INTEGRATED OPTIMIZATION OF AIR TRANSPORTATION SYSTEMS (AIRCRAFT AND NETWORK)

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À minha amada família

Luciana (in memoriam)
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" 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

Figure 4.21: Pareto front of the baseline optimization task. (Fuel price = US$ 1.431/kg; Average price = US$ 110). 180

Figure 4.22: Network P1 to fulfill Brazilian passenger demands. From top to bottom, routes performed by Airplanes 14, 37, and 25, respectively. 180

Figure 4.23: Pareto front of the optimization task with increased average ticket price. Some dominated individuals are shown in empty blue circle markers only for clarity. 183

Figure 4.24: The individual P7 from the Pareto front of the second simulation (increased ticket price). 184

Figure 4.25: Pareto front of the simulation with increased fuel price. 185

Figure 4.26: Connections displayed are performed by Airplanes No. 14, 38, and 25 from the simulation that considered increased fuel price. 185

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)....157

Table 4.11d : Max NP - Integrated optimization x fixed network baseline (5 airports)....157

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

Table 4.19 : Individuals selected in the Pareto front (baseline optimization) 180

Table 4.20 : Characteristics of optimal individuals from the baseline optimization 182

Table 4.21 : Data for the network with maximum profit (P7)...183

Table 4.22 : Individual characteristics for the network with increased fuel price................185

List of Abbreviations

a_0	Speed of sound at sea level on standard atmosphere [m/s]
ACO	Ant colony optimization algorithm
AD_j	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
B_i	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 [%]
b_k	Passenger capacity of k-th aircraft
BuffMGN	Buffet margin (g)
CARGO	Total cargo loaded onboard [kg]
C	City pair airport catchment area product
C_i	City pair airport catchment related to the i-th airport [km^2]
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
CD_0	Zero lift drag coefficient
$CD_{0\ ubridge}$	Zero lift drag increase due to wing-fuselage interference
CD_{flap}	Drag increase due to takeoff flap extended
CD_{ind}	Induced drag coefficient
CD_{gear}	Drag increase due to landing gear extended
CD_{MMO}	Drag coefficient evaluated at maximum operating Mach number
CD_{wave}	Wave drag coefficient
CD_{wing}	Total wing drag coefficient
$CD_{windmill}$	Drag increase due to wind milling of a failed engine
CD_{rudder}	Drag increase due to ruder deflection

$CD_{0.70}$	Drag coefficient evaluated at 0.7 Mach number
Ceiling	Maximum aircraft certified altitude [ft]
C_{flt}	Flight component of direct operational cost (crew, oil, fuel and insurance) [US$/nm]
C_{maint}	Maintenance (labor and material) component of the direct operational cost [US$]
C_{depr}	Depreciation (airframe, engines and avionics) component of the direct operational
C_{fee}	Fees (Navigation, Airport and Register) component of the direct operational cost [US$]
C_{fin}	Financial (airframe and engine leasing) component of the direct operational cost [US$]
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
CL_{MAX}	Maximum lift coefficient at undeflected flap/gear up configuration
$CL_{MAX\ APP}$	Maximum lift coefficient at approach flaps/gear up configuration
$CL_{MAX\ LD}$	Maximum lift coefficient at landing flaps/gear down configuration
$CL_{MAX\ TO}$	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
$C_{m\alpha}$	Pitch moment coefficient

$C_{n\beta}$	Yawing moment coefficient
CO	Collaborative optimization framework
CO_2	Carbon dioxide
CORSIA	Carbon Offsetting and Reduction for International Aviation
CRAD	Catchment area radius [km]
Crew	Number of crew members (flight attendants + pilots)
c_k	Average direct operational cost [$/nm] of k-th aircraft at design range
D	Total aircraft drag [N]
DATCOM	United States Air Force Stability and Control Data Compendium
DD_i	Departure delay at i-th airport [min]
DESC	Sales price discount rate
d_{ij}	Distance from i-th to j-th airport [nm]
DOC	Direct operational cost [US$/nm]
DOC_{ijk}	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
l_e	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 [m^2]
eTIT	Engine turbine inlet temperature [K]
F	Frequency of sound source [Hz]
FASAL	Flight Attendant´s hourly salary [US$/h]
FAR25	Part 25 of the United States Code of Federal Regulations Title 14 (Airworthiness Standards: Transport Category Airplanes)
FCt	Cashflow at period t
f_{ij}	Daily demand from airport i-th to j-th airport
fp	Vector of fixed parameters
FF	Engines total fuel flow [kg/s]
FOB	Total fuel on board [kg]
FOSAL	First Officer´s hourly salary [US$/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 [m^2]
g	Gravity acceleration [m/s^2]

g(x,fp)	Inequality constraint function
G	Combined city pair Gross Domestic Product [US$]
GA	Genetic algorithm
GAFA	Go-around fuel allowance [kg]
GATA	Go-around time allowance [min]
GDP	Gross Domestic Product [US$]
GDP_i	Gross Domestic Product related to the city of the i-th airport [US$]
GSP	Gas Turbine Simulation Program
h(x,fp)	Equality constraint function
$Hmax_{buffet}$	Maximum pressure altitude limited by buffet margin [ft]
hAR	Horizontal tail aspect ratio
hS	Horizontal tail area [m^2]
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
k_1	Total operational costs to direct operational costs ratio
k_2	Total revenue to ticket revenue ratio
KinkPos	Wing kink semispan position [%]
l_{co}	Forward fuselage length [m]
l_f	Fuselage length [m]
l_{tail}	Tailcone length [m]
L	Airplane lift force [N]
LAT	Airport's reference point latitude [o]
LAT_i	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]
LON_i	Longitude of the origin airport [º]
LON_j	Longitude of the destination airport[º]
LPM	Linear Programming Model
LRWY	Most used landing runway

LW	Landing weight [kg]
$L/D_{best\ ROC}$	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]
$\dot{m}_c$	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]
$Nacft_k$	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$/ nm]
NFP	Network fixed parameters
NLR	National Aerospace Laboratory of Netherlands
NPV	Net present value [US$]
n_e	Number of engines installed in the aircraft
Ngalleys	Number of galley stations in the aircraft
NP	Total network profit [US$/(PAX.nm)]
Npax	Number of Passengers (single class, pitch 32")
Nseat	Number of Seat Abreast
NPV	Total sum of manufacturer´s net present value cashflow during the aircraft development and production period
NSGA	Non-Dominated Sorting Genetic Algorithm
NSGA-II	Fast Non-Dominating Sorting Genetic Algorithm
OEW	Operational empty weight [kg]
OPR	Engine overall pressure ratio
p	Average ticket price [US$]
p_0	Static air pressure at sea level on International Standard Atmosphere (102325Pa)
pt_{in}	Engine turbofan compressor inlet total pressure [Pa]
Pt_{out}	Engine turbofan compressor outlet total pressure [Pa]
P	City pair population product
P_i	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]
r_0	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 [m^2]
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]

T_0	Static air temperature at sea level on International Standard Atmosphere (288,15K)
TAT	Turnaround time [min]
tc	Airfoil thickness ratio
tc_{max}	Airfoil maximum thickness chord-wise position
tc_{kink}	Airfoil thickness ratio at wing kink
tc_{root}	Airfoil thickness ratio at wing root
tc_{tip}	Airfoil thickness ratio at wing tip
$Tctc_{max}$	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 [m^2]
ToW_{req}	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
$V_{best\ ROC}$	Best rate of climb speed [m/s]
vS	Vertical tail area [m^2]
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]
Wf_{app}	Total fuel burned on approach phase [kg]
$Wf_{alternate}$	Total fuel burned from destination to alternate airport [kg]
$Wf_{contingency}$	Contingency fuel [kg]
$Wf_{holding}$	Fuel for the holding flight phase [kg]
Wf_{taxi}	Taxi fuel [kg]
wAR	Wing aspect ratio
wDih	Wing Dihedral [o]
WingletPres	Winglet presence flag
wb	Wing semi-span [m]

WoS_{req}	Required wing load [N/m^2]
wS	Wing reference area [m^2]
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/m^2]
x	Vector of design parameters
xl_e	Wing leading edge position
x_{LB}	Design variable lower band limit
x_{UB}	Design variable upper band limit
XDSM	Extended Design Structure Matrix
Yc_{max}	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)
XYc_{max}	Camber at maximum thickness chord-wise position

List of Symbols

α	Angle of attack [º]
β	Sideslip angle [º]
δ	Atmospheric pressure ratio (*static air pressure/p0*) at a given pressure altitude
δ_1	Inner wing panel dihedral [º]
δ_2	Outer wing panel dihedral [º]
δ_{max}	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]
Π	Engines throttle position [%]
η	Turbofan engine compressor efficiency
ρ	Air density at a given pressure altitude [kg/m^3]
ρ_0	Air density at sea level on International Standard Atmosphere (1,225kg/m^3)
Ψij	Average true heading at the great circle path from origin airport *i* to destination airport *j*
σ	Atmospheric density ratio (*air density/ρ_0*) at a given pressure altitude
θ	Atmospheric temperature ratio (*static air temperature/T_0*) 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]
$\Delta Ddiv$	Airplane total drag percentual increase due to compressibility effects near MMO [%]

Sumary

1. Introduction 31
1.1 Commercial transport aircraft ("Airliners") 39
1.2 Aircraft conceptual design 42
1.3 Objective 46
1.4 Research contribution 47
1.5 Chapters structure 49
2. Literature Review 50
2.1 Multidisciplinary design optimization 50
2.2 Design optimization techniques 57
2.3 Air transport network optimization 64
2.4 Integrated aircraft and network optimization 68
3. Methodology 71
3.1 The aircraft framework 80
3.1.1 MTOW and OEW estimation 82
3.1.2 Aerodynamics 91
3.1.3 Propulsion 98
3.1.4 Noise 99
3.1.5 Airplane design performance check 101
3.2 Network framework 108
3.2.1 Network optimization 109
3.2.2 Mission performance 113
3.2.3 Network economics 124
3.3 The optimization cycle 129
4. Simulations and Analysis 131
4.1 Optimized aircraft design for a given network 132
4.2 Optimized network for a given aircraft design 144
4.3 Integrated network and aircraft design optimization 149
4.4 Integrated complex network and aircraft fleet optimization 164

5. Conclusions 179

6. Areas of improvements and future work 187

References 189

Appendix A - Passenger demand model analysis 199

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

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

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

Appendix B – Network data 202

Table B.1: Airport data 202

Table B.2: Econometric data 202

Table B.3: Network route distances -D_{ij} [nm] 203

Table B.4: Magnetic headings -Ψ_{ij} [°] 203

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

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

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

Appendix F - Optimization results: Optimum network/Optimum aircraft (10 airports) 220

Appendix G - Aircraft Database 224

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

Appendix I - Optimum network and 3-aircraft fleet characteristics (20 airports) 229