INTEGRATED OPTIMIZATION OF AIR TRANSPORTATION SYSTEMS (AIRCRAFT AND NETWORK)

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À minha amada família

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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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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