

INTEGRATED OPTIMIZATION OF AIR TRANSPORTATION SYSTEMS (AIRCRAFT AND NETWORK)

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ITA

À minha amada família

Luciana (in memoriam)

Anna Carolina

Enzo

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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.

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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
b_{flap}	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
$CD_{0ubridge}$	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
<i>Ceiling</i>	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\$]
<i>CFD</i>	Computer fluid dynamics
<i>CG</i>	Aircraft's center of gravity
<i>chordc</i>	Airfoil chord length at central fuselage [m]
<i>chordk</i>	Airfoil chord length at wing kink [m]
<i>chordr</i>	Airfoil chord length at wing root [m]
<i>chordt</i>	Airfoil chord length at wing tip [m]
<i>City</i>	City name
<i>CL</i>	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
<i>CMA</i>	Wing mean aerodynamic chord length [m]
<i>CNS</i>	Communication, Navigation and Surveillance Technologies
C_{ma}	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 [°]
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
$epyz$	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 [°]
$flapTO$	Takeoff flap deflection [°]
$fusd$	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
$GAF A$	Go-around fuel allowance [kg]
$GAT A$	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
$Hmax_{buffer}$	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 taper 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 [°]
$inc\ root$	Airfoil incidence at wing root [°]
$inc\ tip$	Airfoil incidence at wing tip [°]
$J(x,fp)$	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 [°]
LAT_i	Latitude of the origin airport [°]
LAT_j	Latitude of the destination airport [°]
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 [°]
LON_i	Longitude of the origin airport [°]
LON_j	Longitude of the destination airport [°]
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
N_c	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]
N_{acft_k}	Total number of k-th aircraft
$Naisles$	Number of aisles in the cabin

<i>NAND</i>	Nested Analysis Design
<i>NASA</i>	United States National Aeronautics and Space Administration
<i>NDOC</i>	Average air transport network's direct operational cost [US\$/ nm]
<i>NFP</i>	Network fixed parameters
<i>NLR</i>	National Aerospace Laboratory of Netherlands
<i>NPV</i>	Net present value [US\$]
n_e	Number of engines installed in the aircraft
<i>Ngalleys</i>	Number of galley stations in the aircraft
<i>NP</i>	Total network profit [US\$/(PAX.nm)]
<i>Npax</i>	Number of Passengers (single class, pitch 32")
<i>Nseat</i>	Number of Seat Abreast
<i>NPV</i>	Total sum of manufacturer's net present value cashflow during the aircraft development and production period
<i>NSGA</i>	Non-Dominated Sorting Genetic Algorithm
<i>NSGA-II</i>	Fast Non-Dominating Sorting Genetic Algorithm
<i>OEW</i>	Operational empty weight [kg]
<i>OPR</i>	Engine overall pressure ratio
p	Average ticket price [US\$]
p_0	Static air pressure at sea level on International Standard Atmosphere (102325Pa)
p_{tin}	Engine turbofan compressor inlet total pressure [Pa]
P_{tout}	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
<i>PAX</i>	Passenger or Passengers

<i>PAXWT</i>	Total passenger's weight including baggage [kg]
<i>PAYLOAD</i>	Total payload carried by the aircraft [kg]
<i>POP</i>	City population
<i>PR</i>	Turbofan engine compressor pressure ratio
<i>PSO</i>	Particle swarm optimization algorithm
<i>qHTeff</i>	Dynamic pressure efficiency on horizontal tail [%]
<i>r</i>	Distance from the sound source to the receiver [m]
<i>R</i>	Earth's average radius [km]
<i>r₀</i>	Airfoil leading edge radius
<i>RANGE</i>	Design Range, Full passengers @ 100kg, ISA conditions [nm]
<i>RROC</i>	Residual rate of climb [ft/min]
<i>rsparps</i>	Rear spar position on mean aerodynamic chord [%]
<i>S</i>	Accumulated enroute distance [m]
<i>SA</i>	Simulated annealing optimization algorithm
<i>SAND</i>	Simultaneous analysis and design
<i>SeatW</i>	Passenger's seat width
<i>sflap</i>	Flap area [m ²]
<i>SlatPres</i>	Slat presence flag
<i>SFC</i>	Engine specific fuel consumption [kg/s/N]
<i>SPDLIM</i>	Speed Limit below 10000ft pressure altitude in terms of indicated airspeed [kt]
<i>SP</i>	Aircraft sales price [Millions of US\$]
<i>SPL</i>	Sound Pressure Level [dB]
<i>T</i>	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]
T_{ij}	Trip time spent between i-th and j-th airports [min]
T_{Bij}	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
T_{ref}	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]
$wSweep_{l/4}$	Wing quarter-chord sweepback angle [$^\circ$]
$wSweep_{LE}$	Wing leading edge sweepback angle [$^\circ$]
wTR	Wing taper ratio
$wTwist$	Wing Twist Angle [$^\circ$]
WL_AR	Winglet Aspect ratio [m^2]
WL_TR	Winglet taper 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
$XD\mathcal{S}M$	Extended Design Structure Matrix
$Y_{C_{max}}$	Airfoil maximum camber
X_{iltj}	Fraction of the passenger's demand flow f_{ij} from origin i to destination j
Y_{ijk}	Number of type- k airplane linking i -th to j -th city (route frequency)
$XY_{c_{max}}$	Camber at maximum thickness chord-wise position

List of Symbols

α	Angle of attack [°]
β	Sideslip angle [°]
δ	Atmospheric pressure ratio (<i>static air pressure/p0</i>) at a given pressure altitude
δ_1	Inner wing panel dihedral [°]
δ_2	Outer wing panel dihedral [°]
δ_{max}	Atmospheric pressure ratio at altitude where buffet margin is achieved
ε	Airfoil camber line angle at trailing edge [°]
φ	Airfoil thickness line angle at trailing edge [°]
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)
Ψ_{ij}	Average true heading at the great circle path from origin airport <i>i</i> to destination airport <i>j</i>
σ	Atmospheric density ratio (<i>air density/ρ_0</i>) at a given pressure altitude
θ	Atmospheric temperature ratio (<i>static air temperature/T_0</i>) at a given pressure altitude
θ_c	Airfoil camber line angle at leading edge [°]
Θ	Directivity angle of the sound source [°]
ΔISA	Temperature deviation from the temperature predicted by ICAO International Standard Atmosphere at a given pressure altitude (Hp) [°C]
ΔD_{div}	Airplane total drag percentual increase due to compressibility effects near MMO [%]

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