class.

Both minimization problems have been solved through 300 iterations and 90 particles (which correspond to ten times the size of the vector $\mathbf{x}$), *i.e.* 27.000 objective function evaluations even though the solution convergence was acceptable after about 20.000 evaluations. It is noted that in order to calculate NPV, each evaluation requires its computation as many times as the number of samples of the uncertain parameter stochastic distribution are: in this work, following satisfactory initial convergence tests, samples are seven.

Feasible solutions have been identified and depicted normalized with respect to the NPV of comparable currently operating aircraft selected as reference configuration for the both the problems. Pareto fronts have been determined and represented mapped.

The first optimization problem explored the impact on profitability for the uncertainty on the cruise Mach. Fig. 4.26 shows its feasible solutions and Fig. 4.27 depicts the normalized Pareto front.

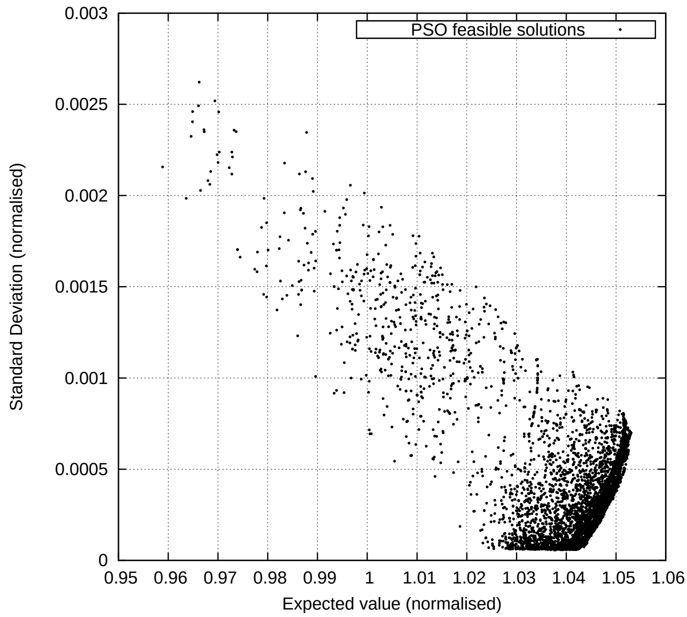


Figure 4.26: Feasible solutions, normalized with regard to a reference configuration, of the robust optimization aimed to maximize the expectation of the Net Present value (NPV) and minimize its standard deviation with regard to the cruise Mach number M_{cr}.

Observing the normalized solutions, it is worth highlighting that along the Pareto front, NPV expected value extension is 1,5% and standard deviation ranges from 0 to 0,08% of NPV reference value. More in detail, the impact relevance of the uncertainty on cruise Mach on an airways company profitability extends from a 0,5% decrease to a 1% increase and even the most profitable solution, being associated to a 0,08% standard deviation is characterized by a limited risk. This solution also minimizes the Ψ function which represents the ANE and therefore it is the favourite one for the inhabitants of areas nearby airport facilities. Furthermore, Tab. 4.8 and Fig. 4.28 show that configurations related to maximum expected value and minimum standard deviation are similar. In conclusion, one might recognize that the cruise Mach even if affected by uncertainties does not really impact the configuration choice.

The second optimization problem explores the effect of an uncertain inflation rate on an airline company profitability. Fig. 4.29 depicts its feasible solutions and Fig. 4.30 shows its normalized Pareto front.

Observing Fig. 4.29, it is worth highlighting that the extension of the expected value among Pareto front solutions is equal to 10% and is much wider than the one in the previous problem, and the standard deviation ranges from 7,6% to 8,3%. In

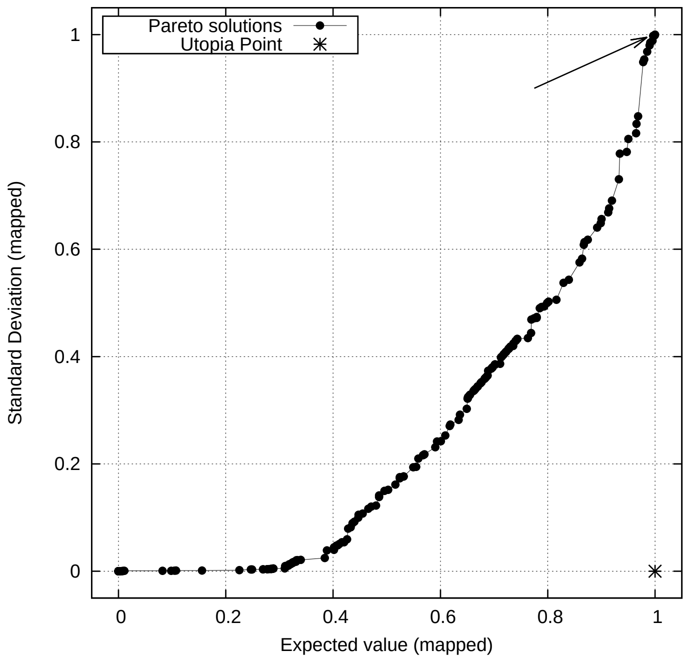


Figure 4.27: Pareto solutions (mapped) of the robust optimization aimed to maximize the expectation of the Net Present value (NPV) and minimize its standard deviation with respect to the cruise Mach number M_{cr}; the minimum average noise ANE solution is shown by the arrow.

Design Variable	$\max[E(NPV)]$	$\min[\sigma(NPV)]$	mix $[ANE]$
Half–span [m]	21.02	15.36	21.02
Root Chord [m]	4.000	5.347	4.000
Tip Chord [m]	1.000	1.464	1.000
Thickness Ratio (root)	0.100	0.100	0.100
Thickness Ratio (tip)	0.075	0.075	0.075
Angle of Incidence (root) [deg]	5.637	4.018	5.637
Angle of Incidence (tip) [deg]	2.000	-2.000	2.000
Sweep [deg]	30.00	30.00	30.00
Dihedral [deg]	7.500	2.500	7.500

Table 4.8: Optimal design variables related to the robust optimization problem aimed to maximize the Net Present Value NPV with uncertain cruise Mach number M_{cr}: maximum expected value $E\left[NPV(\mathbf{x},\mathbf{y})\right]$, minimum standard deviation $\sigma\left[NPV(\mathbf{x},\mathbf{y})\right]$ and minimum average noise exposure ANE.

other terms, the inflation rate uncertainty effect is critical extending from a 3,5% decrease to a 6,5% increase and all the solutions, being related to significant value of standard deviation are affected by a relevant risk. Therefore from an airline company

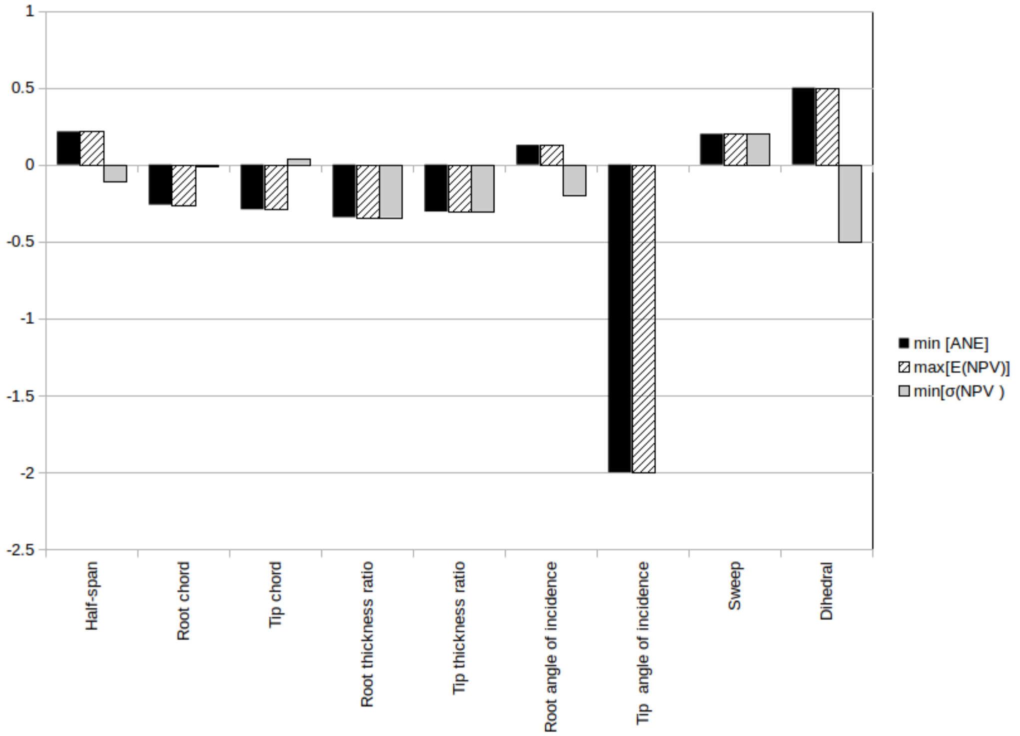


Figure 4.28: Optimal design variables related to the robust optimization problem aimed to maximize the Net Present Value NPV with uncertain cruise Mach number M_{cr}: maximum expected value $E\left[NPV(\mathbf{x},\mathbf{y})\right]$, minimum standard deviation $\sigma\left[NPV(\mathbf{x},\mathbf{y})\right]$, and mininum average noise exposure ANE.

perspective a further study is needed and in order to determine the solution whose risk is acceptable, a confidence interval has been defined as follows

$$CI = [E(NPV) - c\sigma(NPV); E(NPV) + c\sigma(NPV)] \tag{4.26}$$

Solutions maximizing values of bounds of the aforementioned interval represent the preferred trade–off for an airways company both in the best–case and worst–case scenarios. They have been identified and both coincide with the maximum NPV expected valued. This yields to the conclusion that for an airline company, even though the inflation rate uncertainty critically affects its profitability, the ideal configuration is the one maximizing the NPV expected value. However this outcome does not take into consideration the impact due to acoustic emissions suffered by populations of areas nearby airport facilities. Along the Pareto front the solution minimizing ANE has been identified and represented (see Fig. 4.30) and the relative configuration and the ones determining the maximum expected value, minimum standard deviation have been depicted in Tab. 4.9 and Fig. 4.32. The emerging differences reinforce the need for a thorough analysis which embraces si-

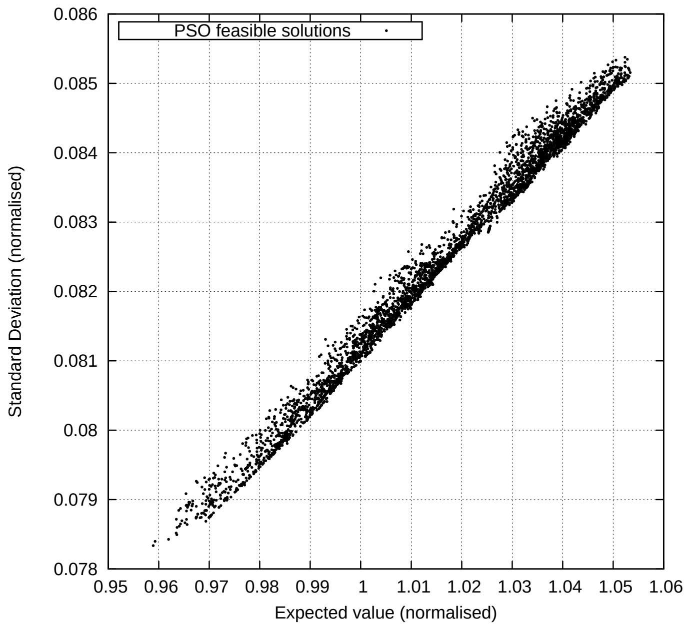


Figure 4.29: Feasible solutions, normalized with regard to a refernce configuration, of the robust optimization aimed to maximize the expectation of the Net Present value (NPV) and minimize its standard deviation with respect to the inflation rate I_r.

multaneously different stakeholders needs from a stochastic perspective. Future development therefore might analyze different functions of interest simultaneously and/or take into account several uncertain parameters in the same analysis.

Design Variable	max$[E(NPV)]$	min$[\sigma(NPV)]$	min $[ANE]$
Half–span [m]	20.98	17.95	23.55
Root Chord [m]	4.000	4.000	4.000
Tip Chord [m]	1.678	1.502	1.000
Thickness Ratio (root)	0.100	0.200	0.100
Thickness Ratio (tip)	0.075	0.150	0.075
Angle of Incidence (root) [deg]	2.000	8.000	2.000
Angle of Incidence (tip) [deg]	0.255	-2.000	-2.000
Sweep [deg]	30.00	20.00	30.00
Dihedral [deg]	7.500	2.500	7.500

Table 4.9: Optimal design variables related to the robust optimization problem aimed to maximize the Net Present Value NPV with uncertain inflation rate I_r: maximum expected value $E\left[NPV(\mathbf{x},\mathbf{y})\right]$, minimum standard deviation $\sigma\left[NPV(\mathbf{x},\mathbf{y})\right]$ and minimum average noise exposure ANE).

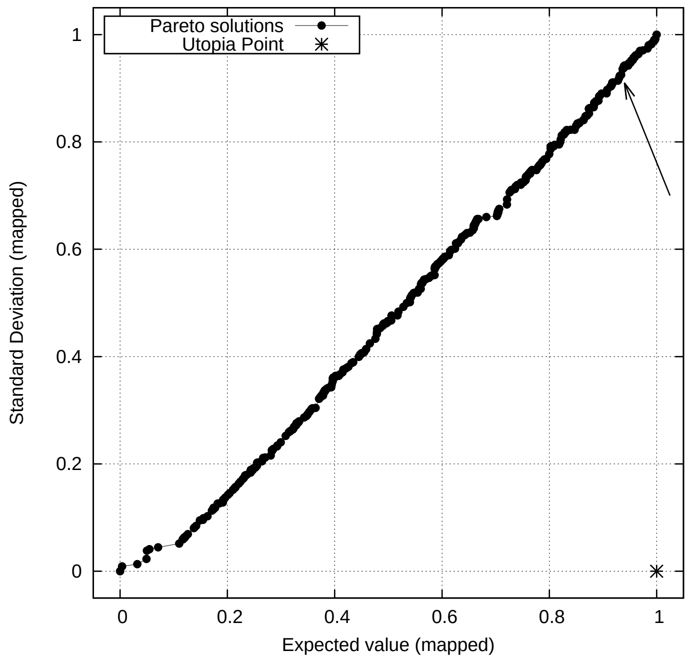


Figure 4.30: Mapped Pareto solutions of the robust optimization aimed to maximize the expectation of the Net Present value (NPV) and minimize its standard deviation with respect to the inflation rate I_r; the minimum average noise ANE solution is shown by the arrow.

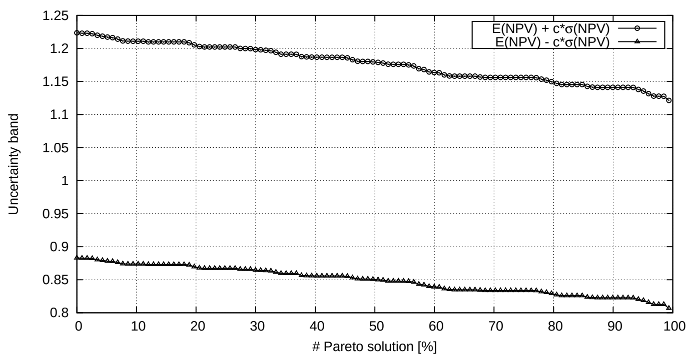


Figure 4.31: Confidence interval for each solution of Pareto front of the robust optimization, normalized with regard to a refernce configuration, aimed to maximize the expectation of the Net Present value (NPV) and minimize its standard deviation with respect to the inflation rate I_r.

4.4 Conclusions and future developments

This work has analyzed the aircraft conceptual design from a multi–disciplinary perspective with a specific focus on technical, environmental and economic features through the study of several campaigns of multi–objective optimization problems.

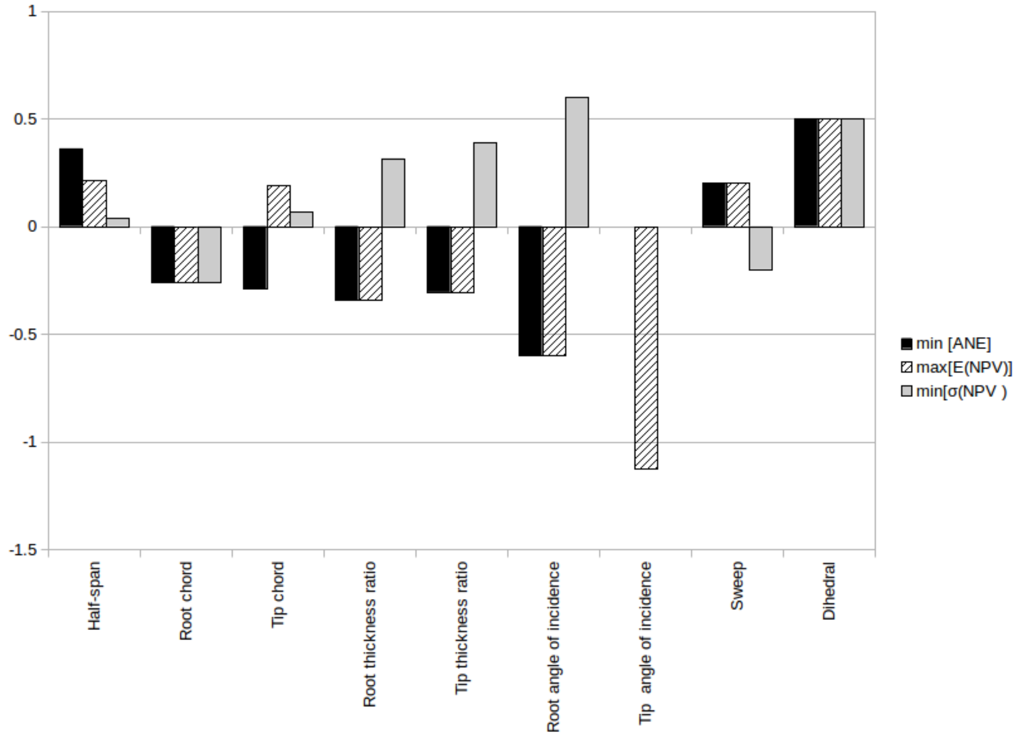


Figure 4.32: Optimal design variables related to the robust optimization problem aimed to maximize the Net Present Value NPV with uncertain inflation rate I_r: maximum expected value $E\left[NPV(\mathbf{x},\mathbf{y})\right]$, minimum standard deviation $\sigma\left[NPV(\mathbf{x},\mathbf{y})\right]$, and min average noise exposure ANE.

In order to perform this task, a detailed inquiry of the political, economic, legal, context has been carried out and an in–depth investigation about optimization problems, uncertainties and their mathematical formulation has been executed, as well. The work initially explored, from an accounting viewpoint, the marketability of sustainable–developed airplane. The resulting Pareto fronts and configurations reveal that optimal solutions yield underperforming aircraft. However, since the financial and accounting items are compared and they are characterized by a strong dependency, the problem could be ill-posed. Therefore a "pure" financial formulation has been proposed and it has been applied in two sets of simulation, comparing the classic performance approach combining airline company financial implications to the aircraft performance, with an unusual one exploring the impact of acquisition price on the negative cash–flows. The results show that the configuration leading to acoustical emissions abatement is aligned with the one that guarantees the minimum of annual negative cash flows of an airline company.

Furthermore the financial model has been enriched with the evaluation of the investment magnitude expressed through its net present value. This way, both cash inflows and outflows have been considered.

Four sets of simulation have leveraged on this enhanced formulation and they reveal that a conceptual design, based exclusively on technical–performance considerations, could determine an unsustainable economic output. They also highlight the need for appropriate noise fees as an instrument to encourage the aeronautical industry towards a strategy in the development of eco–friendly configurations.

Finally, the impacts on profitability of an airline company due to uncertainties on operational and financial parameters have been analysed. Specifically, uncertain cruise Mach number and inflation rate have been taken into account. The resulting Pareto fronts and configuration show how the first parameter does not significantly affect the configuration choice, while the second one might determine relevant variations on the investment value. The identified solution represents the most suitable one in both worst–case and best–case scenarios for an airline company, on the other hand, it does not minimize the acoustic emissions.

This work has validated the proposed model, analyzing conventional tube–and–wings configurations, in order to verify its feasibility on widely assessed concepts. Since the consolidate technology has approached a saturation point, the model has to be extended in order to assess innovative configurations investment values and ecological footprints. Furthermore, novel aircraft might require infrastructural enhancements which will necessitate corresponding investments and which could be charged to airline companies. A further development has to include the estimate of these extra costs. Additional improvements involve an extension of both operational and financial uncertain parameters affecting profitability analyses and the study of uncertain parameters combination effects, since considerations closer to real–life scenarios could emerge.

Part III

Appendices

APPENDIX A

FRIDA

All the optimization problems have been explored according to the analysis models required to study the aircraft throughout its mission, including its noise generation and propagation.

The Multi–disciplinary Conceptual Design Optimization (MCDO) framework, `FRIDA` (FRamework for Innovative Design in Aeronautics), provides an accurate description of the aircraft. `FRIDA` thoroughly depicts the airplane especially in a multi–disciplinary context, which requires to incorporate considerations about the aircraft configuration definition, the environmental impact (taking into account both the acoustical and chemical pollution) and financial implications. In order to improve the study of innovative aircraft configurations, prime–principle based algorithms have been implemented for the airplane analysis, so that past experience or literature data are not required, not being available for unusual aircraft. The modules of `FRIDA` deal with steady and unsteady aerodynamics, statics and dynamics of the structures, aeroelasticity, flight mechanics and performances, propulsion aeroacoustic and financial profitability estimation from an airline company viewpoint. An outline of the modules included in the framework follows.

Aerodynamics The aerodynamics is physically modelled according to a quasi–potential flow, *i.e.* the flow is considered potential in every point with the exception of the wake surface [36], enriched by a boundary–layer integral model to take into account the effects of viscosity, and provide an adequate estimate of the viscous drag. Assuming the flow is incompressible and fixing the wake surface, through a boundary element method, from an integral formulation, the velocity–potential is

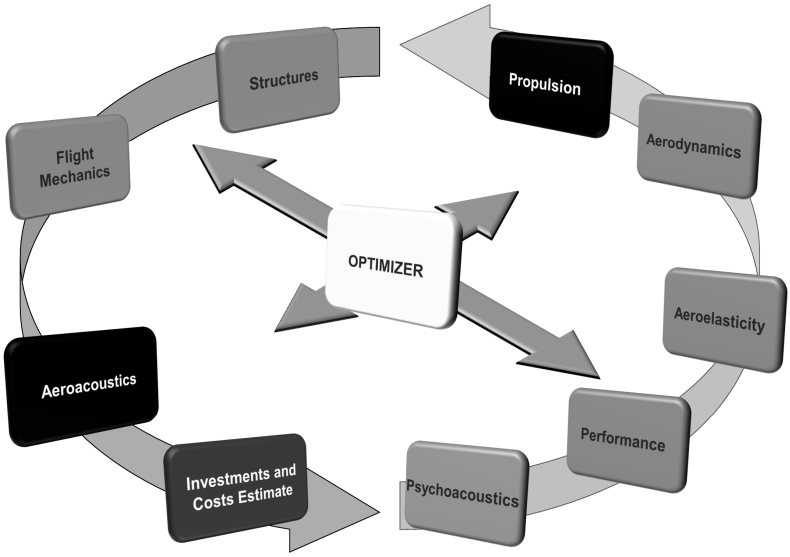


Figure A.1: The FRamework for Innovative Design in Aeronautics integrated with models for the economic evaluations estimate: highlighted key modules for optimization campaign of this work.

then calculated .

$$\varphi(\mathbf{x}, t) = \int_{S_B} \left(G\chi - \varphi \frac{\partial G}{\partial n} \right) dS(\mathbf{y}) - \int_{S_w} [\Delta\varphi_{TE}]^{\tau} \frac{\partial G}{\partial n} dS(\mathbf{y}) \qquad \text{(A.1)}$$

being $G = -1/4\pi||y - x||$ and $[\cdot]^{\tau}$ indicates evaluation at the retarded time $t - \tau$. The boundary conditions of impermeability on the body surface S_B integrates the above equation:

$$\frac{\partial \varphi}{\partial n} = \chi = \chi_B = \mathbf{v}_B \cdot \mathbf{n} \qquad \mathbf{x} \in \mathcal{S}_B \qquad \text{(A.2)}$$

and on the wake S_W on has

$$\Delta\varphi(\mathbf{x}_w, t) = \Delta\varphi(\mathbf{x}_{TE}, t - \tau) \qquad \text{(A.3)}$$

where τ is the convection time from $\mathbf{x}_{TE}$ to $\mathbf{x}_w$. The numerical solution of Eq. A.1 in the frequency domain is achieved by Laplace–transforming, $\tilde{\cdot}$ indicates Laplace transform, and applying a a zeroth–order Boundary Element Method (BEM) formulation. One can therefore discretise the boundary in N panels and consider the solution over the whole panel as constant and equal to the solution on the collocation point, which is located in the centroid of the panel.

$$\tilde{f}_{\varphi} = E_{TE}(s)\tilde{f}_{\chi} \tag{A.4}$$

being the vectors $\tilde{f}_{\varphi} = \{\tilde{\varphi}_j\}$, and $\tilde{f}_{\chi} = \{\tilde{\chi}_j\}$ the values of the velocity potential, $\tilde{\varphi}$, and its normal derivative,$\tilde{f}_{\chi}$ at the centroids of the surface elements, and s the Laplace variable.

The quasi–potential formulation is coupled with a boundary–layer integral model in order to include the viscosity effects and, to provide an adequate estimation of the viscous drag, a critical element in the flight mechanics and performance analysis study.

Weight estimation From wing and tail elements (spars, stringers, ribs and coverings) characteristic dimensions, in addition to the fuselage geometric outline, the estimation of structural aircraft weight originates. Afterwards, engines, landing gear and fixed equipments weights are included. Furthermore, distribution of masses (crew, payload, fuel and operational items included) is accurately analysed in order to estimate the actual aircraft configuration gravity center $\mathbf{x}_{cg}$.

Structural analysis The structural analysis of the wing is modelled according to a 6–D.O.F. bending–torsional beam model, with structural and geometric parameters varying along the three spatial directions, with a linear variation relationship. These include structural element geometric dimensions (rib area, spar and skin panel thickness, etc.), wing twist, mass characteristics in addition to bending and torsional moments of inertia. Furthermore, in order to take into account the wing–fuselage junction, clamped boundary conditions at root have been included.

The structural problem is solved through a modal approach with constant boundary conditions at the joint sections of wings and tail surfaces with the fuselage. A Finite Element Method (FEM) model of the wing allows the computation of the vibration approximate modes, whose displacements are expressed as follows:

$$\mathbf{u}(\mathbf{x}, t) = \sum_{m=1}^{M} q_m(t)\Phi_m(\mathbf{x}) \tag{A.5}$$

Through the solution of the Eq. A.5, one can determine the diagonal matrix Ω of the natural frequencies of the beam representing the wing. Moreover the nodal generalized forces due to the aerodynamic loads acting on the wing are calculated, therefore the direct and shear stresses distributions are estimated as well. Consequently, both the normal and the shear stress at the wing root location can be computed.

Aeroelasticity The interaction between the aerodynamic variables, and the structural dynamics ones gives rise to aeroelastic phenomena. In order to perform an effective and efficient aeroelastic analysis, which is to say, to evaluate the the matrix collecting the aerodynamic forces, a reduced order model (ROM) based on a finite–state approximation is employed [37], so that the heavy computational burden deriving from the classical methods for the flutter and divergence speeds estimation, can be avoided since the analysis can be limited to the roots locus study.

Flight mechanics The aerodynamic loads are computed for the clean configuration with the integral formulation (see Eq. A.1) for the wing system and the horizontal tail. The fuselage drag contribution, as well as the aerodynamic effects of high–lift devices (flaps and slats), airbrakes and landing gears are included in the analysis through appropriate corrections with the aim to assess the global aerodynamic loads for the actual configuration [43]. Thereafter, through the vertical balance of the forces, the aircraft trim (in terms of fuselage angle of attack) is calculated. Simultaneously, the static longitudinal stability, essential requirement for each flight condition, must be guaranteed: the derivative of the pitching moment with respect to center of gravity $\mathbf{x}_{cg}$ is less than zero.

Propulsion The intrinsic complexity of the thermofluidynamic phenomena involved with the engines operations in addition to the lack of available literature data, make the aircraft engines operational characteristic estimation remarkably arduous. In order to bypass these complications, a semi–empirical turbofan model, based on both prime–principle and available experimental data, was implemented within `FRIDA`: given a flight condition, being the engine features known, the model yields the percentage of throttle as a function of the flight mechanics variables $\mathbf{X}_{FM}$ (altitude, drag force, actual aircraft weight, acceleration of the aircraft, etc.) and the propulsion system characteristics $\mathbf{X}_{Eng}$ (number of engines, engine pitch, bypass ratio, maximum thrust per engine at sea level, etc.).

$$t_{\%} = f(\mathbf{X}_{FM}, \mathbf{X}_{Eng}) \tag{A.6}$$

Afterwards, the rotational speeds $N1$ and $N2$ of respectively low–pressure and high–pressure spools are determined through the overspeeds ($N1_{os}$ and $N2_{os}$) and *idle* conditions ($N1_i$ and $N2_i$) in terms of revolutions per minute.

$$N1_{rpm} = f(t_{\%}, N1_{os}, N1_i), \quad N2_{rpm} = f(t_{\%}, N2_{os}, N2_i) \tag{A.7}$$

For each flight condition, the momentum equation yields the jets velocity and the energy balance ushers in its temperatures.

Aeroacoustic The estimate of the airframe and the propulsion noises, are calculated through aeroacoustic models within `FRIDA`, as functions of the distance from the observers, the directivity (polar and azimuthal) angles and the actual aircraft configuration, in terms of wet surfaces and engine operating–point. Specifically, the noises of wing, tail, high–lift devices and landing gears are based on semiempirical functions: the calculation is performed, according to the Fink's model [18, 19], in the *far–field* through the combination of elementary sources (monopoles, dipoles and quadrupoles) whose spectral and directivity characteristics are known. The fan and the compressor contributions estimation to propulsion noise is based on Heidmann's model [23], while the *buzz–saw* addition assessment on Morfey and Fisher model [35]. The jet–noise is evaluated by means polynomial regressions of experimental data.

In order to calculate the 1/3 octave band Sound Pressure Level (SPL), the Doppler effect, the atmospheric absorption [46] and the ground reflection have been considered. The Sound Exposure Level (SEL) and the Effective Perceived Noise Level (EPNL) are also determined through an appropriate postprocessing. Moreover `FRIDA` includes an innovative sound–quality assessment method [29, 28, 12, 26], developed during progression of EC–funded SEFA (Sound Engineering For Aircraft, FP6, 2004–2007) and COSMA (Community Noise Solutions to Minimise aircraft noise Annoyance, FP7, 2009–2012) projects.

Finance The financial implications estimate, from an airline company viewpoint is performed within the finance module which has been implemented and then enhanced according to the models previously described (see Sects. 4.1.1, 4.1.2). The initial investment, *i.e.* the aircraft acquisition price, depreciation, maintenance and fuel costs, which are the most relevant financial direct operating cost categories, in addition to noise charges are determined. The price of the aircraft P_{AC} has been linked to its performance and profitable features and then computed following the empirical formula proposed by Ferreri [17]. In order to calculate the cost of fuel, the consumption over an average route, the number of missions and the average price of fuel have been determined. Maintenance costs have been considered directly proportional to the value of the aircraft. Noise has a social impact on the properties in areas nearby airports facilities: this negative externality is converted into an economic loss of value according to a method developed by Grampella et al. [20] as depicted in Eq. 4.6. This method is based on thorough analysis of hedonic prices and willingness to pay proposed by Schipper [44].

Bibliography

[1] Harish Agarwal and John Renaud. Reliability based design optimization using response surfaces in application to multidisciplinary systems. *Engineering Optimization*, 36(3):291–311, jun 2004.

[2] N E Antoine and I M Kroo. Framework for aircraft conceptual design and environmental performance studies. *AIAA Journal*, 43(10):2100–2109, 2005.

[3] Dimitris Bertsimas, David B. Brown, and Constantine Caramanis. Theory and Applications of Robust Optimization. *SIAM Review*, 53(3):464–501, 2011.

[4] M Bettex. Fly the eco–friendly skies. MIT News, May 2010. http://news.mit.edu/2010/nplus3-0517, accessed April 2016.

[5] Hans Georg Beyer and Bernhard Sendhoff. Robust optimization - A comprehensive survey. *Computer Methods in Applied Mechanics and Engineering*, 196(33-34):3190–3218, 2007.

[6] G Calabresi and A D Melamed. Property Rules, Liability Rules and Inalienability: One View of the Cathedral. *Harvard Law Review*, 85:1089–1128, 1972.

[7] E Campana, M Diez, G Fasano, and D Peri. Initial Particles Position for PSO, in Bound Constrained Optimization. In *4th International Conference, ICSI*, 2013.

[8] Wei Chen, J. K. Allen, Kwok-Leung Tsui, and F. Mistree. A Procedure for Robust Design: Minimizing Variations Caused by Noise Factors and Control Factors. *Journal of Mechanical Design*, 118(4):478, 1996.

[9] D Collin. European aviation noise research network (x–noise). In *InterNoise 2014 Proceedings, Melbourne*, 2014.

[10] K Deb, A Pratap, A Agarwal, and T Meyarivan. A fast and elitist multiobjective genetic algorithm: NSGA–II. In *IEEE Transactions on Evolutionary Computation*, 2002.

[11] Morris H. DeGroot. *Optimal Statistical Decisions.* John Wiley & Sons, Inc., Hoboken, NJ, USA, apr 2004.

[12] M Diez and U Iemma. Multidisciplinary conceptual design optimization of aircraft using a sound–matching–based objective function. *Engineering Optimization*, 44(5):591–612, 2012.

[13] C Drury. *Management accounting for business.* Cengage Learning, Andover, UK, 2009.

[14] Xiaoping Du and Wei Chen. Towards a Better Understanding of Modeling Feasibility Robustness in Engineering Design. *Journal of Mechanical Design*, 122(4):385, 2000.

[15] Eurocontrol. Challenges of growth 2013 – european air traffic in 2050. Technical report, EUROCONTROL - European Organisation for the Safety of Air Navigation, June 2013.

[16] K Ferjan. Airline Cost Management Group. In *Airline Cost Conference, Geneva*, 2014.

[17] D Ferreri. *Marketing and Management in the High–Technology Sector*. Praeger, Westport, Connecticut, 2003.

[18] M R Fink. Approximate prediction of airframe noise. *Journal of Aircraft*, 13(11):833–834, 1976.

[19] M R Fink. Airframe Noise Prediction Method. Technical report, FAA, 1977.

[20] M Grampella, G Martini, D Scotti, F Tassan, and G Zambon. The environmental costs of airports' aviation activities: a panel data econometric analysis of Italian airports. In *17th Air Transport Research Society (ATRS) World Conference*, 2013.

[21] Arjun K. Gupta and Saralees Nadarajah. *Handbook of Beta Distribution and Its Applications.* 2004.

[22] A Hall, I Wuggetzer, T Mayer, and P R N Childs. Future aircraft cabins and design thinking: optimisation vs. win-win scenarios. *Journal of Propulsion and Power Research*, 2(2):85–95, 2013.

[23] M F Heidmann. Interim prediction method for fan and compressor source noise. Technical report, NASA, 1979.

[24] Assembly resolution in force. Technical report, International Civil Association Organization, September 2007.

[25] ICAO. ICAO's policies on charges for airports and air navigation service. Technical report, Internation Civil Aviation Organization, 2012.

[26] U Iemma, L Burghignoli, F Centracchio, and V Galluzzi. Multi–objective optimization of takeoff and landing procedures: level abatement vs quality improvement of aircraft noise. In *InterNoise 2014, Melbourne*, 2014.

[27] U Iemma and M Diez. Optimal Life–cycle-costs Design of New Large Aircraft Including the Cost of Community Noise. In *International Conference on Computational & Experimental Engineering and Sciences*, 2005.

[28] U Iemma, M Diez, C Leotardi, and F Centracchio. On the use of noise annoyance as a design optimization constraint: the COSMA experience. In *18th international congress on sound and vibration, Rio de Janeiro*, 2011.

[29] U Iemma, M Diez, and V Marchese. Matching the aircraft noise to a target sound: a novel approach for optimal design under community noise constraints. In *13th international congress on sound and vibration, Vienna*, 2006.

[30] U Iemma, F Pisi Vitagliano, and F Centracchio. Life–cycle costs and infrastructural investments induced by unconventional low-noise aircraft. In *InterNoise 2015 Proceedings, San Francisco*, 2015.

[31] J Kennedy and R C Eberhart. Particle swarm optimization. In *IEEE International Conference on Neural Networks*, 1995.

[32] J Marczyk. Stochastic multidisciplinary improvement: Beyond optimization. *American Institute of Aeronautics and Astronautics*, pages AIAA–2000–4929, 2000.

[33] J Markish and K Willcox. Value–Based Multidisciplinary Techniques for Commercial Aircraft System Design. *AIAA Journal*, 41(10):2004–2012, 2003.

[34] D Milmo. Easyjet unveils 'ecojet'. The Guardian, June 2007. http://www.theguardian.com/environment/2007/jun/14/theairlineindustry.business, accessed April 2016.

[35] C L Morfey and M J Fisher. Shock–wave radiation from a supersonic ducted rotor. *Aeronautical Journal*, 74(515):579–585, 1970.

[36] L Morino. Boundary integral equations in aerodynamics. *Applied Mechanics Reviews*, 46(8):445–466, 1993.

[37] L Morino, F Mastroddi, R De Troia, L Ghiringhelli, and Mantegazza P. Matrix fraction approach for finite–state aerodynamic modeling. *AIAA Journal*, 1995.

[38] National Assembly of France. *Declaration of the Rights of Man and Citizen.* Paris, France, 1789.

[39] R E Peoples and K E. Willcox. Value–based multidisciplinary optimization for commercial aircraft design and business risk assessment. *Journal of Aircraft*, 43(4):913–921, 2006.

[40] A C Pigou. *The Economics of Welfare.* Macmillan, London, UK, 1920.

[41] R M Pirsig. *Zen and the art of motorcycle maintenance: an inquiry into values.* William Morrow and Co., New York, USA, 1974.

[42] M E Porter. How competitive forces shape strategy. *Harvard Business Review*, 57(2):137–145, 1979.

[43] D P Raymer. *Aircraft design: a conceptual approach.* AIAA, Washington, D.C., 1992.

[44] Y Schipper. Environmental costs in European aviation. *Transport Policy*, 11(2):141–154, 2004.

[45] R. Sues, M Cesare, S. Pageau, and J. Wu. Reliability-based optimization considering manufacturing and operational uncertainties.pdf. *Journal of Aerospace Engineering*, pages 166–174, 2001.

[46] L C Sutherland, J E Piercy, Bass H E, and Evans L B. Method for calculating the absorption of sound by the atmosphere. In *88th Meeting of the Acoustical Society of America*, 1974.

[47] G. Taguchi. *Introduction to quality engineering: Designing quality into products and processes*, volume 4. 1986.

[48] M W Trosset, N M Alexandrov, and L T Watson. New Methods for Robust Design Using Computer Simulation. In *Proceedings of the Section on Physical and Engineering Sciences, American Statistical Association*, 2003.

[49] J Tu, K K Choi, and Y H Park. A New Study on Reliability-Based Design Optimization. *Journal of Mechanical Design*, 121(4):557–564, 1999.

[50] J C Wood and M C Wood. *Peter F. Drucker: Critical Evaluations in Business and Management.* Number v. 1 in Critical evaluations in business and management. Routledge, London, UK, 2005.