Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

Contributions to Aircraft Preliminary Design and Optimization

Ing. Dipl. Mihaela Niţă

Supervisors:

CS I Dr. Ing. Mihai Neamţu and **Prof. Dr.-Ing. Dieter Scholz**

Faculty of Aerospace Engineering

Department of Aerospace Sciences “Elie Carafoli”

28 March 2012

Motivation

"There is little use of optimization and optimization tools in industry! The understanding of a solution, the transparency of the solution is of prime importance to achieve credibility."

Prof. Dr. Dieter Schmitt
(Vice President, Research and Future Projects Airbus, retired) about aircraft design of commercial aircraft

Task

1. Finding optimal parameters for aircraft preliminary design and aircraft cabin design

2. Proposing scientific solutions to process chains optimizations for cabin conversions

Aircraft preliminary design is defined here as aircraft preliminary sizing and conceptual design

Objectives

1. Aircraft preliminary design

   - Developing an aircraft preliminary design methodology
   - Creating a transparent tool that incorporates the methodology
   - Understanding the effect of aircraft and cabin design parameters to the optimal design
   - Understanding the effect of innovative technologies

2. Process chain optimization

   - Finding the optimal sequence of engineering work processes in cabin design and cabin refurbishing

Method

1. Aircraft Preliminary Design

- Equations and methods for aircraft preliminary design were adjusted and new ones were introduced.

- Equations were combined to an aircraft design methodology that ensured a balanced view on benefits and penalties of changing values of design parameters.

- Methodology was implemented into Microsoft Excel to create a preliminary design and optimization tool, called *OPerA – Optimization in Preliminary Aircraft Design*.

Method

2. Process Chain Optimization

- Process representation models were searched
- Three methods were selected and applied on the selected representation model

1. Aircraft Preliminary Design

Research so far…

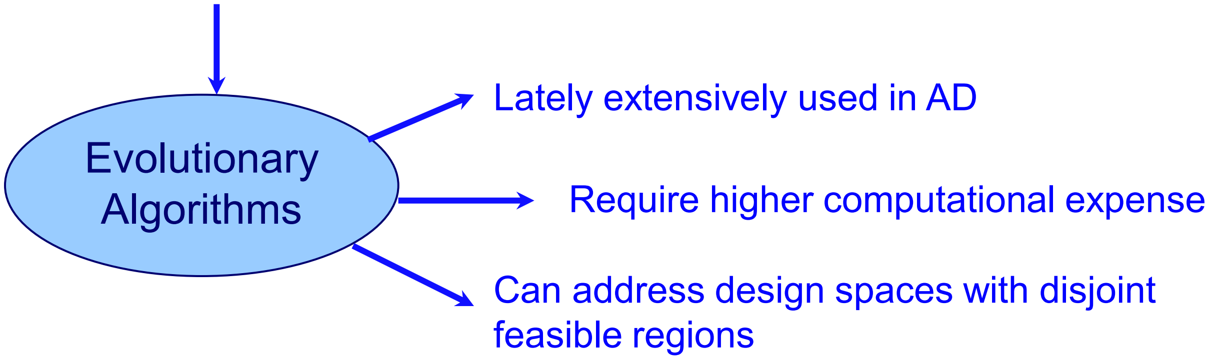
Aircraft Design (AD) **software tools**:

- Based on books, lecture notes or dissertations (AAA, RDS, PreSTO, QCARD)
- From companies or Research centers (APD, PIANO, CAPDA, ACSYNT, PRADO, FLOPS)
- Cabin Design software tools (FPCC, FPPD)

Research so far…

Optimization in Aircraft Design (AD):

- D. Raymer (Dissertation): aircraft conceptual design process can be improved by the proper application of optimization methods

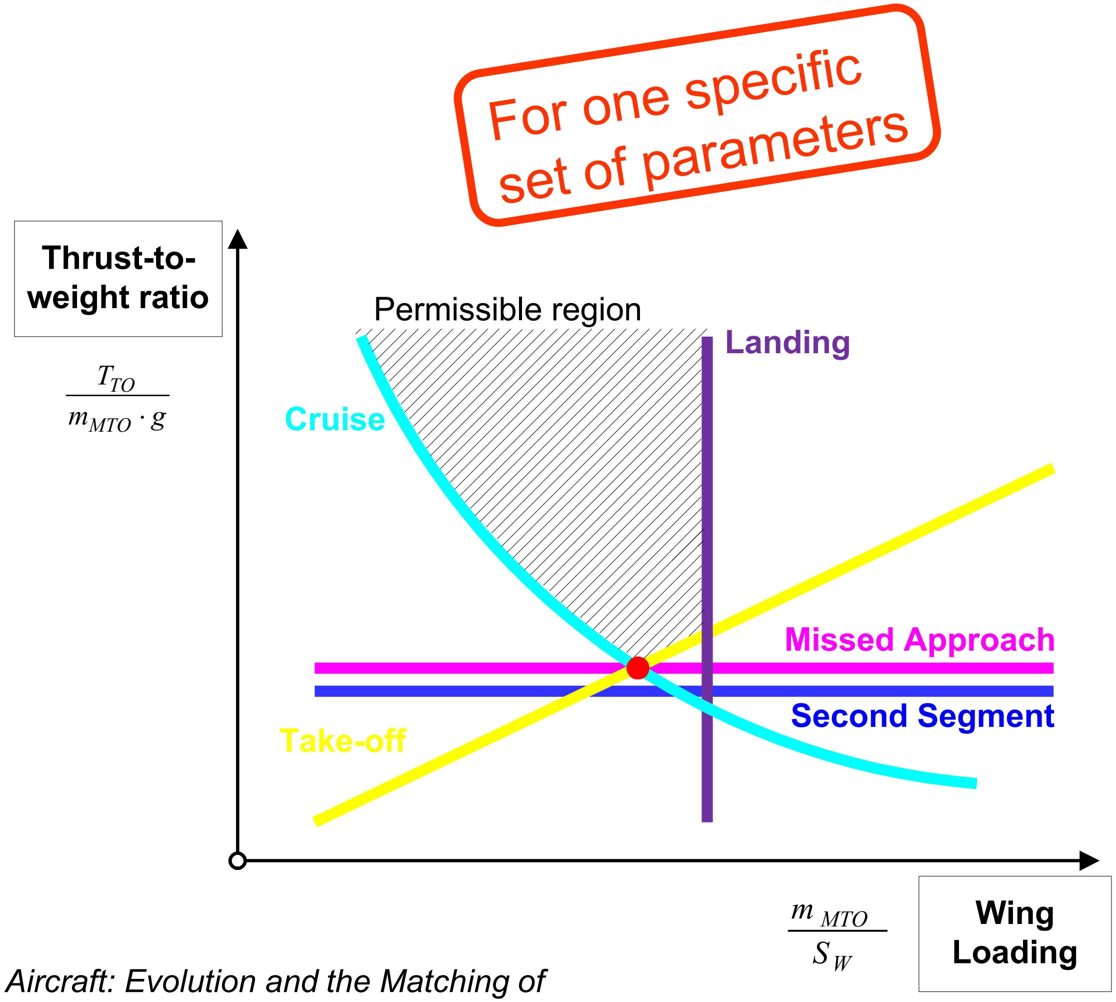


- Y. Crispin: *Aircraft Conceptual Optimization Using Simulated Evolution*
- N. Ali: *Conceptual Aircraft Design – A Genetic Search and Optimization Approach*
- A.W. Crossley: *Design of helicopters via Genetic Algorithm. Journal of Aircraft*
- F. Cantelimi: *Stochastic Optimization for Aircraft Preliminary Design*
- I. Kroo: *Multidisciplinary Optimization Methods for Aircraft Preliminary Design*
- R. Metzger: *Gesamtheitliche Optimierung von Rumpfquerschnitten im Flugzeugvorentwurf*

Classical Aircraft Sizing

- Two-dimensional optimization problem for five requirements

- This is the initial optimization



LOFTIN, Laurence K. Jr.: *Subsonic Aircraft: Evolution and the Matching of Size to Performance*. Hampton, VA. Langley : National Aeronautics and Space Administration, Research Center, 1980

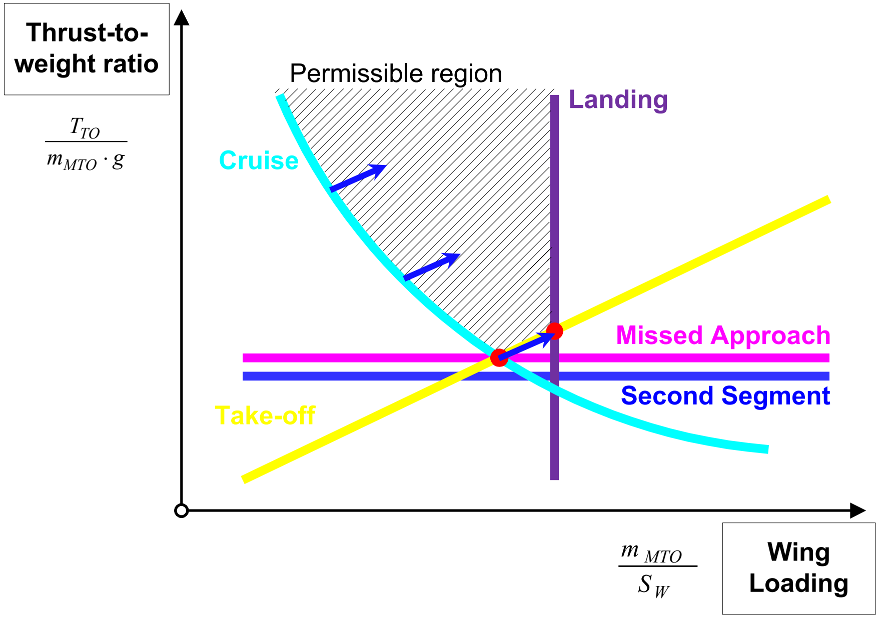
From Classical Aircraft Sizing to Formal Optimization

1. Automatically finding the design point for each set of parameters (inner optimization)

$$C_{L,Cruise} = C_{L,md}$$

$$C_L / C_{L,m} = 1/(V/V_m)^2$$

$$E = E_{\max} \cdot \frac{2}{\frac{1}{\left(\frac{C_l}{C_{l,m}}\right)} + \left(\frac{C_l}{C_{l,m}}\right)}$$



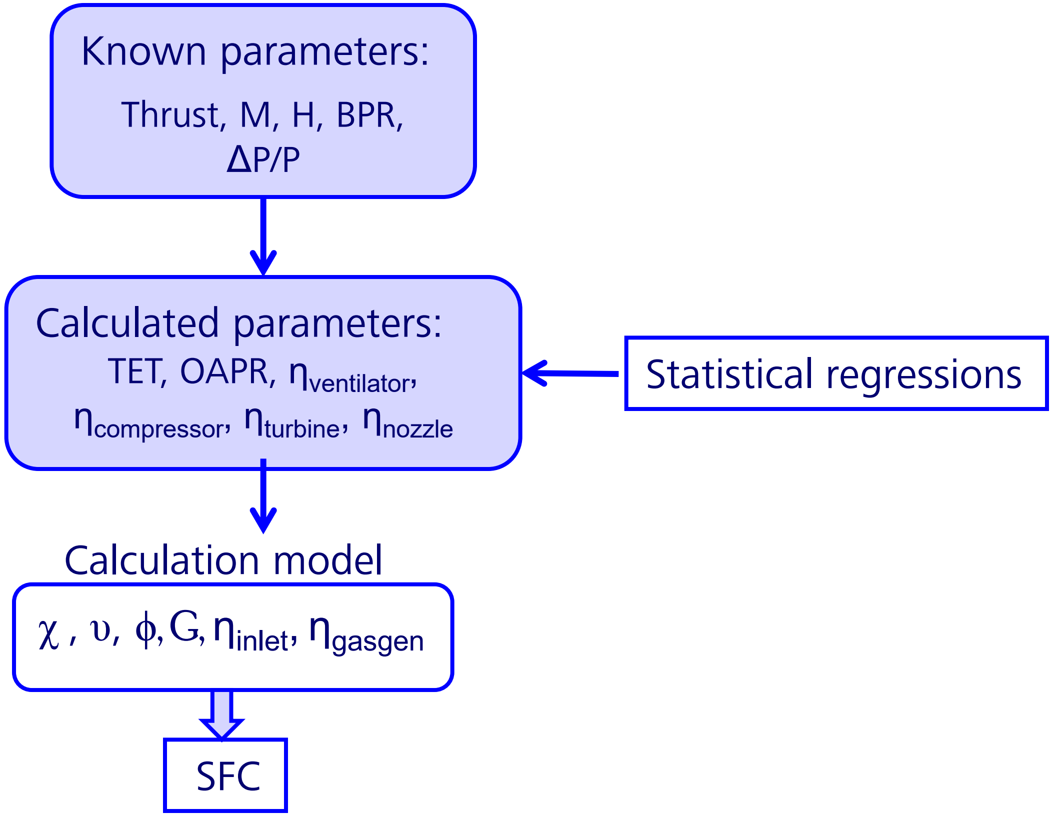
Two optimization levels

2. Automatically evaluation of multiple sets of parameters and formal optimization (outer optimization)

This special optimization hierarchy is new and allows efficient and traceable optimization

The method more precisely...

Thrust specific fuel consumption



HERRMANN, S.: *Untersuchung des Einusses der Motorenzahl auf die Wirtschaftlichkeit eines Verkehrsugzeuges unter Berücksichtigung eines optimalen Bypassverhältnisses.* Graduation Thesis, Technical University Berlin, 2010

The method more precisely...

Thrust specific fuel consumption

Necessary parametrs: BPR, OAPR, TET, ΔP/P and engine component efficiencies: $\eta_{ventilator}$, $\eta_{compressor}$, $\eta_{turbine}$, η_{nozzle}, η_{inlet}

$$SFC = \frac{0.697 \cdot \sqrt{\frac{t}{t_0}} \cdot (\phi - \vartheta - \frac{\chi}{\eta_{compressor}})}{\sqrt{5 \cdot \eta_{nozzle} \cdot (1 + \eta_{ventilator} \cdot \eta_{turbine} \cdot BPR) \cdot (G + 0.2 \cdot M^2 \cdot BPR \cdot \frac{\eta_{compressor}}{\eta_{ventilator} \cdot \eta_{turbine}})} - M \cdot (1 + BPR)}$$

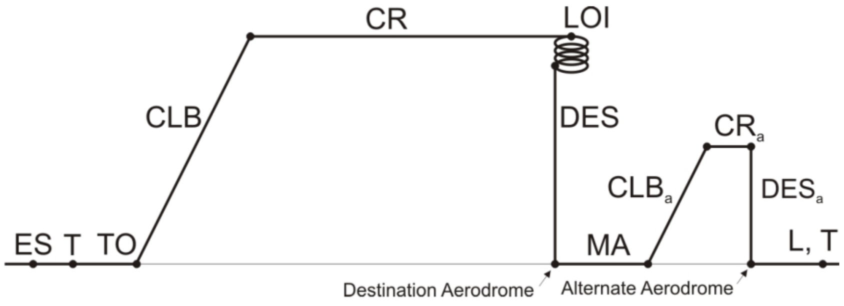
$$G = (\phi - \frac{\chi}{\eta_{compressor}}) \cdot \left(1 - \frac{1.01}{\eta_{gasgen}^{\frac{\kappa-1}{\kappa}} \cdot (\chi + \vartheta) \cdot (1 - \frac{\chi}{\phi \cdot \eta_{compressor} \cdot \eta_{turbine}})} \right);$$

$$\phi = T / t = 1 + \frac{\kappa - 1}{2} \cdot M^2; \qquad \chi = \vartheta \cdot \left(OAPR^{\frac{\kappa-1}{\kappa}} - 1 \right); \qquad \eta_{gasgen} = 1 - \frac{0.7 M^2 (1 - \eta_{inlet})}{1 + 0.2 M^2}$$

The method more precisely...

Refinement of mission fuel fractions

$$m_{MTO} = \frac{m_{PL}}{1 - \frac{m_F}{m_{MTO}} - \frac{m_{OE}}{m_{MTO}}}$$



$$m_F / m_{TO} = 1 - M_{ff}$$

0.997 for taxi; 0.993 for take-off, climb, descent, landing

$$M_{ff} = \frac{m_{SO}}{m_T} \cdot \frac{m_T}{m_L} \cdot \frac{m_L}{m_{DES}} \cdot \frac{m_{DES}}{m_{CR,alt}} \cdot \frac{m_{CR,alt}}{m_{CLB}} \cdot \frac{m_{CLB}}{m_{MA}} \cdot \frac{m_{MA}}{m_{DES}} \cdot \frac{m_{DES}}{m_{LOI}} \cdot \frac{m_{LOI}}{m_{CR}} \cdot \frac{m_{CR}}{m_{CLB}} \cdot \frac{m_{CLB}}{m_{TO}} = \frac{m_{SO}}{m_{TO}}$$

The method more precisely...

New method on Oswald efficiency estimation

$$e = e_{theo} \cdot k_{e,M} \cdot k_{e,stat}$$

$$e_{theo} = \frac{1}{1 + f(\lambda - \Delta\lambda) \cdot A}$$

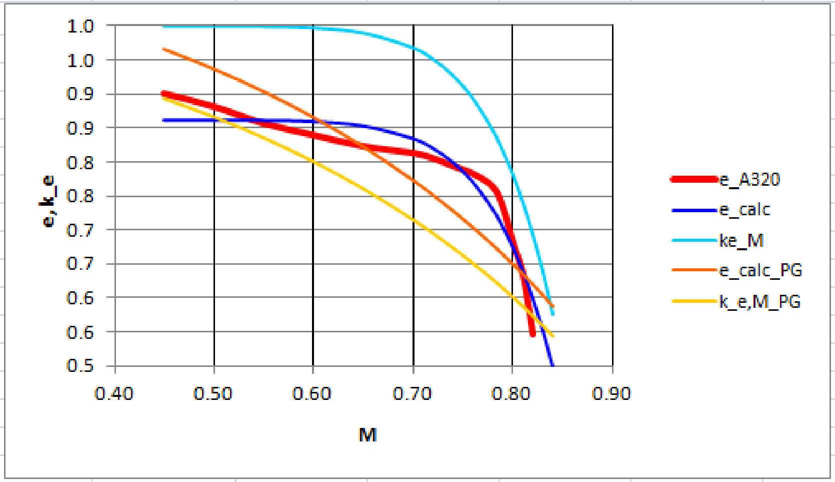
$$\Delta\lambda = -0.35659 + 0.45 e^{0.0375 \varphi_{25}}$$

$$f(\lambda) = 0.0524\,\lambda^4 - 0.15\lambda^3 + 0.1659\lambda^2 - 0.0706\lambda + 0.0119$$

$$k_{e,M} = \begin{cases} a_e \left(\frac{M}{M_{comp}} - 1 \right)^{b_e} + c_e, \; for\ M > M_{comp} \\ 1, \; for\ M \le M_{comp} \end{cases}$$

$$a_e < 0; \quad c_e = 1$$

$$a_e = -0.0027 \; ; \quad b_e = 8.6017$$



Aircraft type	$k_{e,stat}$	Rank
Jet airliner	0.896	1
Propeller aircraft	0.786	3
Business Jet	0.836	2
General aviation aircraft	0.779	4
Fighter	0.762	6

New method on Oswald efficiency estimation

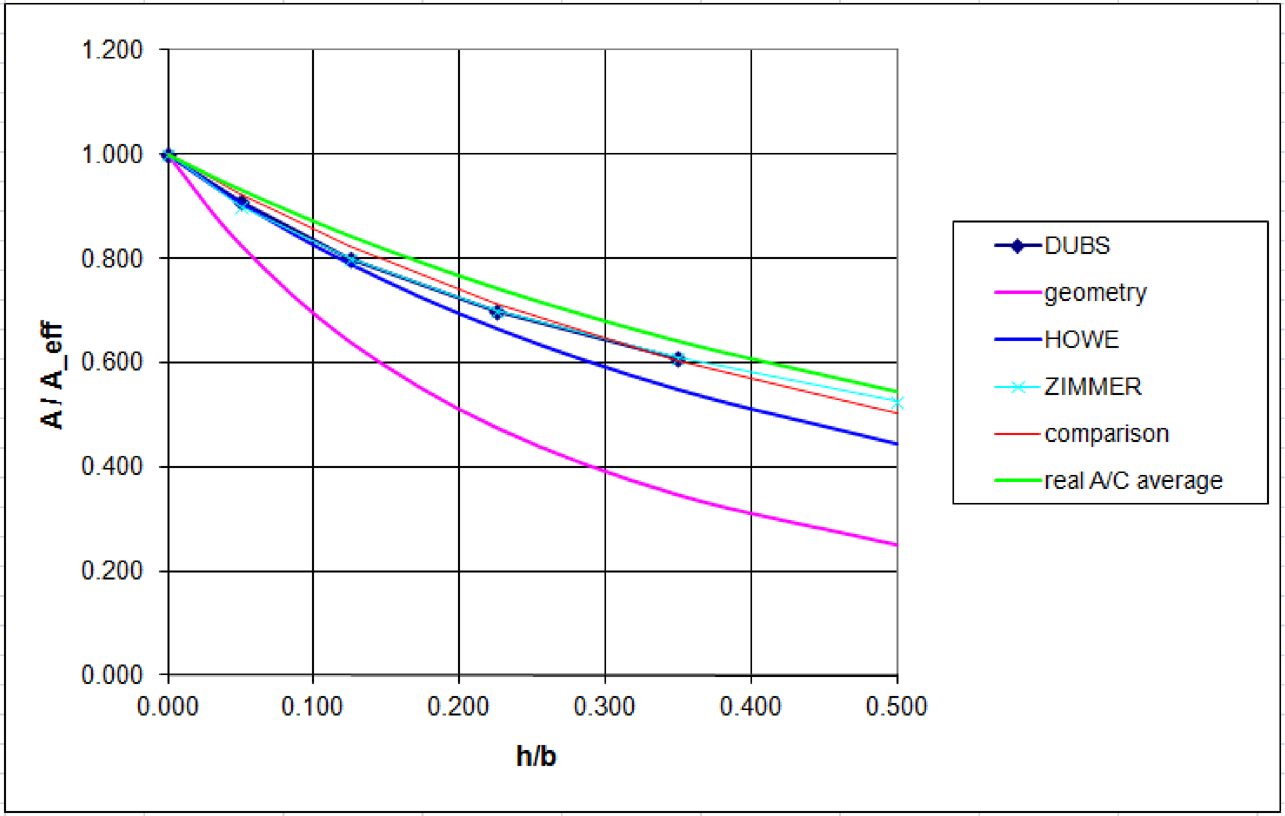
Oswald factor

Type	Number	Total in Group	Aircraft Size	Group Name
General aviation aircraft	5	6	small prop	GA aircraft
GA aircraft, 2-engines	1			
Propeller Aircraft, 2 engines	4	6	medium prop	propeller aircraft
Propeller Aircraft, 4 engines	1			
Medium Bomber	1			
Regionaljet	2	4	medium jet	business jet
Businessjet	2			
Jet aircraft	9	11	large jet	jet airliner
Military transporter	1			
Long range bomber	1			
Fighter	6	6	fighter	fighter

The method more precisely...

Estimation of winglets efficiency

$$\frac{A}{A_{eff}} = \frac{1}{\left(1 + \frac{2}{k_{wl}} \cdot \frac{h_{wl}}{b}\right)^2}$$

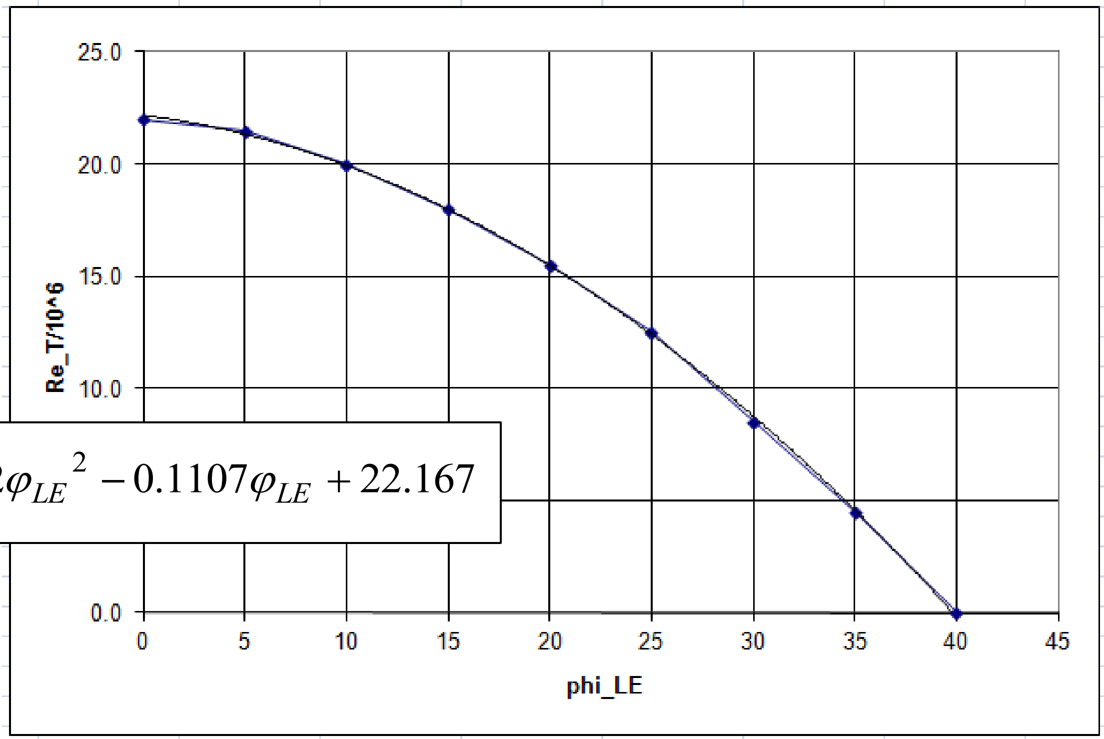


The method more precisely...

Natural Laminar Flow (NLF)

$$Re_T = Re \frac{x_T}{c}$$

$\frac{x_T}{c} \rightarrow k_{laminar}$



$$Re_T / 10^6 = -0.0112\varphi_{LE}^2 - 0.1107\varphi_{LE} + 22.167$$

Based on M. Hepperle: MDO of Forward Swept Wings. In: KATnet II Workshop, 28-29 January 2008, Braunschweig

The method more precisely...

Strut braced wings

- Wing mass reduction (strut force reduces wing bending)
- Increased aspect ratio becomes possible → Reduced induced drag
- Reduced thickness ratio becomes possible → Reduced wave drag
- → Reduced sweep → Increased areas for NLF → reduced zero-lift drag

- Drag increase due to wetted area of the strut and interference drag (is minimal).

Mass reduction compared to cantilever wing (based on Torenbeek):

$$\frac{m_{W,ST}}{m_W} = \left(\frac{b_{ST}}{b}\right)^{1.35} \cdot \frac{1+\sqrt{\frac{b_{ref}}{b_{ST}}}}{1+\sqrt{\frac{b_{ref}}{b}}} \cdot 0.7$$

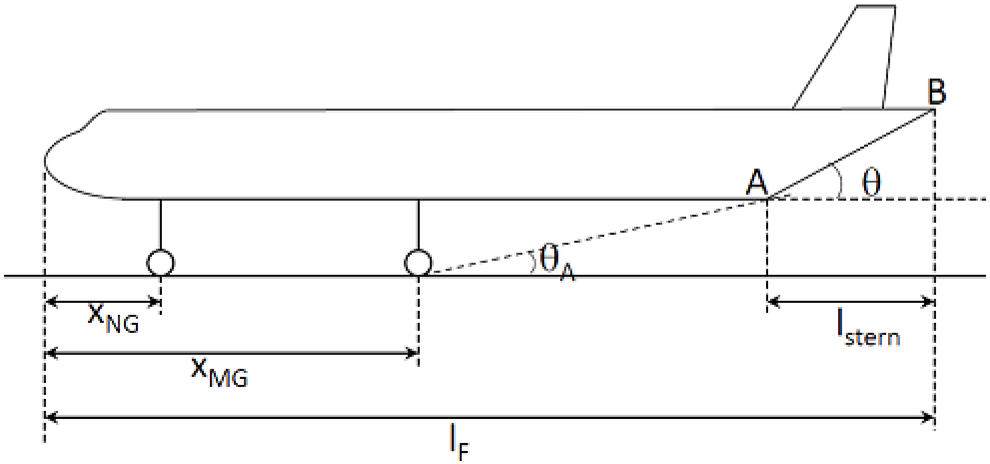
→ Howe: 0.78

The method more precisely...

Landing gear parameters and mass

Geometry constraints:

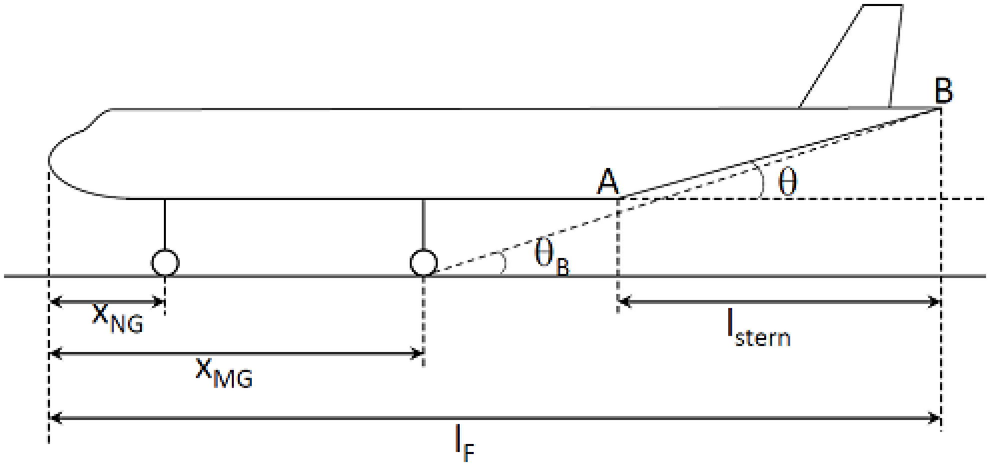
1. Tail strike prevention
2. Engine ground clearance
3. Wing tip ground clearance



$$\tan\theta_A = \frac{L_{MG,short}}{l_F - l_{stern} - x_{MG}}$$

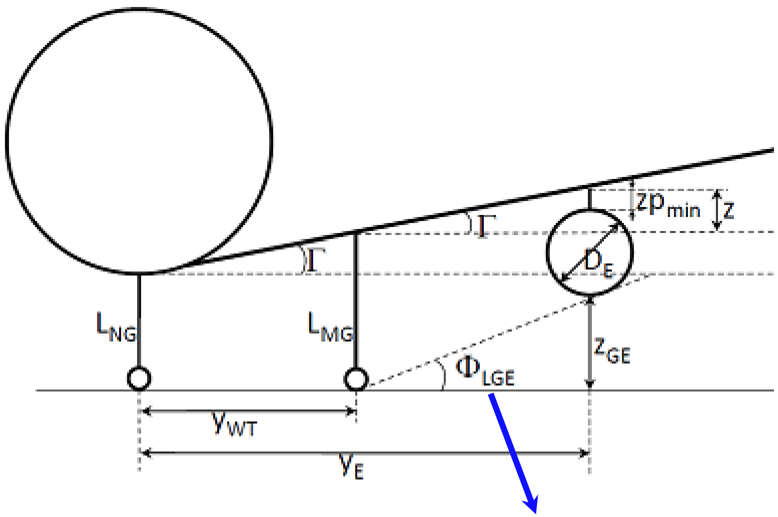
or

$$\tan\theta_B = \frac{L_{MG,long} + d_F}{l_F - x_{MG}}$$



Landing gear parameters and mass

Landing gear lengths (main and nose):



$$L_{MG} = z_{GE} + D_N + z_P - z$$

$$z_{GE} = tan\,(\varphi_{LGE}) \cdot (y_E - y_{wt}); \quad z_{GE} \leq 17''$$

$$z = tan\Gamma \cdot (y_E - y_{wt})$$

$$L_{MG} = y_{wt} - b_{KB} / 2$$

$$L_{NG} = L_{MG} - z_{NG}$$

$$z_{NG} = tan\Gamma \cdot y_{wt}$$

minimum bank angle of 7° must be possible

Landing gear parameters and mass

Mass:

$$m_{LG,main} = 5.496 \cdot V_{FL}^{0.172} \cdot V_S^{0.317} \cdot m_{ML}^{0.942} \cdot L_{MG}^{0.152} \cdot l_{WB}^{0.234} \cdot l_{SPRING,main}^{0.101} \cdot p_T^{-0.068}$$

$$m_{LG,nose} = 5.538 \cdot V_{FL}^{0.179} \cdot V_S^{0.128} \cdot m_{ML}^{0.779} \cdot L_{NG}^{0.276} \cdot l_{SPRING,nose}^{-0.1} \cdot p_T^{-0.161}$$

where:

- V_{FL} Approach speed for flapless landing, with values within [114 ; 269] *km/h*
- V_S Safe landing rate of sink, with values within [1.5 ; 4] *m / s*
- m_{ML} Maximum landing mass
- l_{SPRING} Spring deflection, with values within [0.2 ; 0.71] *m* for main gear and [0.22 ; 0.64] *m* for nose gear
- p_T tire pressure, with values within [0.81 ; 14.03] *bar* for main gear and [2 ; 14.2] *bar* for nose gear

Luftfahrttechnisches Handbuch, Band MA – Masseanalyse, Edition 2008

The method more precisely...

Dihedral

$$\Gamma = \frac{\partial \Gamma}{\partial k_{Z,W}} \cdot k_{Z,W} + \frac{\partial \Gamma}{\partial \varphi_{25}} \cdot \varphi_{25} + \Gamma_0$$

with:

$k_{Z,W}$ = 0.0, for low wing aircraft
$k_{Z,W}$ = 0.5, for mid-wing aircraft
$k_{Z,W}$ = 1.0 for high-wing aircraft

	Own	Raymer
$\frac{\partial \Gamma}{\partial k_{Z,W}}$	- 7.46	- 7
$\frac{\partial \Gamma}{\partial \varphi_{25}}$	- 0.115	- 0.1
Γ_0	6.91	6

- Moving the wing from High to Low, produces the effect of 7.5° of dihedral.
- 8.7° of sweep produce the effect of 1° of dihedral.
- For a low and unswept wing the value of 6.9° of dihedral should be used.

The method more precisely...

Thickness ratio

$$t/c = k_t \cdot M_{DD,eff}^{\,t} \cdot k_M$$

$$M_{DD,eff} = M_{DD}\sqrt{\cos(\varphi_{25})}$$

with:

- k_t 0.100
- t - 0.389
- k_M 1.057 for supercritical airfoils
  1.004 for peaky airfoils
  1.000 for conventional airfoils

better matching with real A/C data

airfoil technology factor

$$M_{DD} = \frac{\kappa_A}{\cos(\varphi_{25})} - \frac{(t/c)}{\cos^2(\varphi_{25})} - \frac{C_L}{10\cos^3(\varphi_{25})}$$

with:

- κ_A 0.87 for NACA 6 series airfoils
  0.95 for supercritical

higher sweep effect

The method more precisely...

Changes in load factor due to gusts (for Added Value calculation)

$$\Delta n = \frac{\rho K U_{DE} V_{CR} C_{L\alpha}}{2(m_{MTO} g / S_W)}$$

$$C_{L,\alpha} = \frac{2\pi A}{2 + \sqrt{A^2 \cdot \left(1 + \tan^2 \varphi_{50} - M^2\right) + 4}}$$

$$K = \frac{0.88\mu}{5.3 + \mu}$$

CS-23

$$\mu = \frac{2(m_{MTO} g / S_W)}{\rho\, c_{MAC} C_{L\alpha} g}$$

$$-1200 \cdot U_{DE}[ft/s] + 80000 = H[ft]$$

$$-1200 \cdot U_{DE}[m/s] + 24384[m] = H[m]$$

CS-25

V_CR is Equivalent Air Speed (EAS)

rho = rho_0 = 1.225 kg/m³
i.e. sea level conditions

The constant 1200 has the unit seconds [s]

The method more precisely...

Refinement of cabin and fuselage preliminary sizing

Methods found for estimation of (Overview):

- Fuselage nose length (not shown here)
- Baggage and cargo volume
- Overhead stowages volume
- 2 methods for generic cabin length
- Cargo compartment height – methods and statistics
- Sill height and cargo hold accessibility factor

Refinement of cabin and fuselage preliminary sizing

Baggage and cargo volume

$$V_{CC} \geq V_C + (V_B - V_{OS})$$

where:

- V_{CC} volume of the cargo compartment,
- V_C volume of cargo,
- V_B volume of baggage,
- V_{OS} volume of overhead stowage (OS).

$$V_{CC} = l_F \cdot k_{CC} \cdot S_{CC}$$

where:

- k_{CC} proportion of the fuselage length used for cargo ranging from 0.35 to 0.55,
- S_{CC} cross section of the cargo compartment.

Refinement of cabin and fuselage preliminary sizing

Overhead stowages volume

with:

$$V_B = m_B / \rho_B \qquad \rho_B = 170 \ \ kg/m^3$$

$$V_C = m_C / \rho_C \qquad \rho_C = 160 \ \ kg/m^3$$

$$V_{OS} = S_{OS,tot} \cdot l_{OS}$$ → for added value calculation

$$S_{OS,tot} = n_{OS,lat} \cdot S_{OS,lat} + n_{OS,ce} \cdot S_{OS,ce}$$

$$l_{OS} = k_{OS} \cdot l_{cabin}$$

where:

- m_B mass of baggage,
- m_C mass of cargo,
- ρ_B density of baggage,
- ρ_C density of cargo,
- $S_{OS,tot}$ total cross section of the OS calculated as a sum of the cross sections of lateral OS, $S_{OS,lat}$, (0.201 for single aisle and 0.208 for wide bodies) and central OS, $S_{OS,ce}$, (0.241 for wide bodies)
- $n_{OS,lat}$ number of lateral rows of OS
- $n_{OS,ce}$ number of central rows of OS: $n_{OS,ce} = n_{aisles} - 1$,
- l_{OS} total length of the OS (lateral and central),
- k_{OS} proportion of the cabin length occupied by the OS: 0.723 for single aisle and 0.751 for wide body

Refinement of cabin and fuselage preliminary sizing

2 methods for generic cabin length

1.

$$L_{cabin} = n_r \cdot k_{cabin} = \frac{n_{pax}}{n_{SA}} \cdot k_{cabin}$$

2.

$$L_{seats} = L_{SP} \cdot n_r$$
$$+$$
$$L_{cross\ aisles} = L_{cross\ aisle} \cdot n_{cross\ aisle}$$
$$+$$
$$L_{lavatories} = S_{lavatory,tot} / w_{tot}$$
$$+$$
$$L_{galleys} = S_{galley,tot} / w_{tot}$$
$$+$$
$$L_{addition}$$
$$= L_{cabin,\ generic}$$

$$l_F = l_{cabin} + l_{cockpit} + l_{tail} = l_{cabin} + 4\ \text{m} + 1.6 \cdot d_F$$

where:

$$S_{galley,tot} = n_{galley} \cdot S_{galley} = n_{trolley} \cdot S_{trolley,average}$$
$$S_{trolley,average} = S_{galley}(n_{trolley}) / n_{trolley}$$
$$S_{lavatory,tot} = n_{lavatory} \cdot S_{lavatory}$$
$$w_{tot} = w_{cabin} - n_{aisle} \cdot w_{aisle}$$

Refinement of cabin and fuselage preliminary sizing

Cargo compartment height (for added value calculation)

Method 1:

$$h_{cargo} = d_F k_{cargo,height}$$

Aircraft	$k_{cargo,height}$
Short range	0.200
Medium range	0.290
Long range	0.281

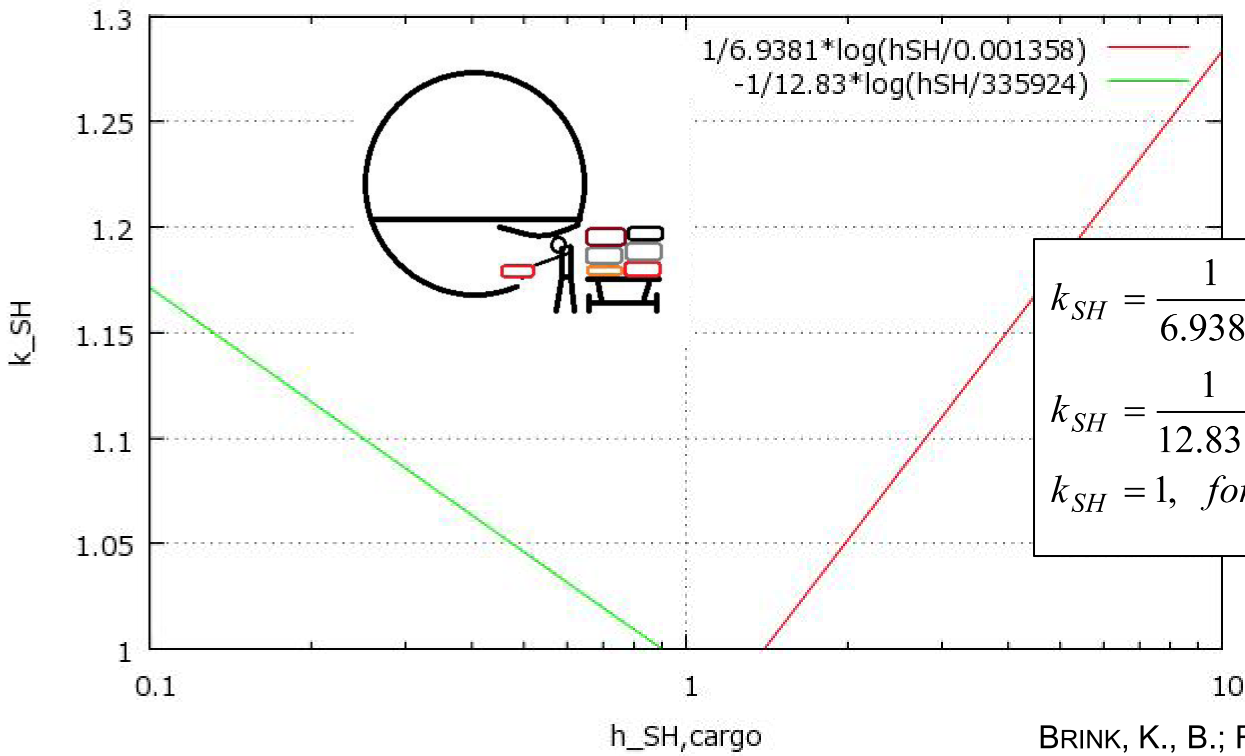
Method 2:

$$h_{cargo} = d_F / 2 - y_{floor,lowering} - t_{floor} - y_{bottom}$$

Parameter	Single Aisle	Wide Body	
$y_{floor,lowering}$	0.511	0.316	[m]
t_{floor}	0.179	0.232	[m]
y_{bottom}	0.225	0.588	[m]
$y_{floor,lowering} / d_F$	0.131	0.054	[-]
t_{floor} / d_F	0.045	0.040	[-]
y_{bottom} / d_F	0.056	0.101	[-]

Refinement of cabin and fuselage preliminary sizing

Sill Height and Cargo Hold Accessibility Factor



$$k_{SH} = \frac{1}{6.9381} Ln \frac{h_{SH,cargo}}{0.001358}, \quad for \quad h_{SH,cargo} > 1.4m$$

$$k_{SH} = \frac{1}{12.831} Ln \frac{h_{SH,cargo}}{335924}, \quad for \quad h_{SH,cargo} > 0.9m$$

$$k_{SH} = 1, \quad for \quad 0.9 < h_{SH,cargo} < 1.4$$

BRINK, K., B.; RIECK, G.: *Wartungsaufwandnalyse auf Systemebene : Qualitatuve und quantitative Wartbarkeits- und Zuverlässigkeitsanalysen.* Verein Deutscher Ingenieure, VDI Bildungswerk, 1973

The method more precisely...

Other contributions:

- Aspect ratio of vertical tail as a function of horizontal tail position

$$A_V = -0.8029 \cdot \frac{z_H}{b_V} + 1.6576$$

- Many updated statistical factors: k_{TO}, k_{APP}, C_{LmaxL}, C_{LmaxTO}
- Pylon wetted area
- Wing-nacelle interference factor as a function of minimum distance between engine and wing

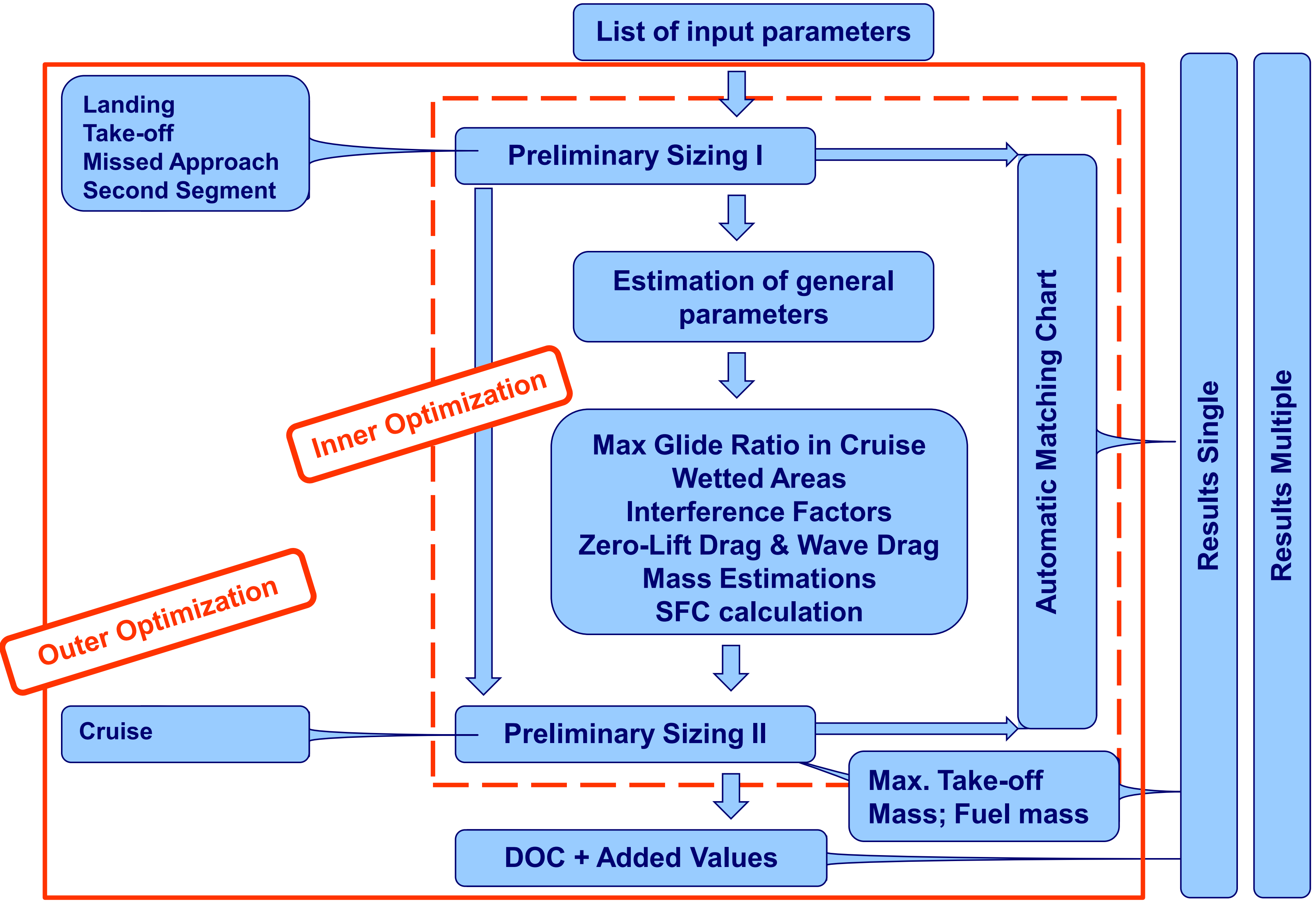
Key Design Variables – Aircraft design

Parameter		Type
Maximum lift coefficient, landing, for 0° sweep angle	$C_{LmaxL,unswept}$	design variable
Maximum lift coefficient, take-off, for 0° sweep angle	$C_{LmaxTO,unswept}$	design variable
Sweep angle	φ_{25}	design variable
Taper ratio	λ	design variable
Relative distance between engine and wing	h_P / D_N	design variable
By-Pass ratio	BPR	design variable
Maximum landing mass to maximum take-off mass ratio	m_{ML} / m_{MTO}	design variable
Number of engines	n_E	design variable
Aspect ratio	A	design variable, but limited to airport requirements
Landing field length	S_{LFL}	requirement
Take-off field length	S_{TOFL}	requirement
Cruise Mach number	M_{CR}	requirement

Key Design Variables – Cabin design

- Number of seats abreast
- Accessibility factor for cargo working conditions, k_{SH}
- Cargo compartment height, h_{cargo}
- Number of “excuse-me” seats
- Sidewall clearance at armrest
- Overhead bin-volume per passenger
- Aisle height and aisle width
- Armrest width and seat width
- Seat pitch

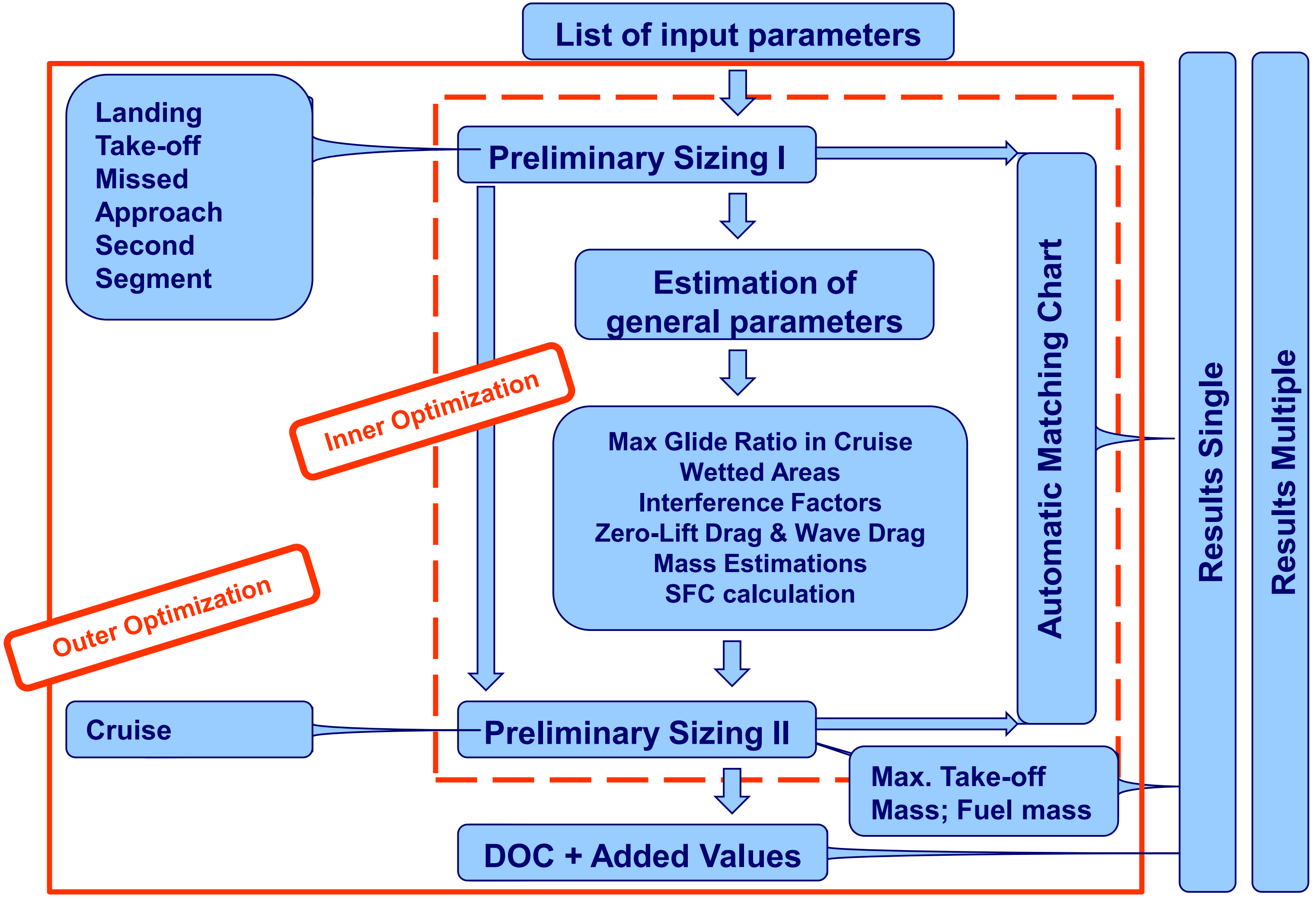
"Excuse-me" seats are those seats that require the permission of two passengers to get to the aisle. Window seats are not considered "excuse-me" seats


List of input parameters
Landing
Take-off
Missed Approach
Second Segment
Preliminary Sizing I
Estimation of general parameters
Max Glide Ratio in Cruise
Wetted Areas
Interference Factors
Zero-Lift Drag & Wave Drag
Mass Estimations
SFC calculation
Inner Optimization
Outer Optimization
Cruise
Preliminary Sizing II
Automatic Matching Chart
Results Single
Results Multiple
Max. Take-off Mass; Fuel mass
DOC + Added Values

Tool Description
OPerA – Optimization in Preliminary Aircraft Design

Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences

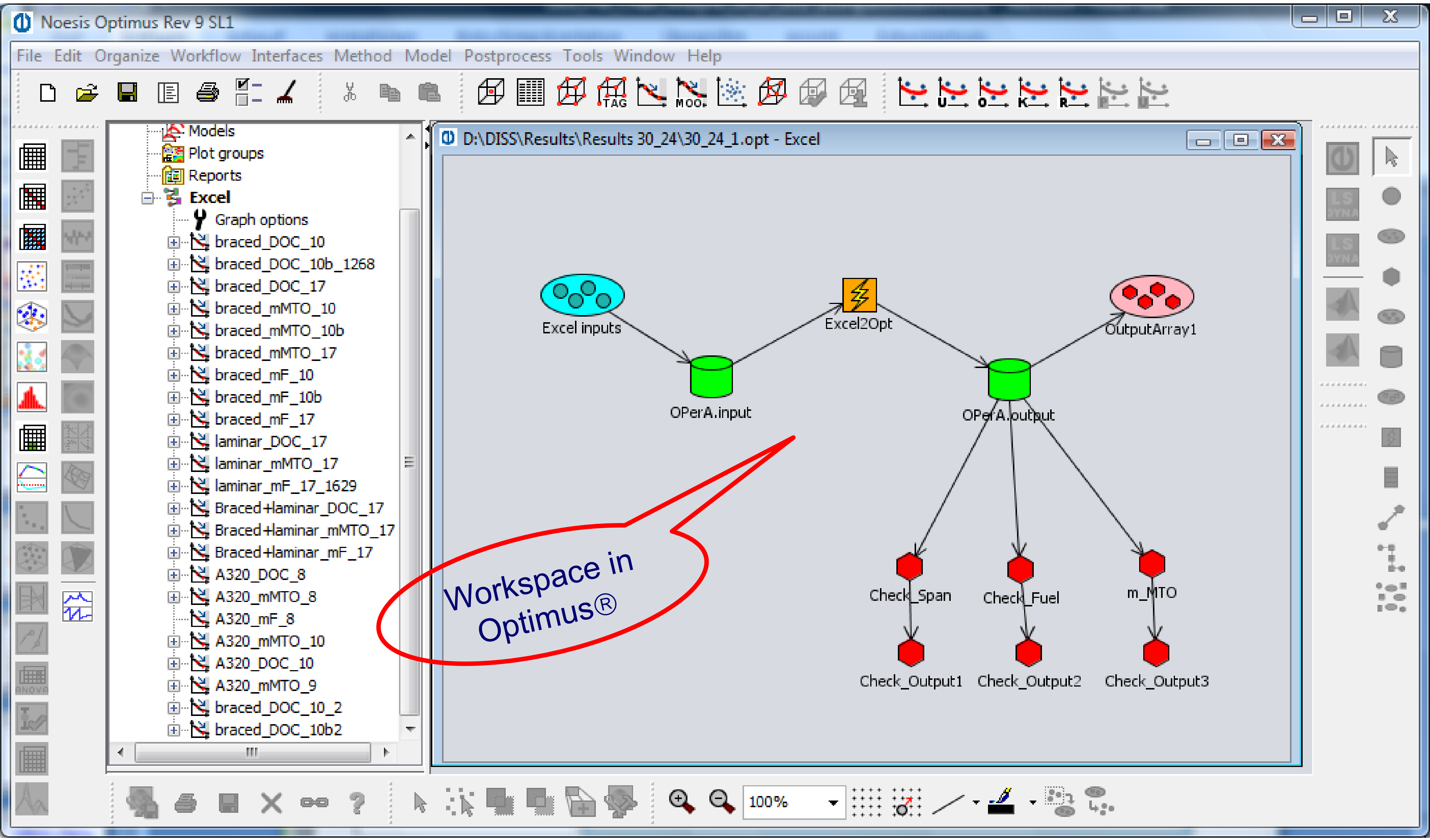
- About 230 input variables
- About 150 geometry parameters
- At least 15 iteration loops
- 20 optimization variables
- 15 calculation sheets



Optimization Methods

Gradient based versus non-gradient based optimization algorithms

Gradient-Based Methods	Non-Gradient-Based Methods
Require gradient information about the objective function Objective function must be continuous, derivable and uni-modal Weak performance for noisy functions Risk to get trapped in local minimum The gradient is calculated at considerable computational cost Multi-objective optimization is only possible through translation to single-objective optimization, through a weighted sum of the objectives	Are more effective, and work in noisy environments Allow direct implementation of constraints Suitable for global optimum (not guaranteed) Allow multiple objectives Require a large number of function evaluations, including for a reduced number of variables


Noesis Optimus Rev 9 SL1
File Edit Organize Workflow Interfaces Method Model Postprocess Tools Window Help
Models
Plot groups
Reports
Excel
Graph options
braced_DOC_10
braced_DOC_10b_1268
braced_DOC_17
braced_mMTO_10
braced_mMTO_10b
braced_mMTO_17
braced_mF_10
braced_mF_10b
braced_mF_17
laminar_DOC_17
laminar_mMTO_17
laminar_mF_17_1629
Braced+laminar_DOC_17
Braced+laminar_mMTO_17
Braced+laminar_mF_17
A320_DOC_8
A320_mMTO_8
A320_mF_8
A320_mMTO_10
A320_DOC_10
A320_mMTO_9
braced_DOC_10_2
braced_DOC_10b2
D:\DISS\Results\Results 30_24\30_24_1.opt - Excel
Excel inputs
OPerA.input
Excel2Opt
OPerA.output
OutputArray1
Check_Span
Check_Fuel
m_MTO
Check_Output1
Check_Output2
Check_Output3
Workspace in Optimus®
100%

Optimization Methods

Testing of methods in OPerA with commercial optimization software Optimus®

→ Decision to use Evolutionary Algorithms

→ Decision to use **Differential Evolution** Algorithm

Implementation of Differential Evolution Algorithm in OPerA

Premise: $\overrightarrow{X_k} = (x_1, x_2 \dots x_n)$

$\overrightarrow{A_k} \neq \overrightarrow{B_k} \neq \overrightarrow{C_k}$

Mutation: $\overrightarrow{\mathrm{Y_k}} = \overrightarrow{\mathrm{A_k}} + F \cdot \left(\overrightarrow{\mathrm{B_k}} - \overrightarrow{\mathrm{C_k}}\right)$

$y_i = a_i + F \cdot (b_i - c_i),\ i = \overline{1..n}$

Recombination: $z_i = \begin{cases} y_i & if \quad r_i \leq C \\ x_i & if \quad r_i > C \end{cases}$

Selection: $\overrightarrow{X_{k+1}} = \begin{cases} \overrightarrow{Z_k} & if \quad f(\overrightarrow{Z_k}) \leq f(\overrightarrow{X_k}) \\ \overrightarrow{X_k} & if \quad f(\overrightarrow{Z_k}) > f(\overrightarrow{X_k}) \end{cases}$

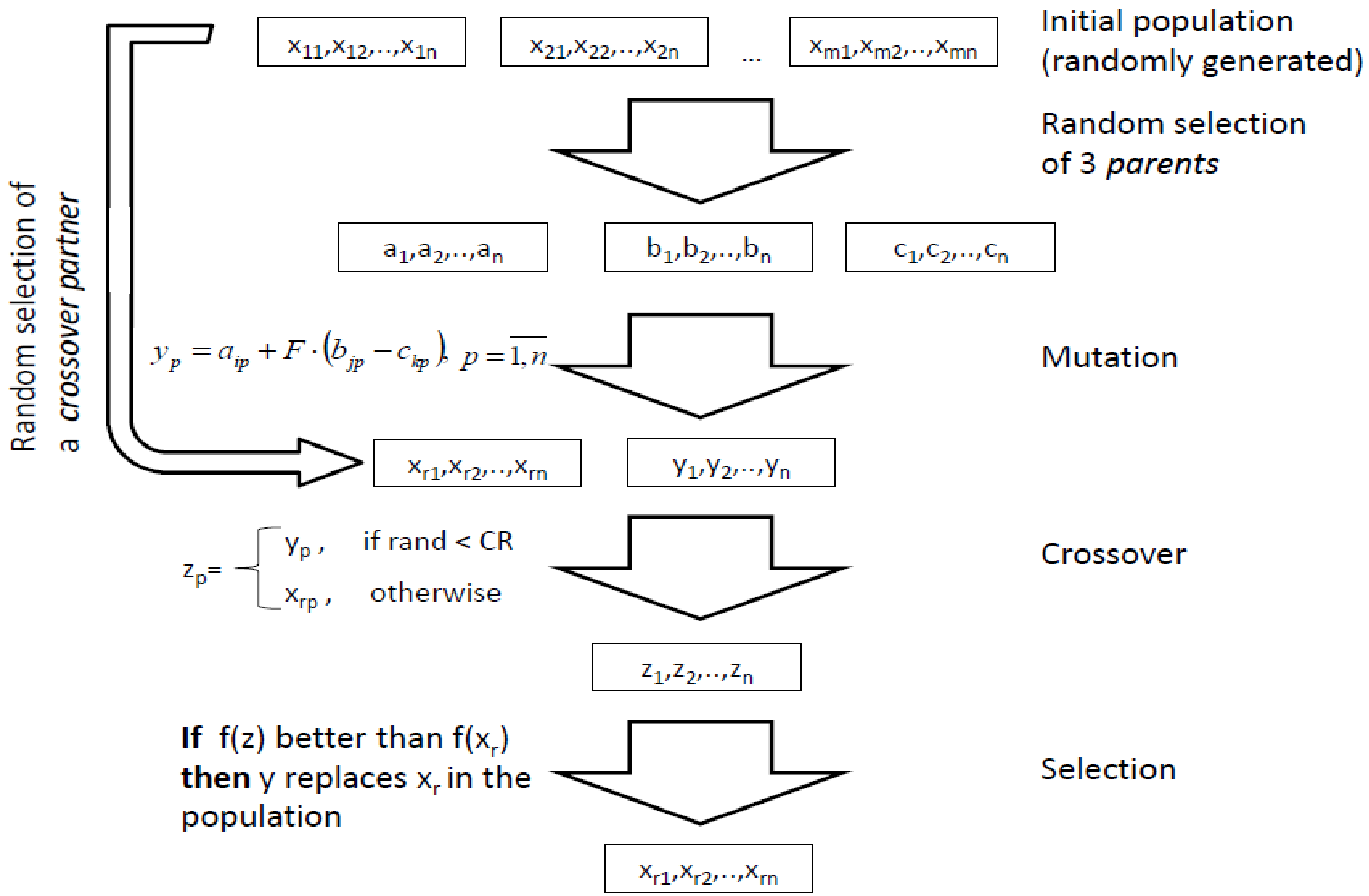
Control parameters:

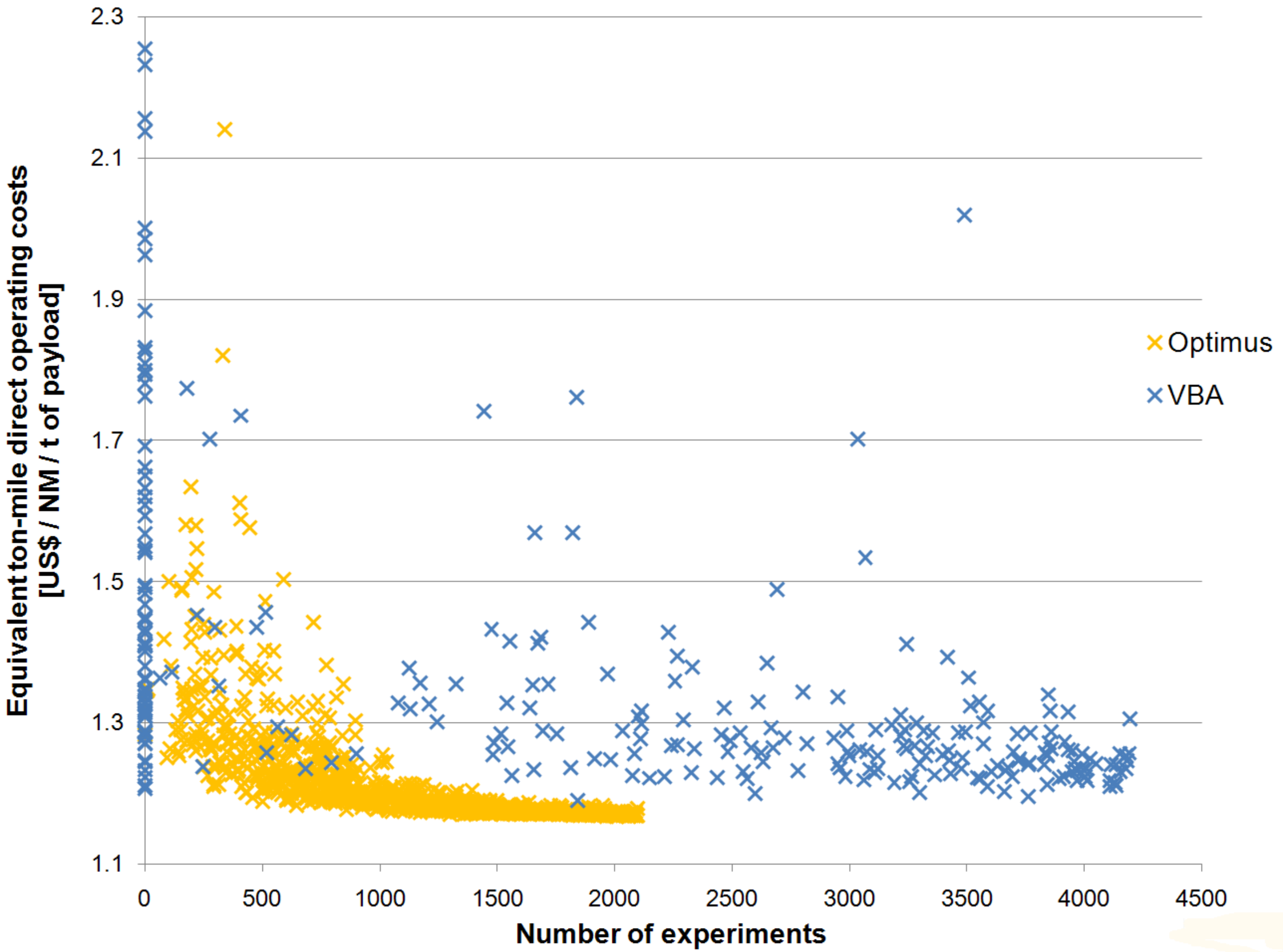
Population size

Weighting factor, F : [0,1]

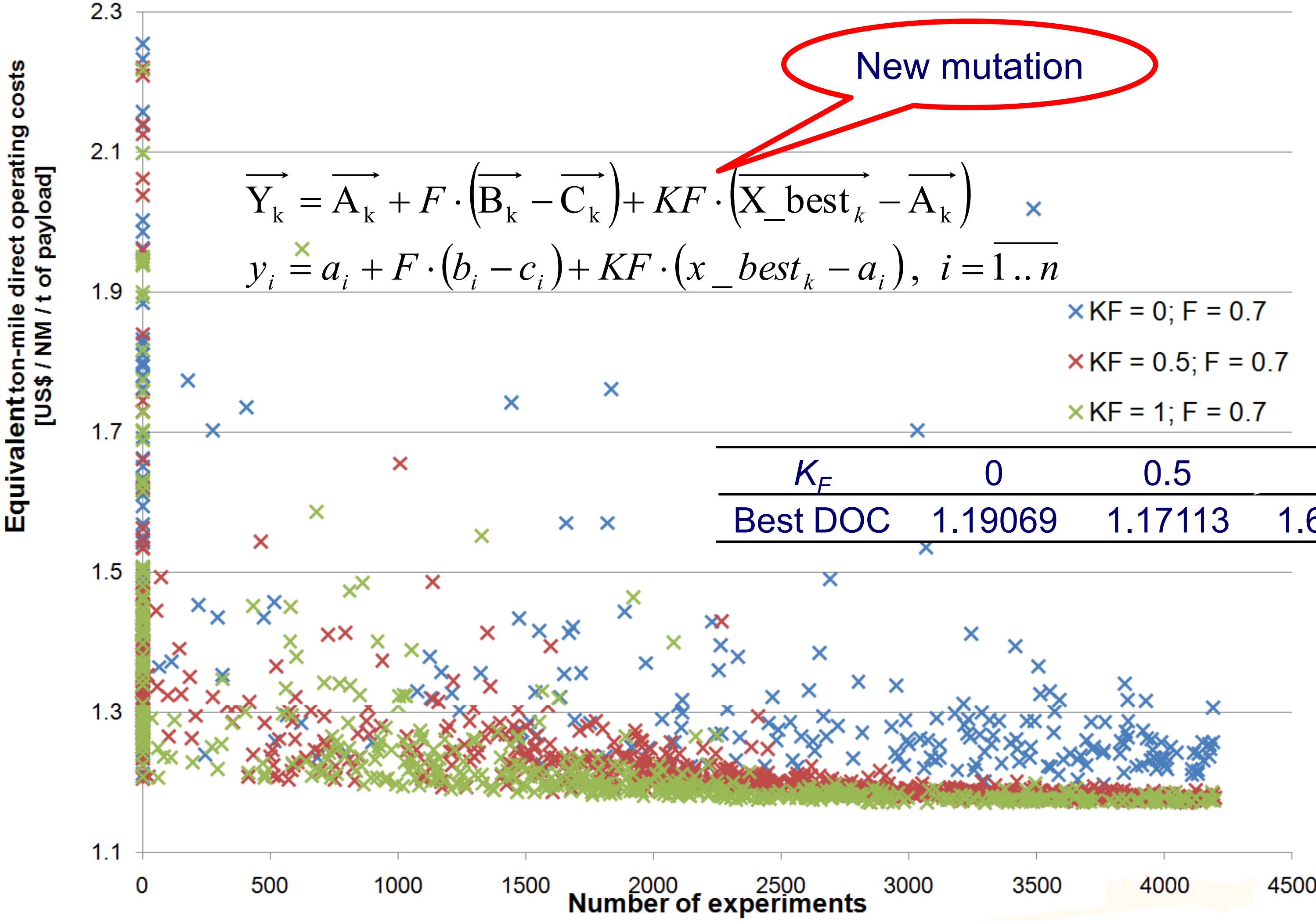
Cross-over factor, C : [0,1]

Implementation of Differential Evolution Algorithm in OPerA




Equivalent ton-mile direct operating costs
[US$ / NM / t of payload]
2.3
2.1
1.9
1.7
1.5
1.3
1.1
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Number of experiments
Optimus
VBA

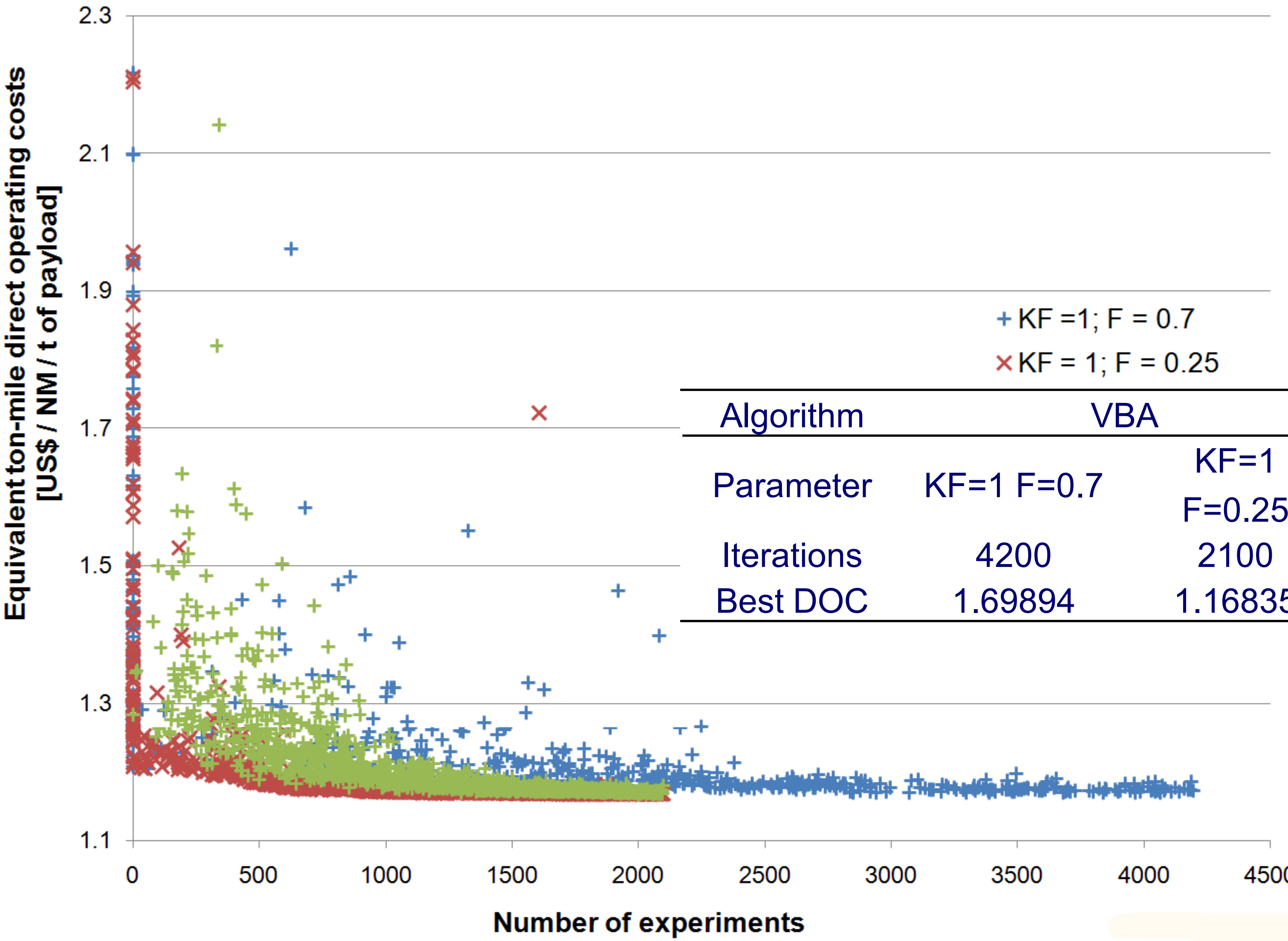
Convergence improvement: additional control factor K_F



$$\overrightarrow{Y_k} = \overrightarrow{A_k} + F \cdot \left(\overrightarrow{B_k} - \overrightarrow{C_k}\right) + KF \cdot \left(\overrightarrow{X\_best_k} - \overrightarrow{A_k}\right)$$

$$y_i = a_i + F \cdot (b_i - c_i) + KF \cdot (x\_best_k - a_i), \; i = \overline{1..n}$$

K_F	0	0.5	1
Best DOC	1.19069	1.17113	1.69894



Algorithm	VBA		Optimus®
Parameter	KF=1 F=0.7	KF=1 F=0.25	KF=?? F=0.7
Iterations	4200	2100	2100
Best DOC	1.69894	1.16835	1.16843

Selected Numerical Results

Constraints

Besides implicit geometrical constraints (built in OPerA, like e.g. the constraints for landing gear length) the following constraints are implemented into the optimization algorithm / Optimus®:

1. Span limitation, according to selected airport category
2. Maximum landing mass to maximum take-off mass so to ensure capacity to carry required fuel reserves $m_{ML} > m_{MZF} + m_{F,res}$
3. Fuel tank volume (depending on wing geometry) so to ensure accomodation of required fuel

Selected Numerical Results

Objective functions

Classical objectives:

Maximum take-off mass, m_{MTO} [kg]

Fuel mass, m_F [kg]

Direct Operating costs: equivalent ton-miles costs, $C_{equiv,t,m}$ [US$ / NM / t of payload]

DOC + Added Values

Selected Numerical Results

Objective function: DOC + Added Values

<table>
<tr><td colspan="4">Economics (represented by equivalent-ton-mile costs)</td></tr>
<tr><td rowspan="15">Added Values</td><td rowspan="3">Performance</td><td rowspan="2">Airport Performance</td><td>Take-off field length</td></tr>
<tr><td>Relative landing mass ratio</td></tr>
<tr><td>Cruise Performance</td><td>Cruise speed</td></tr>
<tr><td rowspan="9">Passenger Comfort</td><td rowspan="7">Concerning all passengers</td><td>Seat Pitch</td></tr>
<tr><td>Seat width</td></tr>
<tr><td>Armrest width</td></tr>
<tr><td>Aisle width</td></tr>
<tr><td>Aisle height</td></tr>
<tr><td>Overhead bin volume per pax</td></tr>
<tr><td>Aircraft gust sensitivity</td></tr>
<tr><td rowspan="2">Concerning part of the passengers</td><td>Sidewall clearance</td></tr>
<tr><td>Number of “excuse-me seats”</td></tr>
<tr><td rowspan="3">Cargo handling</td><td>Concerning Cargo</td><td>Containerized cargo (yes / no)</td></tr>
<tr><td rowspan="2">Concerning working conditions</td><td>Accessibility factor</td></tr>
<tr><td>Cargo compartment height</td></tr>
</table>

Selected Numerical Results

Objective function: DOC + Added Values

Weighting evaluation through questionnaires:

- Airbus Future Projects (4)
- Airbus Senior Expert (1)
- Aircraft Design Professor (1)
- Systems Engineer (1)
- Lufthansa Captain (1)

- PhD students (12)
- Students (5)

2 pages of information: weightings (1..100 %) in a hierarchical table and points (1..10) in a square matrix

Objective function: DOC + Added Values

A \ B		Landing field length	Take-off field length	Relative landing weight (m_{ML}/m_{MTO})	Cruise speed	Seat pitch	Seat width	Armrest width	Aisle width	Aisle height	Overhead bin volume per pax	Aircraft gust sensibility	Sidewall clearance	Number of "excuse-me" seats	Containerized cargo (yes/no)	Accessibility factor	Cargo compartment height
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Landing field length	1		**5**	**7**	**5**	**3**	**4**	**7**	**8**	**8**	**5**	**7**	**10**	**6**	**5**	**8**	**8**
Take-off field length	2	5		**7**	**5**	**3**	**4**	**7**	**8**	**8**	**5**	**7**	**10**	**6**	**5**	**8**	**8**
Relative landing weight (m_{ML}/m_{MTO})	3	3	3		**3**	**1**	**2**	**5**	**6**	**6**	**3**	**5**	**8**	**4**	**3**	**6**	**6**
Cruise speed	4	5	5	7		**5**	**6**	**9**	**10**	**10**	**10**	**9**	**10**	**8**	**7**	**10**	**10**
Seat pitch	5	7	7	9	5		**6**	**9**	**10**	**9**	**7**	**9**	**10**	**8**	**7**	**10**	**10**
Seat width	6	6	6	8	4	4		**6**	**7**	**7**	**5**	**6**	**9**	**6**	**4**	**7**	**7**
Armrest width	7	3	3	5	1	1	4		**6**	**6**	**3**	**5**	**8**	**4**	**3**	**6**	**6**
Aisle width	8	2	2	4	0	0	3	4		**5**	**2**	**4**	**7**	**3**	**2**	**5**	**5**
Aisle height	9	2	2	4	0	1	3	4	5		**2**	**4**	**7**	**3**	**2**	**5**	**5**
Overhead bin volume per pax	10	5	5	7	0	3	5	7	8	8		**6**	**9**	**6**	**4**	**7**	**7**
Aircraft gust sensibility	11	3	3	5	1	1	4	5	6	6	4		**8**	**4**	**3**	**6**	**6**
Sidewall clearance	12	0	0	2	0	0	1	2	3	3	1	2		**2**	**1**	**4**	**4**
Number of "excuse-me" seats	13	4	4	6	2	2	4	6	7	7	4	6	8		**4**	**7**	**7**
Containerized cargo (yes/no)	14	5	5	7	3	3	6	7	8	8	6	7	9	6		**7**	**7**
Accessibility factor	15	2	2	4	0	0	3	4	5	5	3	4	6	3	3		**5**
Cargo compartment height	16	2	2	4	0	0	3	4	5	5	3	4	6	3	3	5	

Selected Numerical Results

Objective function: DOC + Added Values

Level 1			Level 2			Level 3			Level 4		
Economics	75	%	Equiv. ton-mile costs	100	%			%			%
Added Values	25	%	Performance	35	%	Airport performance	50	%	Landing field length	40.0	%
									Take-off field length	40.0	%
									Relative landing weight (m_{ML}/m_{MTO})	20.0	%
						Cruise performance	50	%	Cruise speed	100.0	%
			Passenger Comfort	55	%	Concerning all passengers	80	%	Seat pitch	30.0	%
									Seat width	20.0	%
									Armrest width	10.0	%
									Aisle width	5.0	%
									Aisle height	5.0	%
									Overhead bin volume per pax	20.0	%
									Aircraft gust sensibility	10.0	%
						Concerning part of the passengers	20	%	Sidewall clearance	10.0	%
									Number of "excuse-me" seats	90.0	%
			Cargo Handling	10	%	Concerning cargo	80	%	Containerized cargo (yes/no)	100.0	%
						Concerning cargo working conditions	20	%	Accessibility factor	50.0	%
									Cargo compartment height	50.0	%

Selected Numerical Results

Objective function: DOC + Added Values

Matrix consistency index:

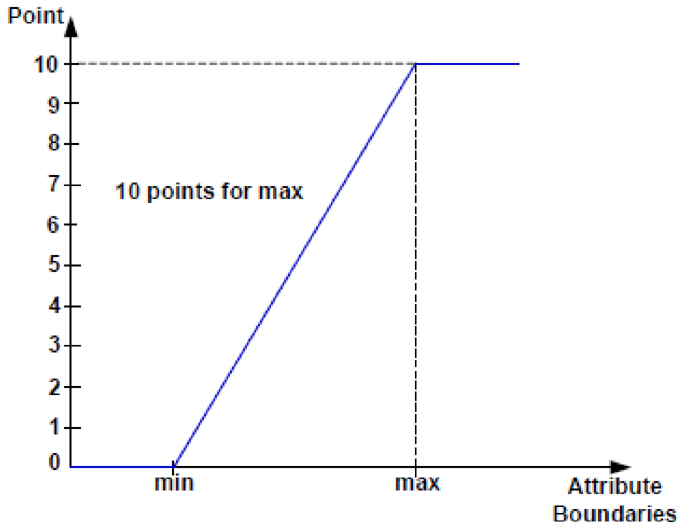
$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad \text{with:} \qquad Aw = \lambda_{max} w$$

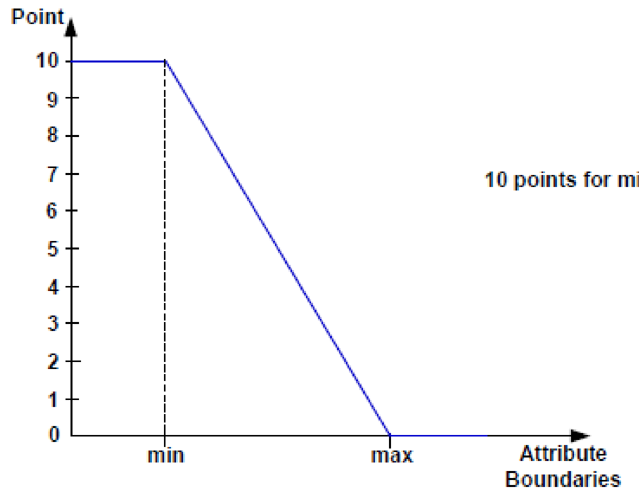
Correlation calculation:

$$R(x,y) = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sqrt{\sum (x - \bar{x})^2 \sum (y - \bar{y})^2}}$$

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \; ; \quad \bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$$

Coefficient of determination: $R^2 = r_{xy}^2$





Selected Numerical Results

Objective function: DOC + Added Values

		Absolute weights	Attribute low limit	Attribute high limit	Values of optimization	Point for optimization	Score for optimization	Comments
Economics (DOC)	100%	75.00%	0.72	0.86	0.785	5.4	4.044	10 points for min
Landing field length		0.00%	1370	2000	1447.8	8.8	0.000	10 points for min
Take-off field length	80%	3.50%	1670	2700	1767.83	9.1	0.317	10 points for min
Relative landing weight (m_{ML}/m_{MTO})	20%	0.88%	0.8	1	0.878	3.9	0.034	10 points for max
Cruise speed[1]	100%	4.38%	224.25	237.3279	224.25	0.0	0.000	10 points for max
Seat pitch	30.0%	3.30%	28	32	29	2.5	0.082	10 points for max
Seat width[2]	20.0%	2.20%	0.44	0.53	0.508	7.4	0.162	10 points for max
Armrest width	10.0%	1.10%	0.04	0.06	0.051	5.4	0.059	10 points for max
Aisle width	5.0%	0.55%	0.2	0.61	0.508	7.5	0.041	10 points for max
Aisle height[3]	5.0%	0.55%	1.75	2.1	2.264	10.0	0.055	10 points for max
Overhead bin volume per pax	20.0%	2.20%	0.03	0.1	0.044	2.1	0.045	10 points for max
Aircraft gust sensibility[4]	10.0%	1.10%	0.1	1	0.34	7.4	0.081	10 points for min
Sidewall clearence[5]	10%	0.28%	0.007	0.02	0.015	6.2	0.017	10 points for max
Number of "excuse-me" seats	90%	2.48%	0	3	0	10.0	0.248	10 points for min
Containerized cargo (yes/no)	100%	2.00%			Yes	10.0	0.200	10 points for yes
Accessibility factor[6]	50%	0.25%	1	1.1	1.09	1.2	0.003	10 points for min
Cargo compartment height	50%	0.25%	0.7	1.8	1.22	4.7	0.012	10 points for max
		100%						
							5.40075693	=maximum

Selected Numerical Results

Test Cases

2 redesign cases: A320-200 reference and A320 NEO

4 optimization cases:

A. Standard configuration
B. Configuration with braced wings
C. Configuration with natural laminar flow on wings
D. Configuration with braced wings and natural laminar flow on wings

Selected Numerical Results

List of parameters for optimization

Parameter		Value for A320-200 aircraft	
Landing field length	s_{LFL}	1447.80	[m]
Take-off field length	s_{TOFL}	1767.83	[m]
Max. lift coefficient, landing for unswept wing	$C_{L,max,L,unswept}$	3.39	
Max. lift coefficient, take-off for unswept wing	$C_{L,max,TO,unswept}$	2.95	
Mass ratio, max landing to max take-off	m_{ML} / m_{MTO}	0.88	
Aspect ratio	A	9.50	
Number of engines	n_E	2.00	
Number of passengers	n_{PAX}	180	
Number of seats abreast	n_{SA}	6	
Wing sweep at 25% chord	φ_{25}	25	[°]
Taper ratio	λ	0.24	
Position of the vertical tail in case of cruciform configuration	z_H/b_V	0.56	
Minimum distance from engine to wing over nacelle diameter	$z_{P,min}/D_N$	0.15	
By-Pass ratio	BPR	6	
Mach number, cruise	M_{CR}	0.76	
Seat pitch	SP	29	[“]
Seat width	w_{seat}	20	[“]
Aisle width	w_{aisle}	20	[“]
Armrest width	$w_{armrest}$	2	[“]
Sidewall clearance (at armrest)	$s_{clearance}$	0.015	[m]

Selected Numerical Results

Optimization strategy

Single design parameter variation

↓

Multiple design parameters variation

↓

Single requirement variation

↓

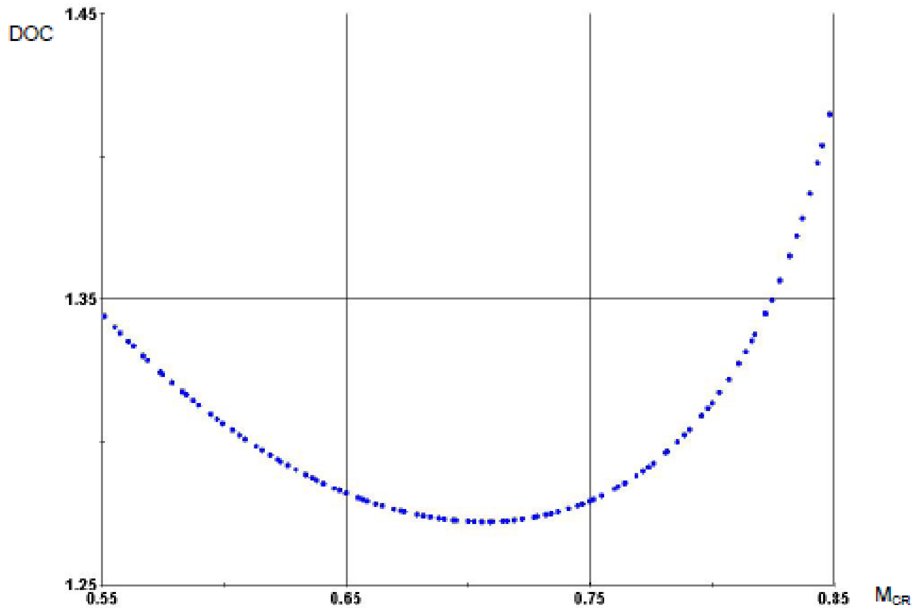
Multiple requirement variation

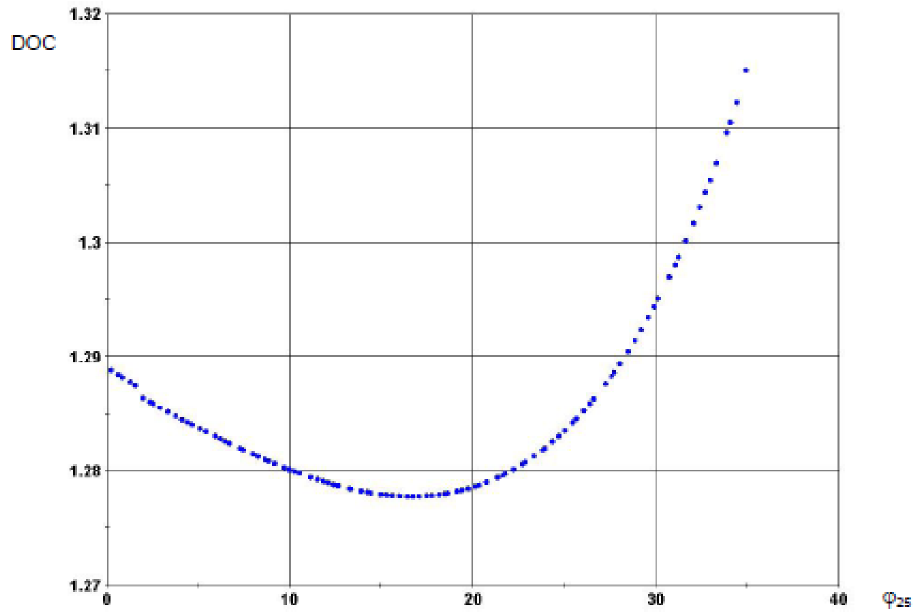
↓

Multiple design parameters and multiple requirements variation

Selected Numerical Results

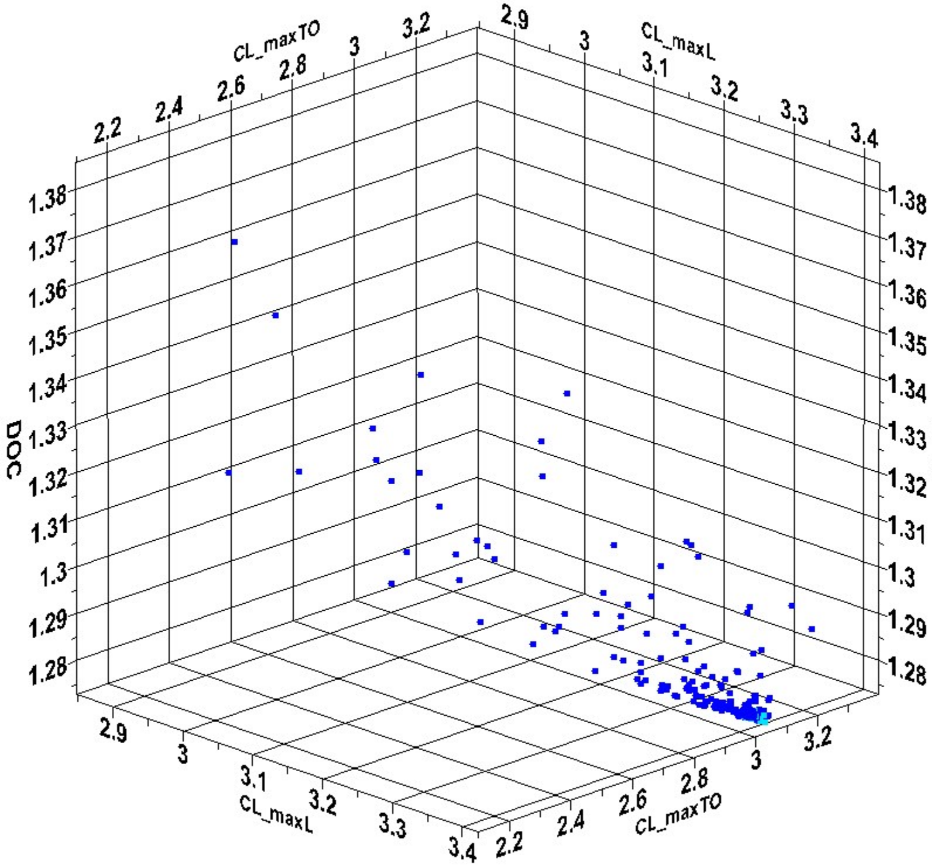
Examples of single parameter (objective DOC)





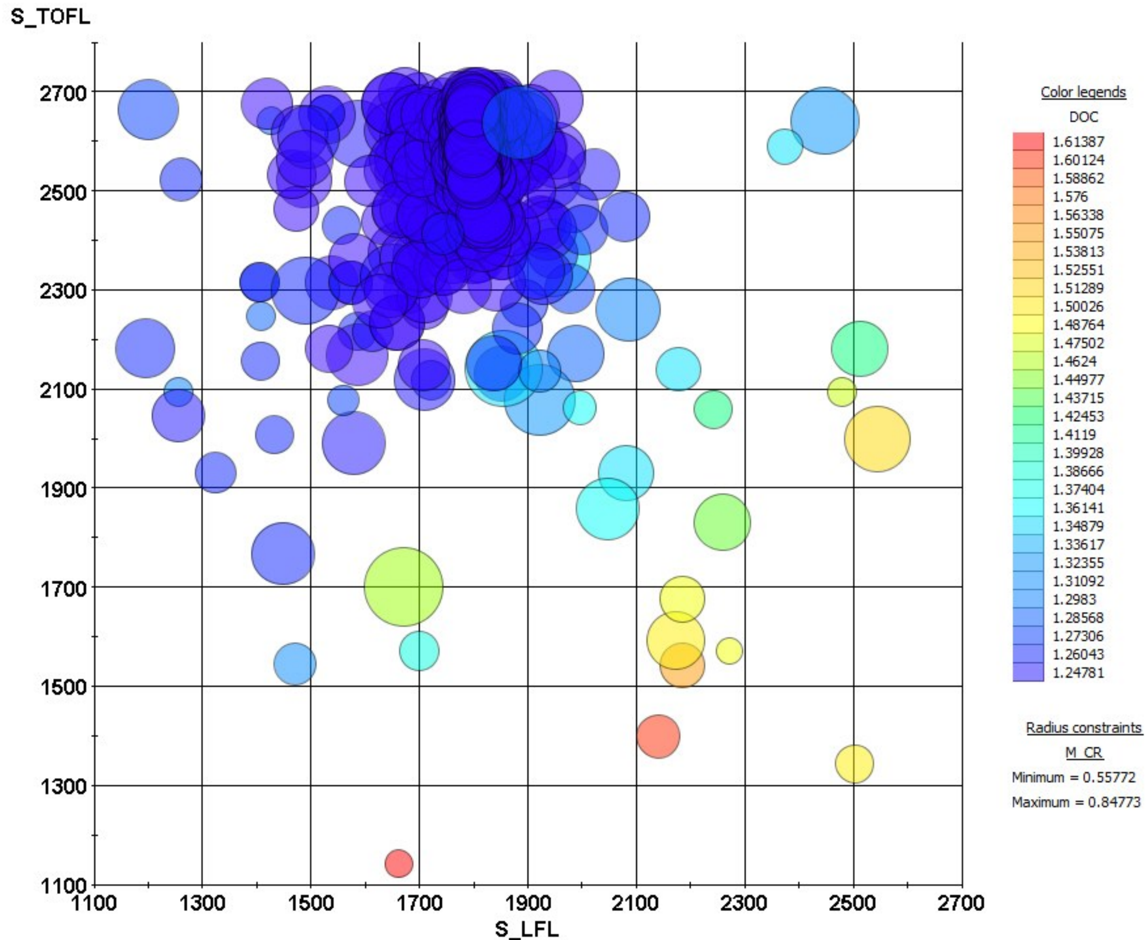
Selected Numerical Results

Examples of two parameter variation (objective DOC)



Selected Numerical Results

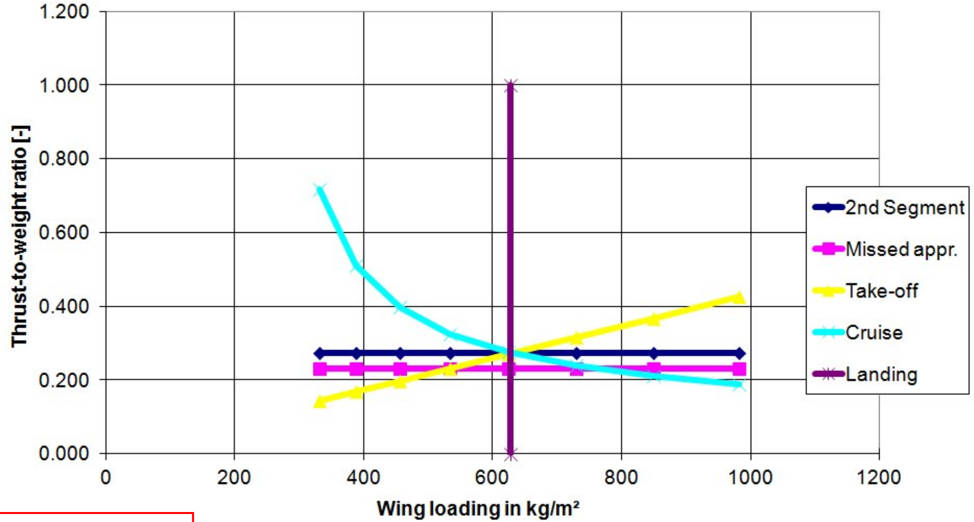
Examples of three parameter variation (objective DOC)



Selected Numerical Results

Case A : A320-200 standard (objective DOC)

Parameter	Optimized value
m_{ML} / m_{MTO}	0.89
A	12.72
$C_{L,max,L,unswept}$	3.38
$C_{L,max,TO,unswept}$	3.29
Phi_{25}	15.27°
λ	0.15
BPR	8.77
$h_{P,min}/D_N$	0.12



3.38 % reduction in maximum take-off mass

15.43 % reduction in fuel mass

3.42 % reduction in DOC

an increase in the DOC + Added Values score from 5 to 6.8

Selected Numerical Results

Case A : A320-200 standard (objective DOC)

- The improvement in DOC when allowing a 52 m span limitation is, 9 % when varying all aircraft parameters , and 11 % when optimizing aircraft parameters together with cabin parameters.

- As a secondary effect of DOC optimization, fuel is improved by 30 % in the first case and 34 % in the second case

Selected Numerical Results

Case A : A320-200 standard (objective DOC)

- To benefit from span increase and yet remain in the same airport category, some solutions are possible:

    - Folding wings up
    - Rotating main landing gear
    - Discussing (in particular) with airports

Selected Numerical Results

Case B : A320-200 with braced wings (objective DOC)

- The assumptions that braced wings consistently reduce mass and allow aerodynamical improvements, are proven.

20.5 % reduction in maximum take-off mass

Aspect ratio of 22

35.5 % reduction in fuel mass

Glide ratio of 23.6

14.5 % reduction in DOC

Selected Numerical Results

Case C : A320-200 with natural laminar flow on wings (objective DOC)

- Compared to case A, NLF brings an additional 1 % improvement in DOC, while braced wing configuration brought a 3.2 % improvement.

Case D : A320-200 braced wings + natural laminar flow (objective DOC)

- For case D expected is an overall additional improvement of more than 4 % in DOC → expectation fulfilled

21.5 % reduction in maximum take-off mass

39.7 % reduction in fuel mass

15.4 % reduction in DOC

Selected Numerical Results

Cases A, B, C, D for objective m_{MTO}

- Design for objective m_{MTO} is similar to DOC, but it prefers smaller speeds
- 2 % of mass reduction compared to DOC is achieved (from 16 % to 18 %).

Case A: A320-200 standard (objective m_F)

- Design for minimum fuel goes more towards extremes: it prefers small speeds, high aspect and by-pas ratios
- Small speed considerably affects the DOC: they increase by 10 % when a limit is set of M_{CR} = 0.1 (with optimum of 0.47) they drop by 2.85 %, when the limit is M_{CR} = 0.55 (optimum is 0.55)
- Total fuel reduction is of 44.1 %

Case D: A320-200 braced wings + natural laminar flow (objective m_F)

- Adding the two innovations produces !! 47.9 % !! For 9.4 % DOC reduction and 15.2 % m_{MTO} reduction.

Selected Numerical Results

Case A : A320-200 standard (objective DOC + AV)

- The weightings of this objective function increase the importance of higher speed, smaller landing and take-off field length, higher comfort standards and better ground handling.

11.2 % reduction in maximum take-off mass

27.5 % reduction in fuel mass

7.3 % reduction in DOC

Case B : A320-200 with braced wings (objective DOC+AV)

- aspect ratio increases and sweep reduces substantially
- better aerodynamic efficiency allows landing and take-off field lengths to be reduced
- …thus reaching a score of 9.1 out of 10

Selected Numerical Results

Case D: A320-200 braced wings + natural laminar flow (objective DOC + AV)

11.0 % reduction in maximum take-off mass

7.4 % reduction in DOC

27.9 % reduction in fuel mass

9.3 score of DOC + AV

2. Process Chain Optimization

Optimization of the Process Chain for Cabin Conversions

1. Identification of the chain of processes for cabin conversions

2. Proposal of 3 methods, based on a square matrix containing the processes and their relations, called DSM (Design Structure Matrix)
   a. Partitioning algorithm – delivering optimized sequence
   b. Eigenstructure analysis – identifying the most important processes
   c. Cross Impact analysis – identifying zones of processes: reactive, dynamic, impulsive, low impact, neutral

Conclusions and Summary of Contributions

A. Setting up a new methodology for preliminary aircraft design and optimization, that finds the equilibrium between penalties and benefits of variables

B. Creating a „white box“ preliminary design and optimization tool, OPerA – Optimization in Preliminary Aircraft Design, that incorporates the matching chart as an inner optimization

C. Producing traceable results:
   - optimal aircraft design parameters
   - technology evaluation

Conclusions and Summary of Contributions

A. Setting up a new methodology for preliminary aircraft design and optimization

1. proposal of new mission fuel fractions
2. method for estimating Oswald factor
3. method for estimating proportion of laminar flow as a function of the transition Reynolds number and leading edge sweep
4. unified method for determining winglet efficiency + extensive literature study
5. incorporation of braced wing configuration + extensive literature study
6. incorporation of a constraint-responsive geometry for landing gear, able to account for the effects of new generation engines (with higher BPR)
7. incorporation of landing gear mass estimation as a function of landing gear length
8. method adjustment for wing thickness ratio
9. estimation of aircraft sensitivity to gusts
10. method for estimating generic cabin length and cabin length factor

Conclusions and Summary of Contributions

A. Setting up a new methodology for preliminary aircraft design and optimization

11. method for estimating the fuselage nose length
12. method for estimating cargo compartment height
13. method for estimating overhead stowage volume (per pax)
14. method for estimating sill height
15. many updated statistical parameters
16. definition of added values for aircraft design
17. incorporation of added values in a new, composed objective function; study on added value boundaries
18. incorporation of decision making techniques and consistency check for establishing weightings of added values
19. utilization of matrix based methodology for process chain optimization

Conclusions and Summary of Contributions

B. Creating a „white box“ preliminary design and optimization tool, OPerA

1. covering aircraft preliminary design optimization, from preliminary sizing to cabin design
2. including independent optimization model, able to compete with commercial optimization tool
3. building on two optimization levels (with automated inner optimization)
4. covering conventional configurations but able to incorporate new technologies (high BPR engines, NLF, braced wings, winglets), thus able to look into the future
5. emphasizing overall intergration (opposite to MDO tools), with adaptable geometries
6. containing cabin and cargo models
7. including various methods for L / D estimation
8. combining the effect of cabin parameters on preliminary aircraft design
9. allowing model traceability and results traceability (facilitating knowledge transfer)
10. allowing efficient research, but also learning (pedagogic side)
11. stressing simplicity and openness

Conclusions and Summary of Contributions

C. Producing traceable results

1. there is an optimum BPR for a given Mach number
2. lower speeds (thus lower altitude) allow an increase in BPR and a reduction in drag, and thus dramatic fuel reduction (43 %)
3. increased landing and take-off distance allow a smaller engine and thus a more efficient design for the same Mach number
4. aircraft can be optimized with higher span, especially with a braced wing
5. winglets are beneficial if span is limited
6. span increase is more efficient than winglets
7. braced wings allow a low wing sweep and enable NLF
8. braced wings alone are more efficient than NLF (on the wing) alone
9. if environment protection is the goal, the objective function should not be DOC
10. when optimizing for DOC, traditional cruise Mach number should be maintained
11. with increasing fuel prices, DOC optimized aircraft will resemble m_F optimized aircraft

Outlook

- The tool opens a lot of roads for reserach:
    - Papers
    - Dissertations
    - Research projects on aircraft designs:
        - Increased span limitations
        - Braced wing
        - New large turboprop aircraft
        - Box Wing Aircraft
        - …

List of publications

1. SCHOLZ, Dieter; NIŢĂ, Mihaela: Preliminary Sizing of Large Propeller Driven Aeroplanes. In: *Czech Aerospace Proceedings*, (2009), No. 2, S. 41-47. - ISSN: 1211—877X

2. NIŢĂ, Mihaela; SCHOLZ, Dieter: The Process Chain to a Certified Cabin Design and Conversion. In: DGLR: *Deutscher Luft- und Raumfahrtkongress 2009 : Tagungsband - Ausgewählte Manuskripte* (DLRK, Aachen, 01.-04. September 2009). - ISBN: 978-3-932182-63-4. DocumentID: 121161. Download: http://CARISMA.ProfScholz.de

3. NIŢĂ, Mihaela; SCHOLZ, Dieter: Business Opportunities in Aircraft Cabin Conversion and Refurbishing. In: *Journal of Aerospace Operations*. Amsterdam : IOS Press (2011), Vol. 1, No. 1-2, pp. 129-153. - ISSN 2211-002X

4. NIŢĂ, Mihaela; SCHOLZ, Dieter: From Preliminary Aircraft Cabin Design to Cabin Optimization. In: *DGLR: Deutscher Luft- und Raumfahrtkongress 2010 : Tagungsband - Ausgewählte Manuskripte* (DLRK, Hamburg, 30.August-02. September 2010). - ISBN: 978-3-932073-87-9ICAS 2010

5. NIŢĂ, Mihaela; SCHOLZ, Dieter: Process Chain Analysis and Tools for Cabin Design and Redesign Activities. In: *CD Proceedings : ICAS 2010 - 27th Congress of the International Council of the Aeronautical Sciences* (ICAS, Nizza, 19.-24. September 2010). Edinburgh, UK : Optimage Ltd, 2010. - ISBN 978-0-9565333-0-2. Paper: ICAS2010-7.3.4 (363.pdf)

6. NIŢĂ, Mihaela; SCHOLZ, Dieter: Parameter Optimization for an Interactive Aircraft Design, EWADE 2011 (10th European Workshop on Aircraft Design Education, University of Naples "Federico II", Italy, 24. - 27. May 2011). - Download: http://OPerA.ProfScholz.de

7. NIŢĂ, Mihaela; SCHOLZ, Dieter: Parameter Optimization for an Interactive Aircraft Design (Aerodays 2011, Madrid, 30. March - 01. April 2011). - Poster for the Student Participation Program. Download: http://OPerA.ProfScholz.de

Papers to be published:

7. NIŢĂ, Mihaela; SCHOLZ, Dieter: Estimating the Oswald Factor from Basic Aircraft Geometrical Parameters. In: *DGLR: Deutscher Luft- und Raumfahrtkongress 2012,* 10-12 September 2012, Berlin (astract was sent)

8. NIŢĂ, Mihaela; SCHOLZ, Dieter: From Preliminary Aircraft Cabin Design to Cabin Optimization. In: Buletin Stiintific, UPB (paper sent, confirmation for publication received)

I dedicate this thesis to all those who encouraged me with their love and support.

Dedic această teză tuturor celor ce m-au încurajat prin susţinerea lor şi dragostea cu care m-au înconjurat

Contributions to Aircraft Preliminary Design and Optimization

Thank you!

Contact:

Mihaela.Nita@HAW-Hamburg.de

Hochschule für Angewandte Wissenschaften Hamburg
Hamburg University of Applied Sciences