INTEGRATED OPTIMIZATION OF AIR TRANSPORTATION SYSTEMS (AIRCRAFT AND NETWORK)

José Alexandre Tavares Guerreiro Fregnani

Thesis Committee Composition:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  |  |  |  |
| Prof. Dr. | Bento Silva de Mattos | Advisor | - | ITA |
| Prof. Dr. | José Antônio Hernandes | Co-advisor | - | ITA |
| Profa. Dra. | Cláudia Regina de Andrade |  | - | ITA |
| Prof. Dr. | Ney Rafael Secco |  | - | ITA |
| Prof. Dr. | Jorge Eduardo Leal Medeiros |  | - | Poli/USP |
| Prof. Dr. | Fernando Martini Catalano |  | - | EESC/USP |

ITA

*À minha amada família*

*Luciana (in memoriam)*

*Anna Carolina*

*Enzo*

Agradecimentos

Este trabalho foi desenvolvido em meio aos anos mais difíceis de minha vida, tanto do ponto de vista pessoal e quanto profissional. Muitas foram as turbulências e desafios passados ao longo deste tempo em meio aos quais tive encorajamento irrestrito e contínuo para concluir o doutorado.

Em primeiro lugar agradeço a Deus, nosso Pai Maior, que permitiu e me proveu as forças necessárias para seguir em frente nos momentos mais difíceis desta caminhada.

Em segundo lugar à minha amada família - a meus filhos Anna Carolina e Enzo, que tanta paciência tiveram com seu pai, renunciando a seu tempo precioso com eles para poder realizar seu sonho. Em especial à minha esposa Luciana, companheira de vinte anos de jornada, pelo apoio incondicional desde o primeiro dia de estudos e mesmo com sua saúde comprometida, sempre esteve me incentivando a não desistir. Agradeço imensamente a eles toda a compreensão e compaixão despendidas ao longo destes anos todos.

Em terceiro lugar agradeço a meu querido orientador Prof. Dr. Bento Mattos, que tanto me ensinou na verdadeira arte de “Projeto de Otimização Multidisciplinar de Aeronaves” e o rigor acadêmico necessário para se desenvolver este trabalho. Obrigado pela paciência e benevolência em meio a tantos desafios que tive em minha vida pessoal em paralelo aos estudos. Ao Prof. José Antônio Hernandez, meu querido co-orientador, pelas valorosas lições na confecção de artigos e escrita acadêmica, além da paz e tranquilidade transmitidas ao longo destes anos. E aos professores da Divisão de Projetos e Estruturas do Departamento de Engenharia Aeronáutica do ITA, cujos cursos de altíssima qualidade me ajudaram a trilhar o bom caminho em minha pesquisa.

Agradecimento especial aos amigos da Boeing Pesquisa e Tecnologia do Brasil, que me encorajaram na ideia inicial deste projeto e nunca deixaram de torcer pelo meu sucesso, apesar de nossa atual distância.

Finalmente meus sinceros agradecimentos à Airbus, a empresa onde trabalho na presente data, que nunca deixou de acreditar no potencial que esta pesquisa pode proporcionar à indústria aeronáutica, na figura do Sr. Bertrand Masson, chefe do Departamento de Ciências de Linhas Aéreas do Escritório de Transformação Digital da Airbus em Toulouse, França.

*"* *Jamais considere seus estudos como uma obrigação, mas como uma oportunidade invejável para aprender a conhecer a influência libertadora da beleza do reino do espírito, para seu próprio prazer pessoal e para proveito da comunidade à qual seu futuro trabalho pertencer.”*

Albert Einstein

Abstract

The determination of optimal aerial transport networks and their associated flight frequencies is crucial for the strategic planning of airlines, as well as for carrying out market research, and for aircraft and crew rostering. In addition, optimum airplane types for the selected networks are crucial to improve revenue and to provide reduced operating costs. The present research proposes an innovative Multidisciplinary Design Optimization (MDO) framework with the objective to optimize a highly detailed airplane design simultaneously with the associated airline network, for a given area of operations and associated demand, in a multiobjective-multivariable problem. In this framework, the aircraft design and network computation modules are executed independently in sequenced blocks and wrapped into a genetic algorithm in the optimization process. Two sets of objective functions were studied, according to the optimization scope: airline operations optimization (considering Network Profit and Network Direct Operational Cost as objective functions) and airline/aircraft manufacturer optimization (considering Network Profit and manufacturer´s Cash Flow Net Present Value as objective functions). In the aircraft design module, several design parameters are used to represent the airplane in finest detail with accurate aerodynamic, stability and control, and propulsion characteristics, necessary for the mission analysis of each route segment considered in the analysis network. The accurate calculation of a realistic mission operational profile was performed thanks to the application of an Artificial Neural Network for aerodynamic coefficient estimation and a robust generic turbofan propulsion model. In the network computation module, disciplines related to network optimization, mission performance and airline economics are integrated. The network optimization module is performed in a sub-optimization framework using an elaborated gravitational demand model to predict passenger flows between city-pairs.

Under this scope, four types of simulation scenarios, considering major Brazilian airports, were evaluated in order to apply the above described methodology: determination of the optimum aircraft design in a given five airports network, determination of the optimum five airports network for a given aircraft design, simultaneous optimization of aircraft design and network (five and ten airports) and simultaneous optimization of a fleet of three aircraft and a network of twenty airports. Results demonstrated significant financial advantages for airlines on using the mentioned objective functions instead of the conventional minimization of Direct Operational Costs approach.

List of Figures

Figure 1.1: Global airlines profit margin since year 2000 31

Figure 1.2: Aviation industry emissions reduction roadmap 33

Figure 1.3: Fuel efficiency improvement since the first commercial jet 34

Figure 1.4: Typical network planning process adopted by airlines 38

Figure 1.5: Conceptual design configurations study 43

Figure 1.6: Aircraft layout after the conceptual design is finished 44

Figure 2.1: Analysis block for range computation. 52

Figure 2.2: Generic MDO framework. 53

Figure 2.3: Latin hypercube sampling. 54

Figure 2.4: Example of Multidisciplinary Feasible framework (MDF) 56

Figure 2.5: Example of Individual Discipline Feasible framework (IDF) 56

Figure 2.6: Example of Collaborative Optimization framework (CO) 57

Figure 2.7: Types of Optimization Algorithms 58

Figure 2.8: GA standard flowchart 61

Figure 3.1: Proposed “Hybrid MDF-CO” MDO framework 72

Figure 3.2: Baseline Aircraft (78 passengers, single class) 73

Figure 3.3: Proposed MDO workflow elaborated with modeFrontier® 80

Figure 3.4: Flowchart of Aircraft Framework calculations 81

Figure 3.5: Single wheel nose and main landing gear configuration 85

Figure 3.6: Main landing gear design clearances considering inner flaps and fuselage geometries 86

Figure 3.7: Typical fuselage cross section computation 87

Figure 3.8: Example of wing and tail placements considering the allowable CG variation (blue) for a certain design 88

Figure 3.9: Scholz method to determine the minimum horizontal tail area 89

Figure 3.10: AVL model for the calculation of stability derivatives 90

Figure 3.11: Flight quality requirements for Dutch Roll and short period 90

Figure 3.12: Wing geometric parameters 92

Figure 3.13: Airfoil geometric parameters 92

Figure 3.14a: Airfoil coordinates and polynomial fittings 93

Figure 3.14b: ML/D and L/D curves for the optimized airfoils (basic airplane) 94

Figure 3.14c: Pressure distributions for the reference airplane at design point 95

Figure 3.15: Comparison between ANN overall drag predictions and CFD results 96

Figure 3.16: Generic compressor map 99

Figure 3.17: Noise measuring points for airplane certification 100

Figure 3.18: Design Diagram check 102

Figure 3.19: Two stop demand model and adopted shares 111

Figure 3.20: Mission Profile 119

Figure 3.21: Flight profile workflow for calculation of trip fuel and time 120

Figure 3.22: Complete mission calculation algorithm 121

Figure 3.23: Cashflow NPV analysis of a 120 seats aircraft design 128

Figure 4.1: Five cities air transport network 133

Figure 4.2: Optimization results – Fixed Network/Optimum Aircraft (5 airports) 137

Figure 4.3: Pareto Front – Fixed Network/Optimum Aircraft (5 airports) 138

Figure 4.4: Baseline and extreme designs – Fixed Network/Optimum Aircraft (5 airports) 139

Figure 4.5: Pearson correlation matrix – Fixed Network/Optimum Aircraft (5 airports) 142

Figure 4.6: Results from the optimum network simulation 146

Figure 4.7a: Optimum network results for baseline and min NDOC aircraft designs 147

Figure 4.7b: Optimum network results for max NP and max NPV aircraft designs 147

Figure 4.8: Optimization results – Integrated Aircraft and Network (5 airports) 151

Figure 4.9: Integrated aircraft and network optimization Pareto front (5 airports) 152

Figure 4.10: Extreme designs – Fixed Network x Optimum Network (5 airports) 153

Figure 4.11a: Optimum Network type #1 - 70 to 109 seats aircraft (5 airports) 154

Figure 4.11b: Optimum Network type #2 – 113 and 114 seats aircraft (5 airports) 154

Figure 4.11c: Optimum Network type #3 – 130 seats aircraft (5 airports) 155

Figure 4.12: Integrated aircraft and network optimization Pareto front (10 airports) 159

Figure 4.13a: Baseline - optimized network and aircraft characteristics (10 airports) 160

Figure 4.13b: Min NDOC – integrated network and aircraft optimization (10 airports) 161

Figure 4.13c: Max NP – integrated network and aircraft optimization (10 airports) 162

Figure 4.14: Max NP – Airplane/Network integrated optimization framework (20 airports) 167

Figure 4.15: ModeFrontier ® optimization framework (20 airports) 168

Figure 4.16a: US$/nm and US$/(nm x Pax) as function of wing reference area (databases aircraft) 169

Figure 4.16b: Some airplanes that compose the database (not in same scale). 170

Figure 4.17: Pareto front and dominated individuals (20 airports) 171

Figure 4.18: Aircraft Design #2 correlation Matrix (20 airports) 172

Figure 4.19 Effect of fuel price and market share on Annual Profit and Network Density 178

Figure 4.20a: Minimum Annual Profit scenario (15% Market Share /150% reference fuel price) impact on max NP 3-fleet network topology 178

Figure 4.20b: Maximum Annual Profit Scenario (25% Market Share /150% reference fuel price) impact on max NP 3-fleet network topology 178

List of Tables

Table 1.1: Global strategies for reducing aviation fuel uses and emissions. 33

Table 1.2: Airframe technologies development impact on fuel efficiency. 35

Table 1.3: Engine technologies development impact on fuel efficiency. 36

Table 1.4: Technical characteristics of reference airliners 41

Table 3.1: Baseline aircraft design requirements. 73

Table 3.2: Aircraft and Engines design parameters 74

Table 3.3: Aircraft fixed parameters. 74

Table 3.4: Aircraft operational and certification fixed parameters. 75

Table 3.5: Network fixed parameters. 75

Table 3.6: Airport and econometrics database parameters. 75

Table 3.7: Aircraft definition parameters. 77

Table 3.8: Engine weight equation exponents and coefficients. 84

Table 3.9: Engine weight equation normalization parameters. 84

Table 3.10: Weight error estimation for typical turbofan/jet engines 84

Table 3.11: Inputs for the ANN computation 92

Table 3.12: Airfoil geometric parameters 94

Table 3.13 Predicted and calculated coefficient values by ANN and full potential code at design point of the basic aircraft 96

Table 3.14: Hourly crew salaries for narrow body aircraft operating in North America 123

Table 3.15: Inflight delay costs as function of MTOW 125

Table 3.16: MOGA-II Optimization parameters setting 131

Table 4.1: Five airports network indicators 133

Table 4.2: Passenger regression model coefficients, based on city-pair demand of the twenty busiest Brazilian domestic routes. 135

Table 4.3 Route passenger’s estimated demand per day (10% market share) 135

Table 4.4 Design variables set to fixed parameters 136

Table 4.5a Pareto Front individuals – Fixed Network/Optimum Aircraft (aircraft characteristics) 137

Table 4.5a Pareto Front individuals – Fixed Network/Optimum Aircraft (network characteristics) 138

Table 4.6 City-pair daily frequencies per aircraft type – Fixed Network/Optimum Aircraft 141

Table 4.7a Economic results for the minimum NDOC design (5 airports network) 143

Table 4.7b Economic results for the maximum NP design (5 airports network) 143

Table 4.8 Optimum network frequencies for Baseline Aircraft, Min DOC and Max NP designs 146

Table 4.9a Optimum network impact on economic parameters – basic aircraft design 148

Table 4.9b Optimum network impact on economic parameters – minimum NDOC 149

Table 4.9c Optimum network impact on economic parameters – maximum NP 149

Table 4.10a Pareto Front individuals – Optimum Aircraft characteristics (5 airports) 151

Table 4.10b Pareto Front individuals – Optimum Network characteristics (5 airports) 152

Table 4.11a : Min NDOC - Integrated optimization x fixed network (5 airports) 156

Table 4.11b : Min NDOC - Integrated optimization x fixed network baseline (5 airports) 156

Table 4.11c : Max NP - Integrated optimization x fixed network (5 airports) 156

Table 4.11d : Max NP - Integrated optimization x fixed network baseline (5 airports) 156

Table 4.12 : Route passenger’s demand per day (10% market share) - 10 airports 158

Table 4.13 : Computational performance of all simulations 158

Table 4.14a : Min NDOC - Integrated optimization x fixed network baseline(10 airports) 163

Table 4.14b : Min NDOC - Integrated optimization x optimum network baseline (10 airports) 163

Table 4.14c : Max NP - Integrated optimization x fixed network baseline (10 airports). 163

Table 4.14d : Max NP - Integrated optimization x optimum network baseline (10 airports) 164

Table 4.15 : Estimated Passengers Demand per day with 20% Market Share (20 airports)166

Table 4.16 : Individuals selected in the Pareto front (20 airports) 172

Table 4.17a : Results for the Maximum NP scenario (20 airports) 174

Table 4.17b : Results for the Maximum NPV scenario (20 airports) 174

Table 4.17c : Difference between Max NPV and Max NP scenarios (20 airports) 174

Table 4.18 : Impact of fuel price and market share on airline profitability and network parameters 177

List of Abbreviations

|  |  |
| --- | --- |
| *a0* | Speed of sound at sea level on standard atmosphere [m/s] |
| *ACO* | Ant colony optimization algorithm |
| *ADj* | Arrival delay at airport j [min] |
| *AED* | Airport and econometrics database |
| *AFA* | Approach and landing fuel allowance [kg] |
| *AFP* | Aircraft fixed parameters |
| *ailpos* | Aileron position on wing semi-span [%] |
| *AisleW* | Aisle width |
| *AIP* | Aeronautical Information Publication |
| *ALD* | Average landing delay [min] |
| *ANN* | Artificial neural network |
| *ANOPP* | Airplane Noise Operations Prediction Program |
| *AOCFP* | Aircraft operational/certification fixed parameters |
| *APTID* | ICAO’s four-letter code airport designator |
| *ATA* | Approach and landing time allowance [kg] |
| *ATAG* | Air Transport Action Group |
| *ATD* | Average takeoff delay [min] |
| *ATM* | Air Traffic Management |
| *AVL* | Aerodynamics Vortex Lattice |
| *B* | City pair combined buying power index |
| *Bi* | Buying power index related to the city of the i-th airport |
| *BPR* | Engine by-pass ratio |
| *b* | Passenger capacity |
| *bflap* | Flap length on semi-span [%] |
| *bk* | Passenger capacity of k-th aircraft |
| *BuffMGN* | Buffet margin (g) |
| *CARGO* | Total cargo loaded onboard [kg] |
| *C* | City pair airport catchment area product |
| *Ci* | City pair airport catchment related to the i-th airport [km2] |
| *CabHt* | Passengers cabin internal height [m] |
| *CAS* | Calibrated airspeed [kt] |
| *CAPEX* | Capital expenditure [US$] |
| *CAPSAL* | Captain´s hourly salary [US$/h] |
| *CD* | Total aircraft drag coefficient |
| *CD0* | Zero lift drag coefficient |
| *CD0 ubridge* | Zero lift drag increase due to wing-fuselage interference |
| *CDflap* | Drag increase due to takeoff flap extended |
| *CD ind* | Induced drag coefficient |
| *CDgear* | Drag increase due to landing gear extended |
| *CDMMO* | Drag coefficient evaluated at maximum operating Mach number |
| *CD wave* | Wave drag coefficient |
| *CD wing* | Total wing drag coefficient |
| *CDwindmill* | Drag increase due to wind milling of a failed engine |
| *CDrudder* | Drag increase due to ruder deflection |
| *CD0.70* | Drag coefficient evaluated at 0.7 Mach number |
| *Ceiling* | Maximum aircraft certified altitude [ft] |
| *Cflt* | Flight component of direct operational cost (crew, oil, fuel and insurance) [US$/nm] |
| *Cmaint* | Maintenance (labor and material) component of the direct operational cost [US$] |
| *Cdepr* | Depreciation (airframe, engines and avionics) component of the direct operational  cost [US$] |
| *Cfee* | Fees (Navigation, Airport and Register) component of the direct operational cost [US$] |
| *Cfin* | Financial (airframe and engine leasing) component of the direct operational cost [US$] |
| *CFD* | Computer fluid dynamics |
| *CG* | Aircraft’s center of gravity |
| *chordc* | Airfoil chord length at central fuselage [m] |
| *chordk* | Airfoil chord length at wing kink [m] |
| *chordr* | Airfoil chord length at wing root [m] |
| *chordt* | Airfoil chord length at wing tip [m] |
| *City* | City name |
| *CL* | Lift coefficient |
| *CLMAX* | Maximum lift coefficient at undeflected flap/gear up configuration |
| *CLMAX APP* | Maximum lift coefficient at approach flaps/gear up configuration |
| *CLMAX LD* | Maximum lift coefficient at landing flaps/gear down configuration |
| *CLMAX TO* | Maximum lift coefficient at takeoff flaps/gear down configuration |
| *CL 2nd seg* | Lift coefficient evaluated at the 2nd segment takeoff flight path |
| *CMA* | Wing mean aerodynamic chord length [m] |
| *CNS* | Communication, Navigation and Surveillance Technologies |
| *Cmα* | Pitch moment coefficient |
| *Cnβ* | Yawing moment coefficient |
| *CO* | Collaborative optimization framework |
| *CO2* | Carbon dioxide |
| *CORSIA* | Carbon Offsetting and Reduction for International Aviation |
| *CRAD* | Catchment area radius [km] |
| *Crew* | Number of crew members (flight attendants + pilots) |
| *ck* | Average direct operational cost [$/nm] of k-th aircraft at design range |
| *D* | Total aircraft drag [N] |
| *DATCOM* | United States Air Force Stability and Control Data Compendium |
| *DDi* | Departure delay at i-th airport [min] |
| *DESC* | Sales price discount rate |
| *dij* | Distance from i-th to j-th airport [nm] |
| *DOC* | Direct operational cost [US$/nm] |
| *DOCijk* | Direct operational cost from i-th to j-th airport [US$/nm] |
| *DOE* | Design of experiments |
| *DMG* | Airport magnetic declination [o] |
| *DU* | Average daily aircraft utilization [h] |
| *eCLR* | Engine minimum clearance to ground [m] |
| *ELEV* | Airport’s reference point elevation [ft] |
| *EPNdB* | Effective perceived noise in decibels |
| *le* | Engine length [m] |
| *eDiam* | Engine fan diameter [m] |
| *eM* | Engine Design Point Mach Number |
| *ePOS* | Engine position flag |
| *epydz* | Engine pylon height [m] |
| *eSwet* | Engine wet area [m2] |
| *eTIT* | Engine turbine inlet temperature [K] |
| *F* | Frequency of sound source [Hz] |
| *FASAL* | Flight Attendant´s hourly salary [US$/h] |
| *FAR25* | Part 25 of the United States Code of Federal Regulations Title 14 (Airworthiness Standards: Transport Category Airplanes) |
| *FCt* | Cashflow at period t |
| *fij* | Daily demand from airport i-th to j-th airport |
| *fp* | Vector of fixed parameters |
| *FF* | Engines total fuel flow [kg/s] |
| *FOB* | Total fuel on board [kg] |
| *FOSAL* | First Officer´s hourly salary [US$/h] |
| *FPR* | Engine fan pressure ratio |
| *flapLD* | Landing flap deflection [o] |
| *flapTO* | Takeoff flap deflection [o] |
| *fusd* | Fuselage diameter [m] |
| *fusdz* | Fuselage external height [m] |
| *fush* | Fuselage height [m] |
| *fush2w* | Fuselage height-to-width ratio |
| *fusw* | Fuselage width [m] |
| *fuswetS* | Fuselage wet area [m2] |
| *g* | Gravity acceleration [m/s2] |
| *g(x,fp)* | Inequality constraint function |
| *G* | Combined city pair Gross Domestic Product [US$] |
| *GA* | Genetic algorithm |
| *GAFA* | Go-around fuel allowance [kg] |
| *GATA* | Go-around time allowance [min] |
| *GDP* | Gross Domestic Product [US$] |
| *GDPi* | Gross Domestic Product related to the city of the i-th airport [US$] |
| *GSP* | Gas Turbine Simulation Program |
| *h(x,fp)* | Equality constraint function |
| *Hmaxbuffet* | Maximum pressure altitude limited by buffet margin [ft] |
| *hAR* | Horizontal tail aspect ratio |
| *hS* | Horizontal tail area [m2] |
| *hSweep* | Horizontal tail sweep angle |
| *hTR* | Horizontal tail aspect ratio |
| *HOLDT* | Regulatory holding time (min) |
| *Hp* | Pressure altitude [ft] |
| *hpos* | Horizontal tail position flag |
| *HT* | Horizontal tail |
| *hTR* | Horizontal stabilizer tapper ratio |
| *ID* | Average inflight delay cost [US$/min] |
| *IDF* | Individual Discipline Feasible framework |
| *IATA* | International Air Transport Association |
| *ICAO* | International Civil Aviation Organization |
| *inc kink* | Airfoil incidence at wing kink [o] |
| *inc root* | Airfoil incidence at wing root [o] |
| *inc tip* | Airfoil incidence at wing tip [o] |
| *J(x,fp)* | Objective function |
| *k1* | Total operational costs to direct operational costs ratio |
| *k2* | Total revenue to ticket revenue ratio |
| *KinkPos* | Wing kink semispan position [%] |
| *lco* | Forward fuselage length [m] |
| *lf* | Fuselage length [m] |
| *ltail* | Tailcone length [m] |
| *L* | Airplane lift force [N] |
| *LAT* | Airport’s reference point latitude [o] |
| *LATi* | Latitude of the origin airport [o] |
| *LAtj* | Latitude of the destination airport [o] |
| *LDA* | Landing distance available [m] |
| *lf* | Fuselage length [m] |
| *LFL* | Design Landing Field Length, @ sea level, ISA conditions [m] |
| *LFref* | Reference Load Factor |
| *LON* | Airport’s reference point longitude [o] |
| *LONi* | Longitude of the origin airport [o] |
| *LONj* | Longitude of the destination airport[o] |
| *LPM* | Linear Programming Model |
| *LRWY* | Most used landing runway |
| *LW* | Landing weight [kg] |
| *L/Dbest ROC* | Best rate of climb lift over drag ratio |
| *M* | Mach Number |
| *MaxAlt* | Maximum Certified Cruise Altitude Ceiling [ft] |
| *MAXFUEL* | Maximum Fuel Capacity @ 0.81kg/l fuel density [kg] |
| *MaxPax* | Maximum Cabin Passengers Capacity |
| *MAXRATE* | Maximum Takeoff Thrust @ sea level / ISA conditions [lbf] |
|  | Engine turbofan compressor actual mass flow [kg/s] |
| *MDA* | Multidisciplinary design analysis |
| *MDF* | Multidisciplinary Feasible |
| *MDO* | Multidisciplinary design and optimization |
| *Nc* | Turbofan engine compressor corrected rotor speed [%] |
| *MAR* | Minimum acceptable rate of return of investment [%] |
| *MILP* | Mixed Integer Linear Programing |
| *MINCRZT* | Minimum cruise time [min] |
| *MIT* | Massachusetts Institute of Technology |
| *MLW* | Maximum landing weight [kg] |
| *MMO* | Maximum certified speed (Mach number) |
| *MOGA* | Multi-objective genetic algorithm |
| *MTOW* | Maximum takeoff weight [kg] |
| *MZFW* | Maximum zero fuel weight [kg] |
| *Nacftk* | Total number of k-th aircraft |
| *Naisles* | Number of aisles in the cabin |
| *NAND* | Nested Analysis Design |
| *NASA* | United States National Aeronautics and Space Administration |
| *NDOC* | Average air transport network’s direct operational cost [US$/ nm] |
| *NFP* | Network fixed parameters |
| *NLR* | National Aerospace Laboratory of Netherlands |
| *NPV* | Net present value [US$] |
| *ne* | Number of engines installed in the aircraft |
| *Ngalleys* | Number of galley stations in the aircraft |
| *NP* | Total network profit [US$/(PAX.nm)] |
| *Npax* | Number of Passengers (single class, pitch 32”) |
| *Nseat* | Number of Seat Abreast |
| *NPV* | Total sum of manufacturer´s net present value cashflow during the aircraft development and production period |
| *NSGA* | Non-Dominated Sorting Genetic Algorithm |
| *NSGA-II* | Fast Non-Dominating Sorting Genetic Algorithm |
| *OEW* | Operational empty weight [kg] |
| *OPR* | Engine overall pressure ratio |
| *p* | Average ticket price [US$] |
| *p0* | Static air pressure at sea level on International Standard Atmosphere (102325Pa) |
| *ptin* | Engine turbofan compressor inlet total pressure [Pa] |
| *Ptout* | Engine turbofan compressor outlet total pressure [Pa] |
| *P* | City pair population product |
| *Pi* | City pair population related to the city of the i-th airport |
| *PAX* | Passenger or Passengers |
| *PAXWT* | Total passenger’s weight including baggage [kg] |
| *PAYLOAD* | Total payload carried by the aircraft [kg] |
| *POP* | City population |
| *PR* | Turbofan engine compressor pressure ratio |
| *PSO* | Particle swarm optimization algorithm |
| *qHTeff* | Dynamic pressure efficiency on horizontal tail [%] |
| *r* | Distance from the sound source to the receiver [m] |
| *R* | Earth’s average radius [km] |
| *r0* | Airfoil leading edge radius |
| *RANGE* | Design Range, Full passengers @ 100kg, ISA conditions [nm] |
| *RROC* | Residual rate of climb [ft/min] |
| *rsparps* | Rear spar position on mean aerodynamic chord [%] |
| *S* | Accumulated enroute distance [m] |
| *SA* | Simulated annealing optimization algorithm |
| *SAND* | Simultaneous analysis and design |
| *SeatW* | Passenger´s seat width |
| *sflap* | Flap area [m2] |
| *SlatPres* | Slat presence flag |
| *SFC* | Engine specific fuel consumption [kg/s/N] |
| *SPDLIM* | Speed Limit below 10000ft pressure altitude in terms of indicated airspeed [kt] |
| *SP* | Aircraft sales price [Millions of US$] |
| *SPL* | Sound Pressure Level [dB] |
| *T* | Engine net thrust [N] |
| *T0* | Static air temperature at sea level on International Standard Atmosphere (288,15K) |
| *TAT* | Turnaround time [min] |
| *tc* | Airfoil thickness ratio |
| *tcmax* | Airfoil maximum thickness chord-wise position |
| *tckink* | Airfoil thickness ratio at wing kink |
| *tcroot* | Airfoil thickness ratio at wing root |
| *tctip* | Airfoil thickness ratio at wing tip |
| *Tctcmax* | Camber at maximum thickness chord-wise position |
| *t* | Time measure [s, min, h, years or months] |
| *Tij* | Trip time spent between i-th and j-th airports [min] |
| *TBij* | Block time spent between i-th and j-th airports [min] |
| *TIT* | Taxi-in time [min] |
| *TODA* | Takeoff Distance Available [m] |
| *TOFL* | Design Takeoff Field Length @ sea level, ISA conditions [m] |
| *TOT* | Taxi-out time [min] |
| *totSwet* | Total aircraft wet area [m2] |
| *ToWreq* | Required thrust-over-weight ratio |
| *Tref* | Airport reference temperature |
| *TOF* | Takeoff fuel (fuel on board at beginning of takeoff run) [kg] |
| *TOFA* | Takeoff and climb-out fuel allowance [kg] |
| *TOTA* | Takeoff and climb-out time allowance [min] |
| *TOW* | Takeoff weight [kg] |
| *TRWY* | Most used takeoff runway |
| *T/W* | Thrust-to-weight ratio |
| *ULH* | Uniform Latin Hippercube |
| *V* | True airspeed [m/s] |
| *vAR* | Vertical stabilizer aspect ratio |
| *VMO* | Maximum certified speed (indicated airspeed, kt) |
| *VT* | Vertical tail |
| *vAR* | Vertical Tail aspect ratio |
| *Vbest ROC* | Best rate of climb speed [m/s] |
| *vS* | Vertical tail area [m2] |
| *vSweep* | Vertical tail sweep angle |
| *vTR* | Vertical stabilizer aspect ratio |
| *W* | Airplane weight [kg] |
| *Wc* | Turbofan engine compressor corrected mass flow [kg/s] |
| *Wf* | Total fuel burned from origin to destination airport [kg] |
| *Wfapp* | Total fuel burned on approach phase [kg] |
| *Wfalternate* | Total fuel burned from destination to alternate airport [kg] |
| *Wfcontingency* | Contingency fuel [kg] |
| *Wfholding* | Fuel for the holding flight phase [kg] |
| *Wftaxi* | Taxi fuel [kg] |
| *wAR* | Wing aspect ratio |
| *wDih* | Wing Dihedral [o] |
| *WingletPres* | Winglet presence flag |
| *wb* | Wing semi-span [m] |
| *WoSreq* | Required wing load [N/m2] |
| *wS* | Wing reference area [m2] |
| *wSweep1/4* | Wing quarter-chord sweepback angle [o] |
| *wSweepLE* | Wing leading edge sweepback angle [o] |
| *wTR* | Wing tapper ratio |
| *wTwist* | Wing Twist Angle [o] |
| *WL\_AR* | Winglet Aspect ratio [m2] |
| *WL\_TR* | Winglet tapper ratio |
| *WL\_sweep* | Winglet sweep angle |
| *WL\_cantl* | Winglet cantlever angle [deg] |
| *WL\_twist* | Winglet twist angle [deg] |
| *W/S* | Wing loading [N/m2] |
| *x* | Vector of design parameters |
| *xle* | Wing leading edge position |
| *xLB* | Design variable lower band limit |
| *xUB* | Design variable upper band limit |
| *XDSM* | Extended Design Structure Matrix |
| *Ycmax* | Airfoil maximum camber |
| *Xiltj* | Fraction of the passenger’s demand flow fij from origin i to destination j |
| *Yijk* | Number of type-k airplane linking i-th to j-th city (route frequency) |
| *XYcmax* | Camber at maximum thickness chord-wise position |
|  |  |

List of Symbols

|  |  |  |
| --- | --- | --- |
| *α* | Angle of attack [o] | |
| *β* | Sideslip angle [o] | |
| *δ* | Atmospheric pressure ratio (s*tatic air pressure/p0*) at a given pressure altitude | |
| *δ1* | Inner wing panel dihedral [o] | |
| *δ2* | Outer wing panel dihedral [o] | |
| *δmax* | Atmospheric pressure ratio at altitude where buffet margin is achieved | |
| *ε* | Airfoil camber line angle at trailing edge [o] | |
| *φ* | Airfoil thickness line angle at trailing edge [o] | |
| *ϕ* | Acceleration factor function | |
| *γ* | Flight path angle [rad] | |
| *П* | Engines throttle position [%] | |
| *η* | Turbofan engine compressor efficiency | |
| *ρ* | Air density at a given pressure altitude [kg/m3] | |
| *ρ0* | Air density at sea level on International Standard Atmosphere (1,225kg/m3) | |
| *Ψij* | Average true heading at the great circle path from origin airport *i* to destination airport *j* | |
| *σ* | Atmospheric density ratio (*air density/ρ0*) at a given pressure altitude | |
| *θ* | Atmospheric temperature ratio (*static air temperature/T0)* at a given pressure altitude | |
| *θc* | Airfoil camber line angle at leading edge [o] | |
| *Θ* | Directivity angle of the sound source [o] | |
| *ΔISA* | Temperature deviation from the temperature predicted by ICAO International Standard Atmosphere at a given pressure altitude (Hp) [oC] | |
| *ΔDdiv* | | Airplane total drag percentual increase due to compressibility effects near MMO [%] | |

Sumary

[1. Introduction 31](#_Toc26221292)

[1.1 Commercial transport aircraft (“Airliners”)](#_Toc26221293) 39

[1.2 Aircraft conceptual design](#_Toc26221293) 42

[1.3 Objective](#_Toc26221294) 46

[1.4 Research contribution](#_Toc26221295) 47

[1.5 Chapters structure](#_Toc26221296) 49

[2. Literature Review 50](#_Toc26221297)

[2.1 Multidisciplinary design optimization 50](#_Toc26221298)

[2.2 Design optimization techniques 57](#_Toc26221299)

[2.3 Air transport network optimization 64](#_Toc26221300)

[2.4 Integrated aircraft and network optimization 68](#_Toc26221301)

[3. Methodology 71](#_Toc26221302)

[3.1 The aircraft framework 80](#_Toc26221303)

[3.1.1 MTOW and OEW estimation 82](#_Toc26221304)

[3.1.2 Aerodynamics 91](#_Toc26221305)

[3.1.3 Propulsion](#_Toc26221306) 98

[3.1.4 Noise](#_Toc26221307) 99

[3.1.5 Airplane design performance check](#_Toc26221308) 101

[3.2 Network framework](#_Toc26221309) 108

[3.2.1 Network optimization](#_Toc26221310) 109

[3.2.2 Mission performance](#_Toc26221311) 113

[3.2.3 Network economics](#_Toc26221312) 124

[3.3 The optimization cycle](#_Toc26221313) 129

[4. Simulations and Analysis](#_Toc26221314) 131

[4.1 Optimized aircraft design for a given network](#_Toc26221315) 132

[4.2 Optimized network for a given aircraft design](#_Toc26221316) 144

[4.3 Integrated network and aircraft design optimization](#_Toc26221317) 149

[4.4 Integrated complex network and aircraft fleet optimization](#_Toc26221318) 164

[5. Conclusions and Final Remarks](#_Toc26221319) 179

[6. Areas of improvements and future work](#_Toc26221319) 187

[References 189](#_Toc26221320)

[Appendix A - Passenger demand model analysis](#_Toc26221321) 199

[Table A.1 - Log-linear regression (twenty busiest Brazilian routes in year 2014) 199](#_Toc26221322)

[Table A.2 - Log-linear regression (twenty busiest Brazilian routes in year 2015)](#_Toc26221323) 200

[Table A.3 - Log-linear regression (twenty busiest Brazilian routes in year 2016)](#_Toc26221324) 201

[Appendix B – Network data 202](#_Toc26221325)

[Table B.1: Airport data](#_Toc26221326) 202

[Table B.2: Econometric data 202](#_Toc26221327)

[Table B.3: Network route distances -Dij [nm]](#_Toc26221328) 203

[Table B.4: Magnetic headings -Ψij [°] 203](#_Toc26221329)

[Appendix C - Optimization results: Fixed network/optimum aircraft case (5 airports) 204](#_Toc26221330)

[Appendix D - Optimization results: Optimum network/Optimum aircraft case ( 5 airports) 209](#_Toc26221331)

[Appendix E - Optimization results: Fixed network/Optimum aircraft case (10 airports) 215](#_Toc26221332)

[Appendix F - Optimization results: Optimum network/Optimum aircraft (10 airports)](#_Toc26221333) 220

[Appendix G - Aircraft Database](#_Toc26221334) 224

[Appendix H - Optimization Results : Optimum Network and 3-Aircraft fleet (20 airports)](#_Toc26221335) 225

[Appendix I - Optimum network and 3-aircraft fleet characteristics (20 airports)](#_Toc26221336) 229