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

|  |  |
| --- | --- |
| *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 [%] | |

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