Optimisation in Aeronautics

W. Haase[1], J. Grashof[2], G. Wedekind[3]

[1,2] Flight Physics Department
[3] Preliminary Design Department
EADS Deutschland GmbH Military Aircraft
D-81663 Munich, Germany

Part of this work was sponsored by the EU via the AEROSHAPE project

SUMMARY

- Aircraft design cycle
- Inverse two-point airfoil optimisation
- Drag reduction of RAE2822, a three-point optimisation challenge
- Supersonic commercial transport optimisation
- High Altitude Long Endurance (Hale) – Loiter time optimisation
- Why ‚Robust Design‘ ?
- Conclusion

Optimisation in Aeronautics

Design network

2-point airfoil

Drag minimisation on RAE2822

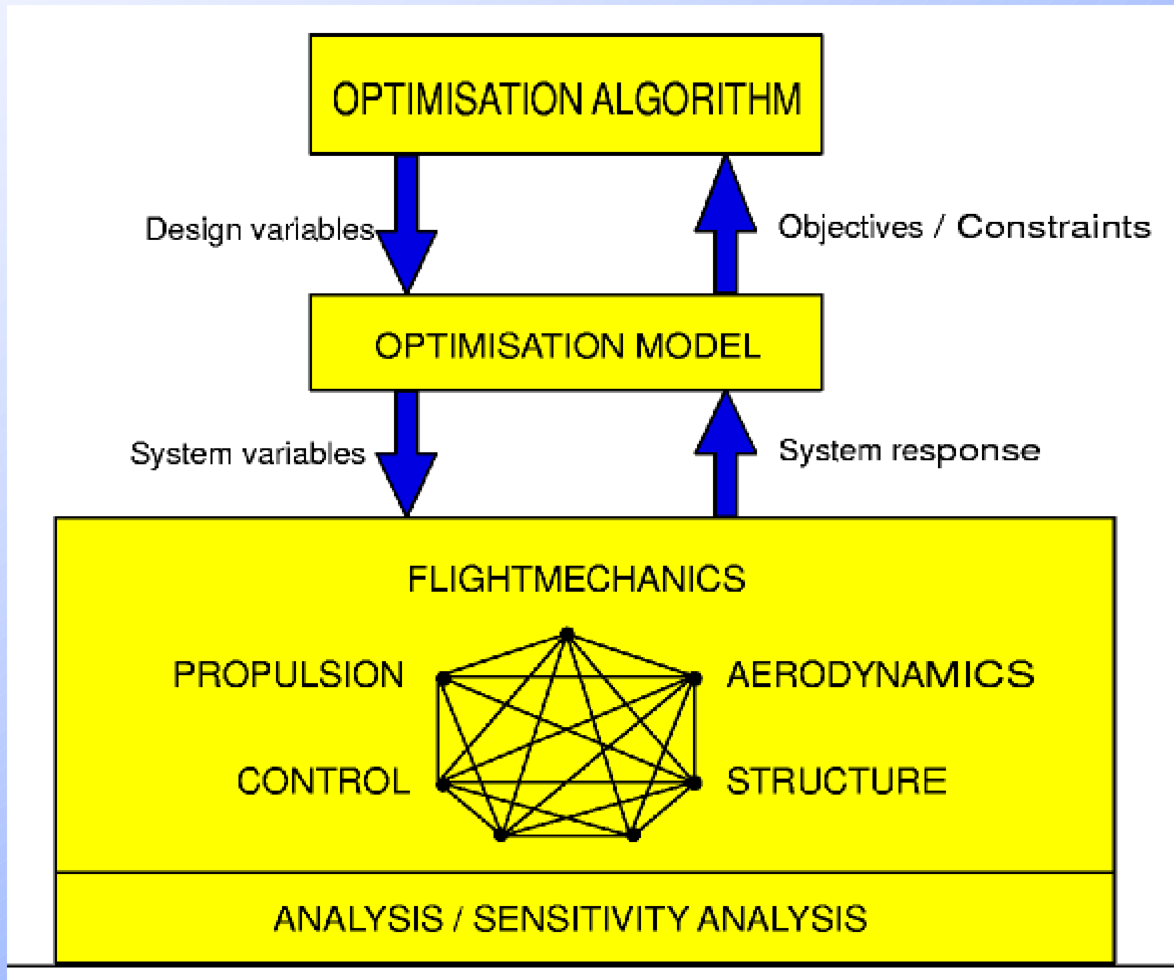
SCT drag minimisation

Hale – Loiter time

Robust Design

Conclusions

Network of influences in aircraft design optimisation



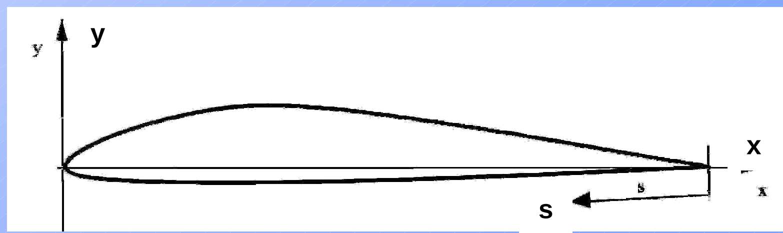
2-point (inverse?) airfoil design - Test Case Description

- Design network
- **2-point airfoil**
- Drag minimisation on RAE2822
- SCT drag minimisation
- Hale – Loiter time
- Robust Design
- Conclusions

- Minimisation of an objective function which is the difference between computed/optimised pressure distribution at **two different design points with two pre-defined target pressures** (originally proposed by T. Labruyere, NLR)

- The objective function reads:

$$F(\alpha_1, \alpha_2, x(s), y(s)) = \sum_{n=1}^{2} \left[W_n \int_0^1 \left(C_p^n(s) - C_{p,target}^n(s) \right)^2 ds \right]$$



Two-point airfoil design - Test Case Description

Two different design conditions (i=1,2):

i=1: Typical high-lift airfoil at subsonic conditions

i=2: Typical high-speed airfoil at transonic conditions

Case	i=1	i=2
Ma	0.20	0.77
Re	5×10^6	10^7
Incidence	10.8^o	1.0^o
X_{trans}/c	0.03	0.03

Inverse/two-point airfoil design - Numerical approach

Design network

2-point airfoil

Drag minimisation on RAE2822

SCT drag minimisation

Hale – Loiter time

Robust Design

Conclusions

Approach

- 2D (full) Navier-Stokes method
- Mesh resolution has been set to the lowest possible level (with respect to predictive accuracy) of 128x32 mesh points
- Computation time for one individual: < 60 sec. on 850MHz PC
- Parameterisation via Bezier Splines

First test on transonic case only

Optimisation in Aeronautics

Design network

2-point airfoil

Drag minimisation on RAE2822

SCT drag minimisation

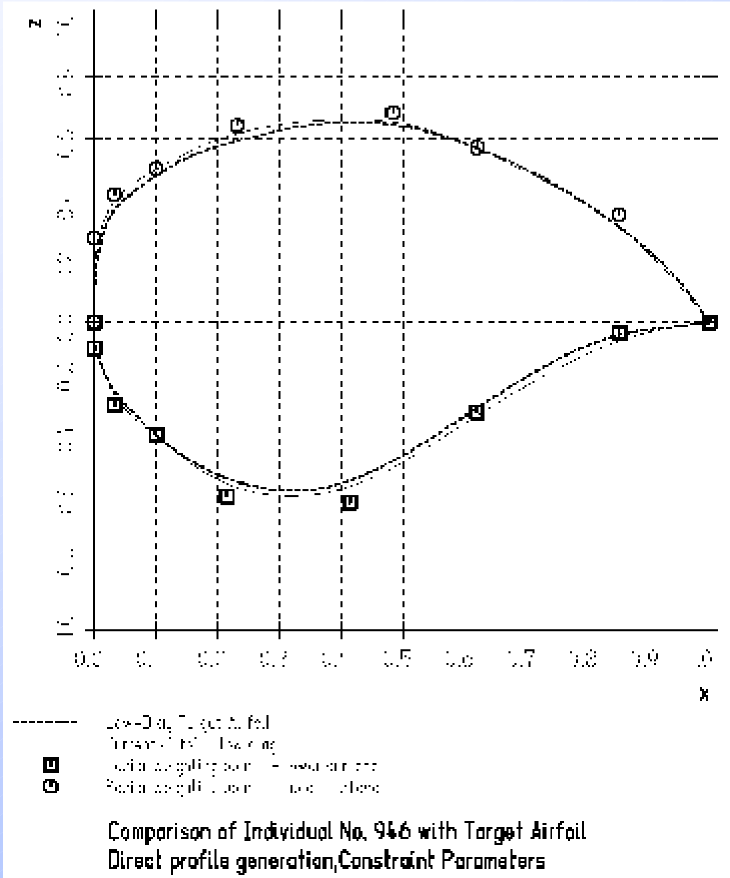
Hale – Loiter time

Robust Design

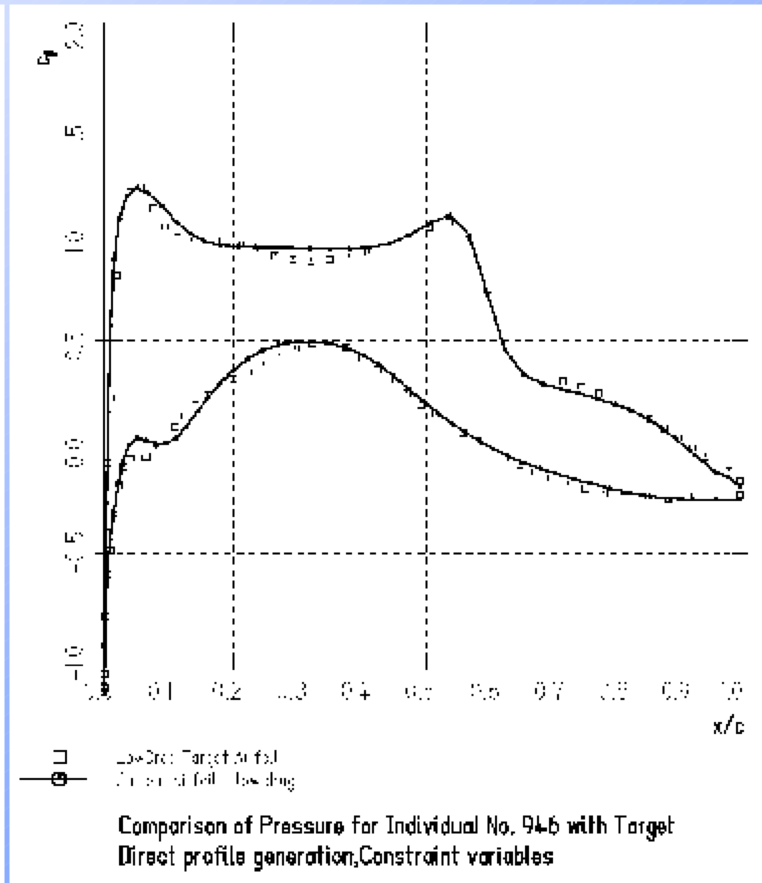
Conclusions

Inverse airfoil design - GA results (64x16)

Shape



Pressure



Optimisation in Aeronautics

Inverse airfoil design - ES results by NUTECH

Strategy used: DES, elitism incorporated

Design network

2-point airfoil

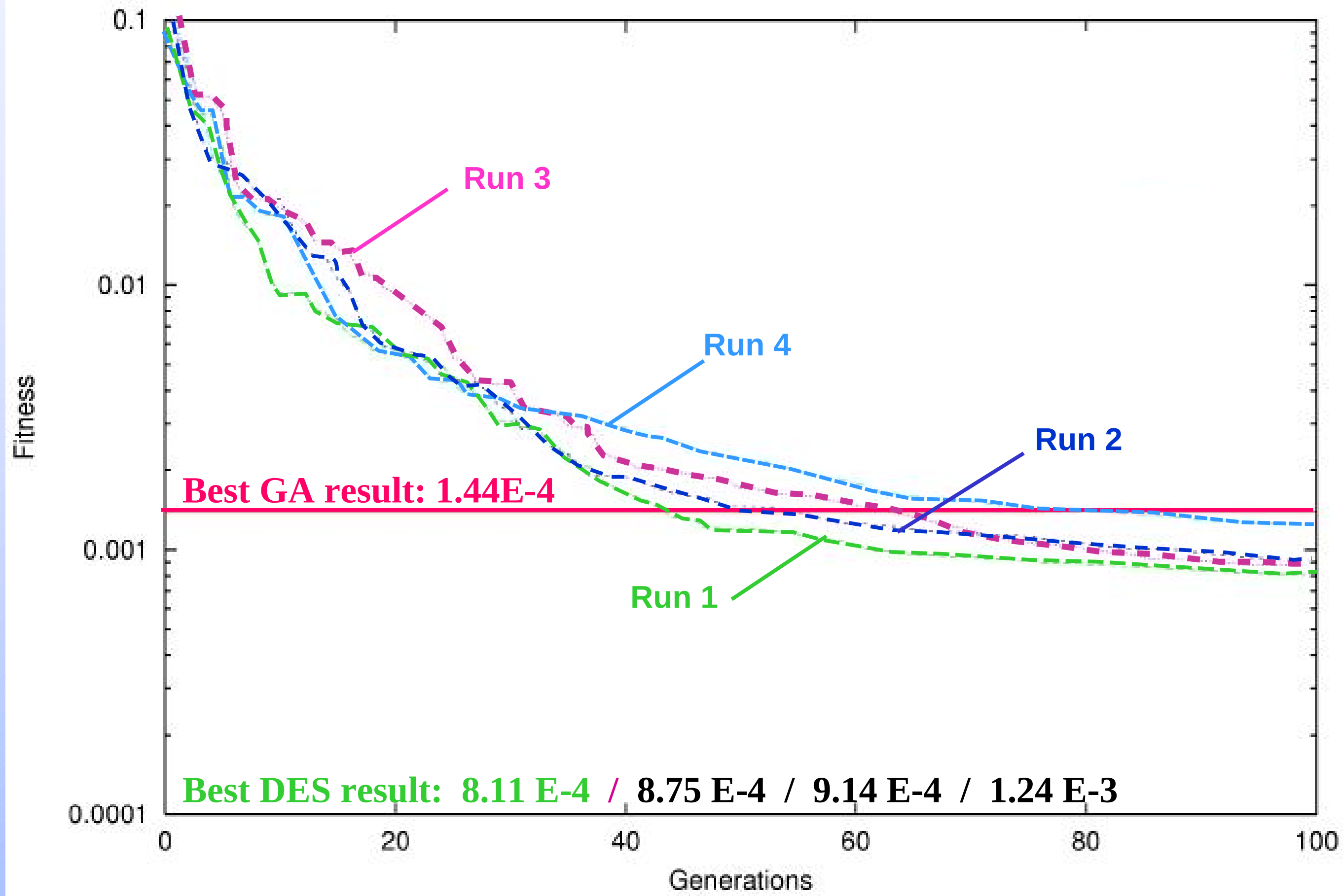
Drag minimisation on RAE2822

SCT drag minimisation

Hale – Loiter time

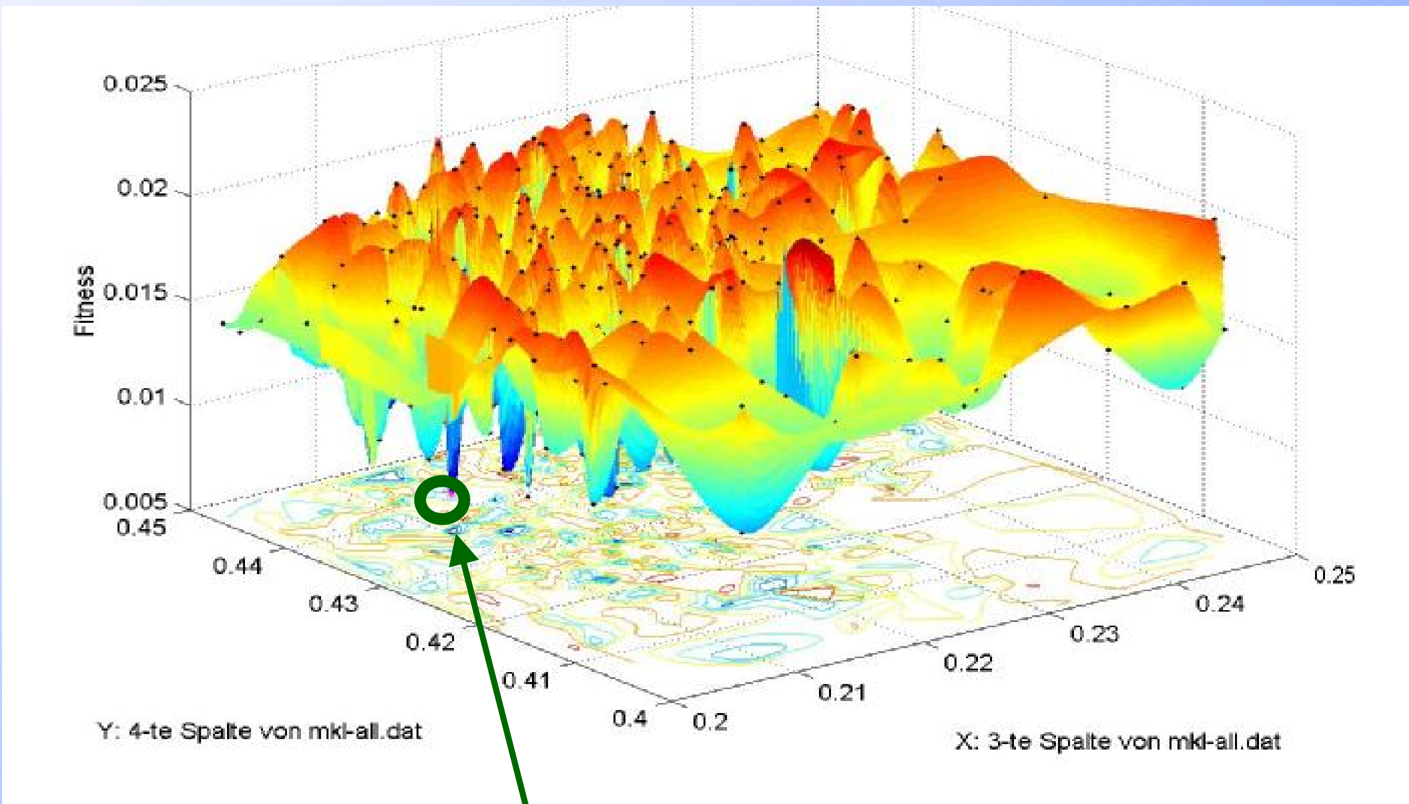
Robust Design

Conclusions



Inverse airfoil design - ES results by NUTECH

Fitness vs. first and second design parameter - low drag case



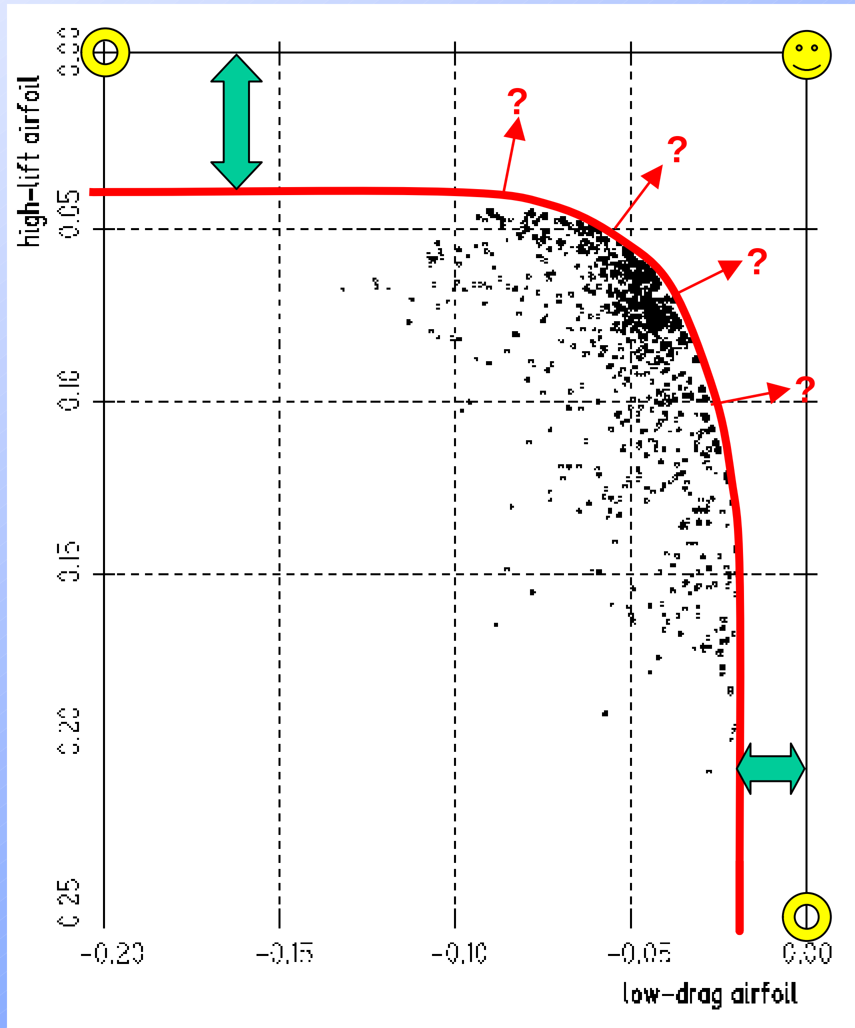
Optimum

Two-point airfoil design - Parameterisation

Axes values:
Objective function =
Difference in pressure

Pareto "gap" due to

Parameterisation



Optimisation in Aeronautics

Two-point airfoil design - Pareto results

Design network

2-point airfoil

Drag minimisation on RAE2822

SCT drag minimisation

Hale – Loiter time

Robust Design

Conclusions

Individual 25 is the best non-dominated individual for the high lift airfoil with objective function values of:

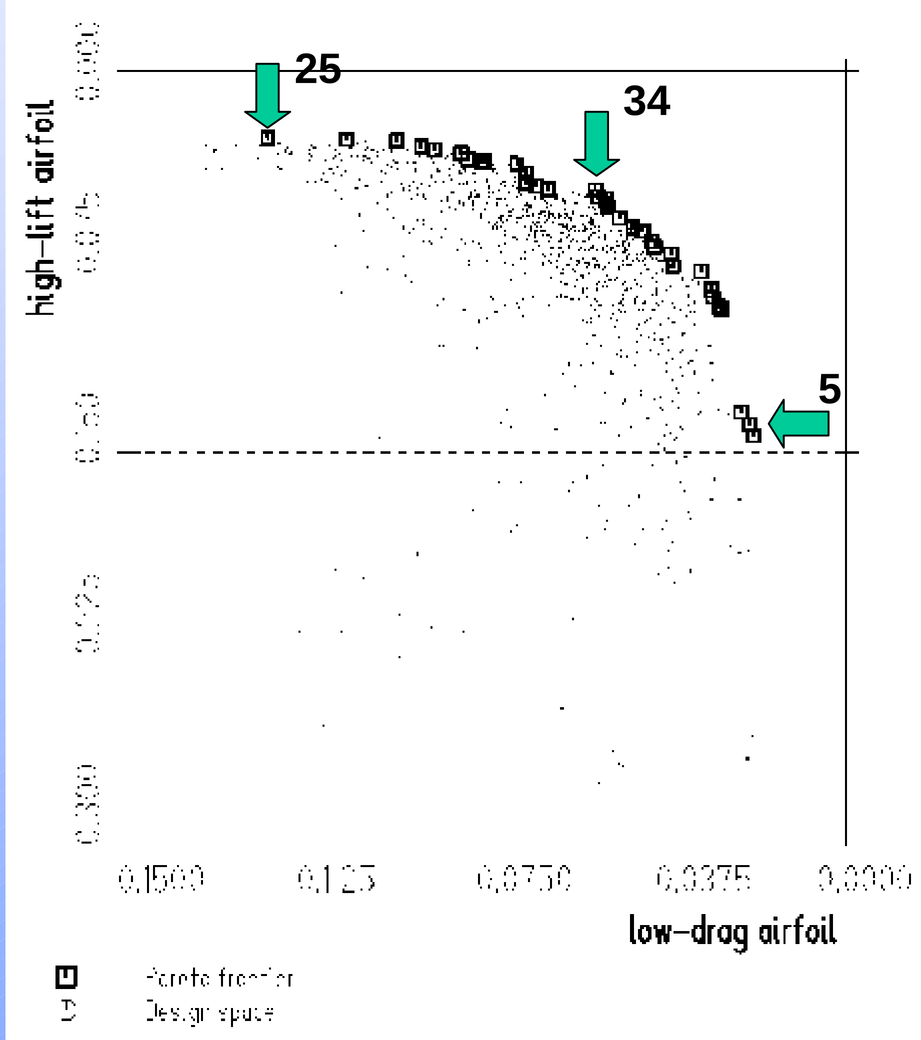
LD: $1.21 \cdot 10^{-1}$

HL: $2.60 \cdot 10^{-2}$

Individual 5 denotes the best low-drag, non-dominated individual with objective function values of:

LD: $2.03 \cdot 10^{-2}$

HL: $1.39 \cdot 10^{-1}$



Optimisation in Aeronautics

Design network

2-point airfoil

Drag minimisation on RAE2822

SCT drag minimisation

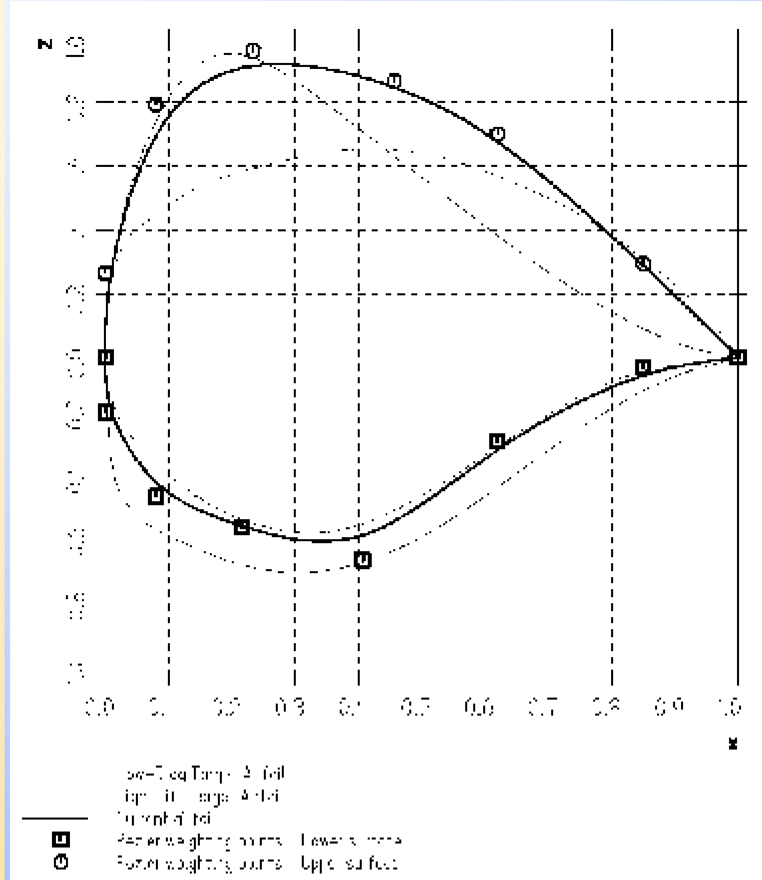
Hale – Loiter time

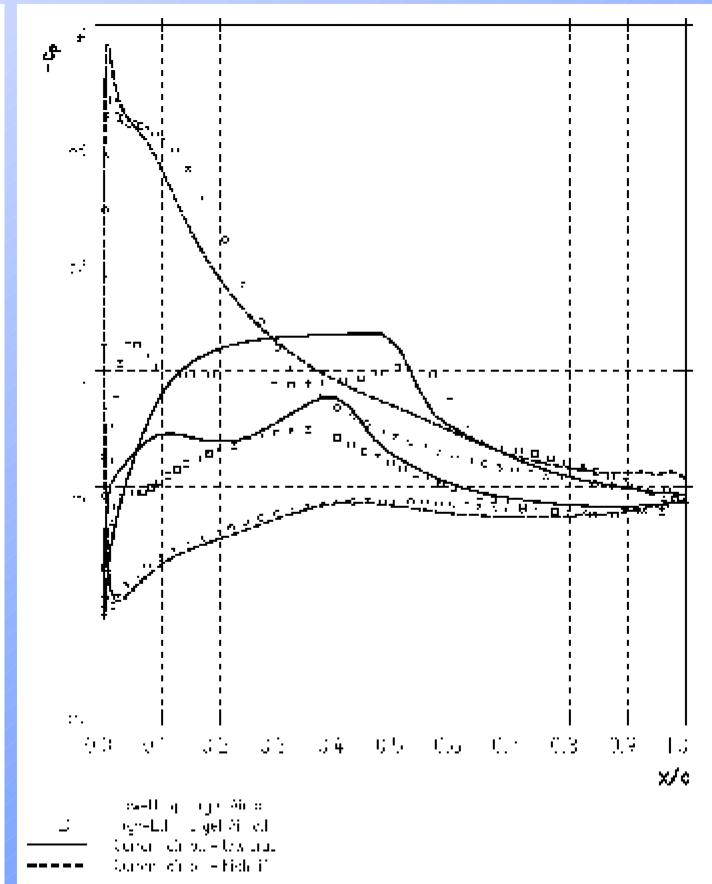
Robust Design

Conclusions

Two-point airfoil design - „Compromise“ result

Non-dominated **individual 34** from Pareto frontier as an engineering compromise between low-drag and high-lift airfoil





Optimisation in Aeronautics

Design network

2-point airfoil

Drag minimisation on RAE2822

SCT drag minimisation

Hale – Loiter time

Robust Design

Conclusions

RAE2822
Drag minimisation
=
Three-point airfoil design

Design points:

1. $M_1 = 0.734,\ \alpha_1 = 2.8°$, Re = 6.5 x 10^6
2. $M_2 = 0.754,\ \alpha_2 = 2.8°$, Re = 6.2 x 10^6
3. $M_3 = 0.680,\ \alpha_3 = 1.8°$, Re = 5.7 x 10^6

Objective:

$$OBJ = 2\,C_d(\alpha_1, M_1) + C_d(\alpha_2, M_2) + C_d(\alpha_3, M_3)$$

Constraints:

1. $C_l(\alpha_1, M_1) \geq C_l^t(\alpha_1, M_1)$,
2. $C_m(\alpha_1, M_1) \simeq C_m^t(\alpha_1, M_1)$ - variation of $\pm 2\%$ allowed,
3. $C_l(\alpha_2, M_2) \geq C_l^t(\alpha_2, M_2)$,
4. $C_m(\alpha_2, M_2) \simeq C_m^t(\alpha_2, M_2)$ - variation of $\pm 2\%$ allowed,
5. $C_l(\alpha_3, M_3) \geq C_l^t(\alpha_3, M_3)$,
6. $C_m(\alpha_3, M_3) \simeq C_m^t(\alpha_3, M_3)$ - variation of $\pm 2\%$ allowed,
7. leading – edge – radius $\geq 0.91 \mathrm{l.e.r}^t$,
8. trailing – edge – angle $\geq 0.8\, t.e.a^t$,
9. thickness(5%) $\geq 0.96\,\mathrm{th.}^t(5\%)$.

Design network

2-point airfoil

Drag minimisation on RAE2822

SCT drag minimisation

Hale – Loiter time

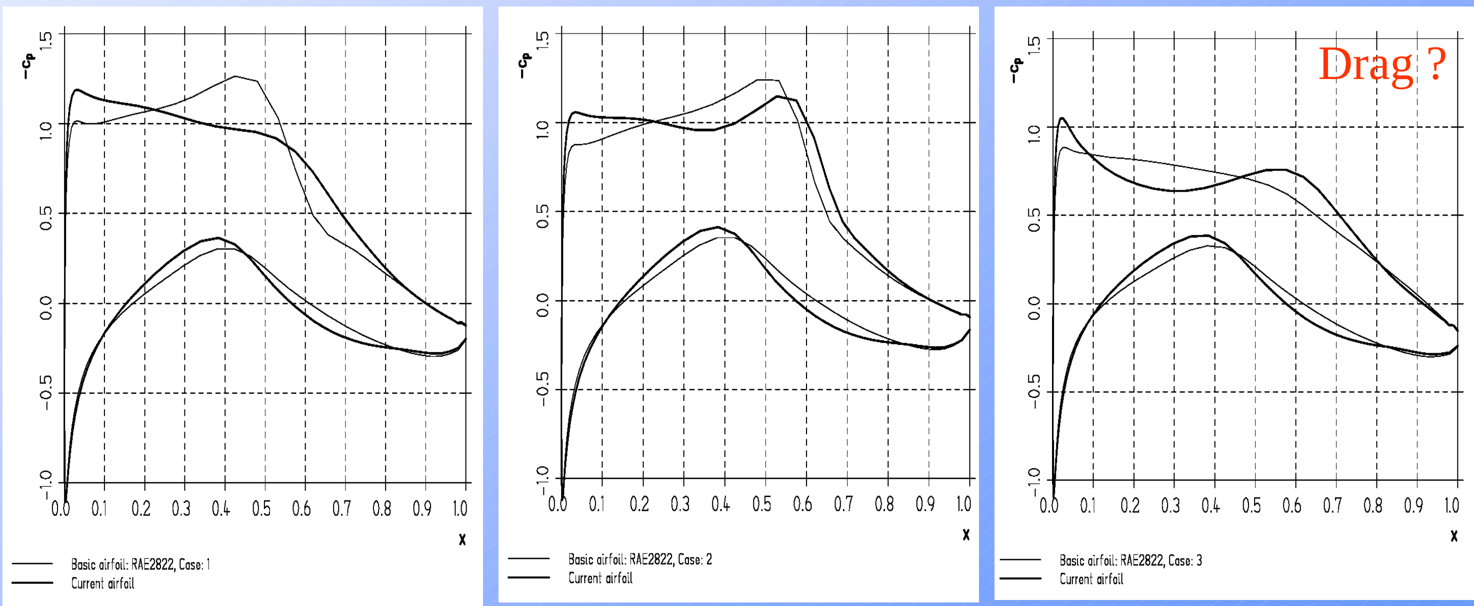
Robust Design

Conclusions

RAE2822 Drag minimisation - Pressure results

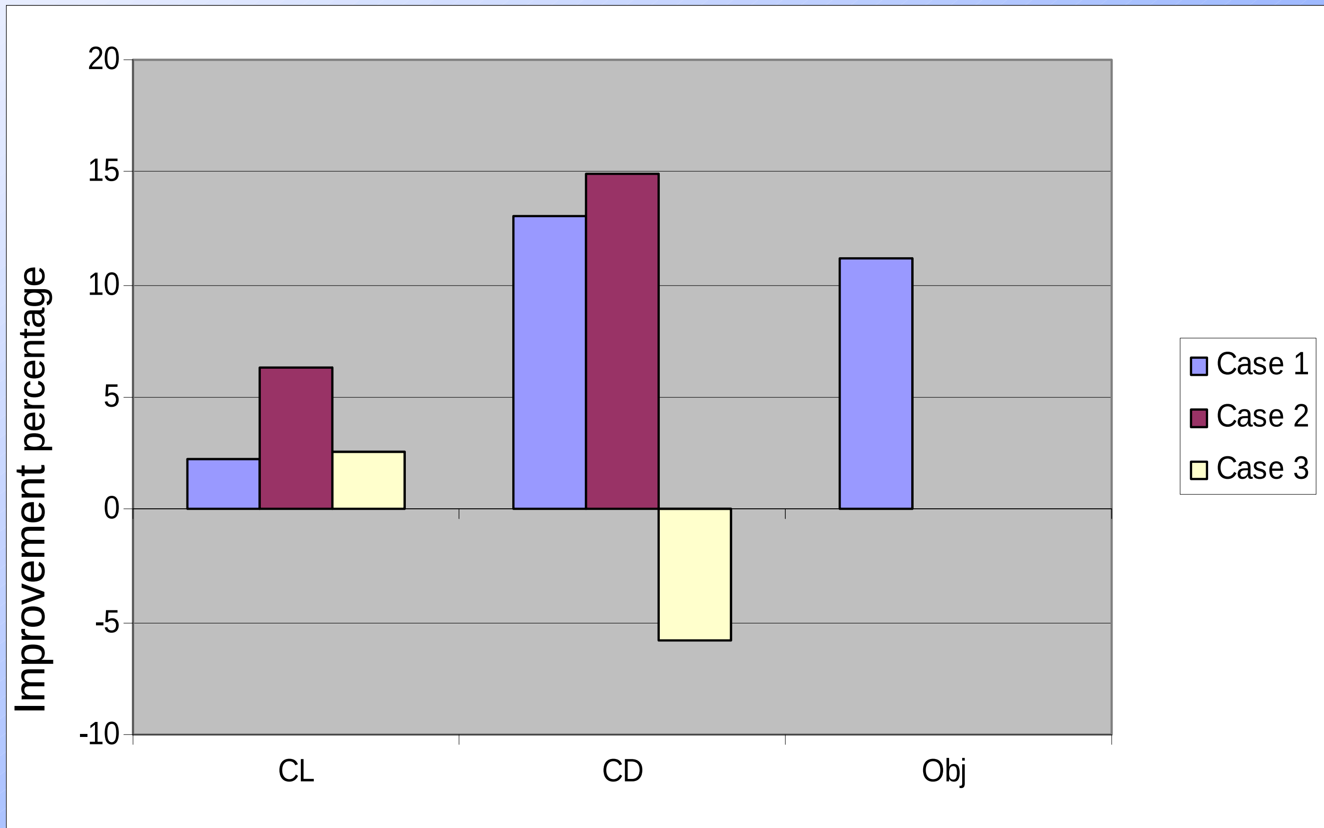
MMES (20,2,20) with 1 Objective
Coarse mesh / Design 251
Hybrid approach with NLPQLP

Pressure distributions for optimised and initial shape for all three points



RAE2822 Drag minimisation - Results

FMOGA (16,16) with 3 Objectives
Coarse mesh / Design 148



Design network

2-point airfoil

Drag minimisation on RAE2822

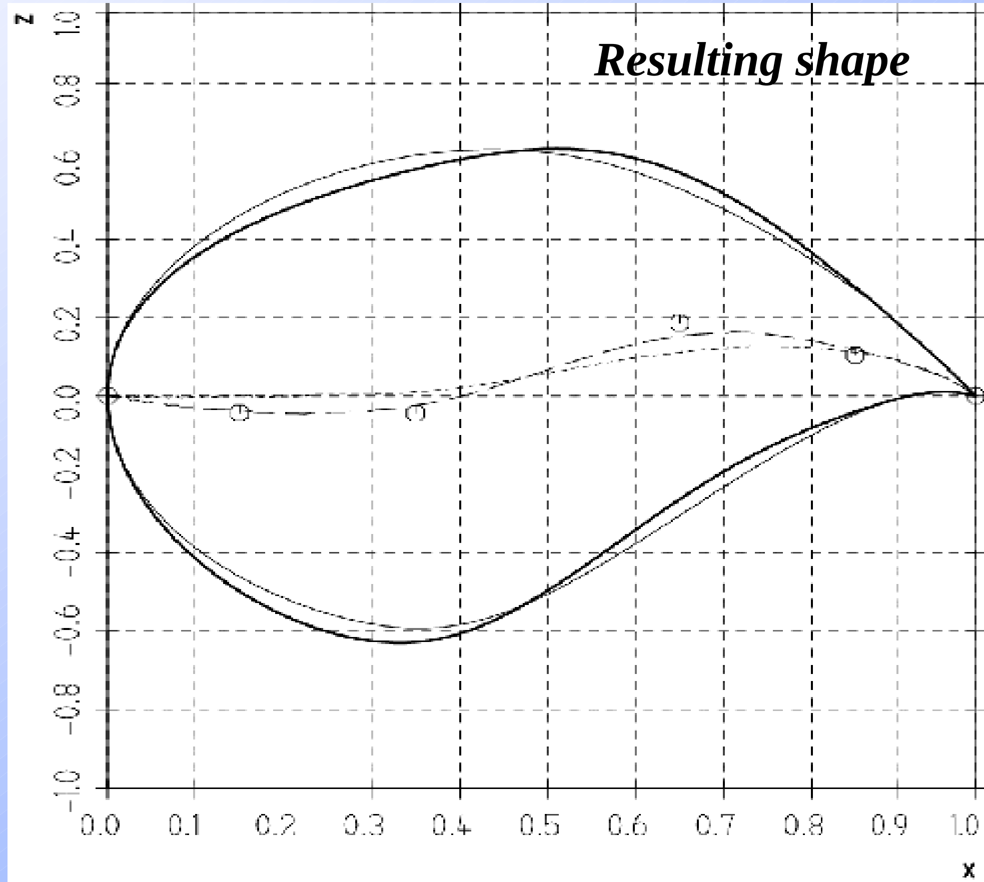
SCT drag minimisation

Hale – Loiter time

Robust Design

Conclusions

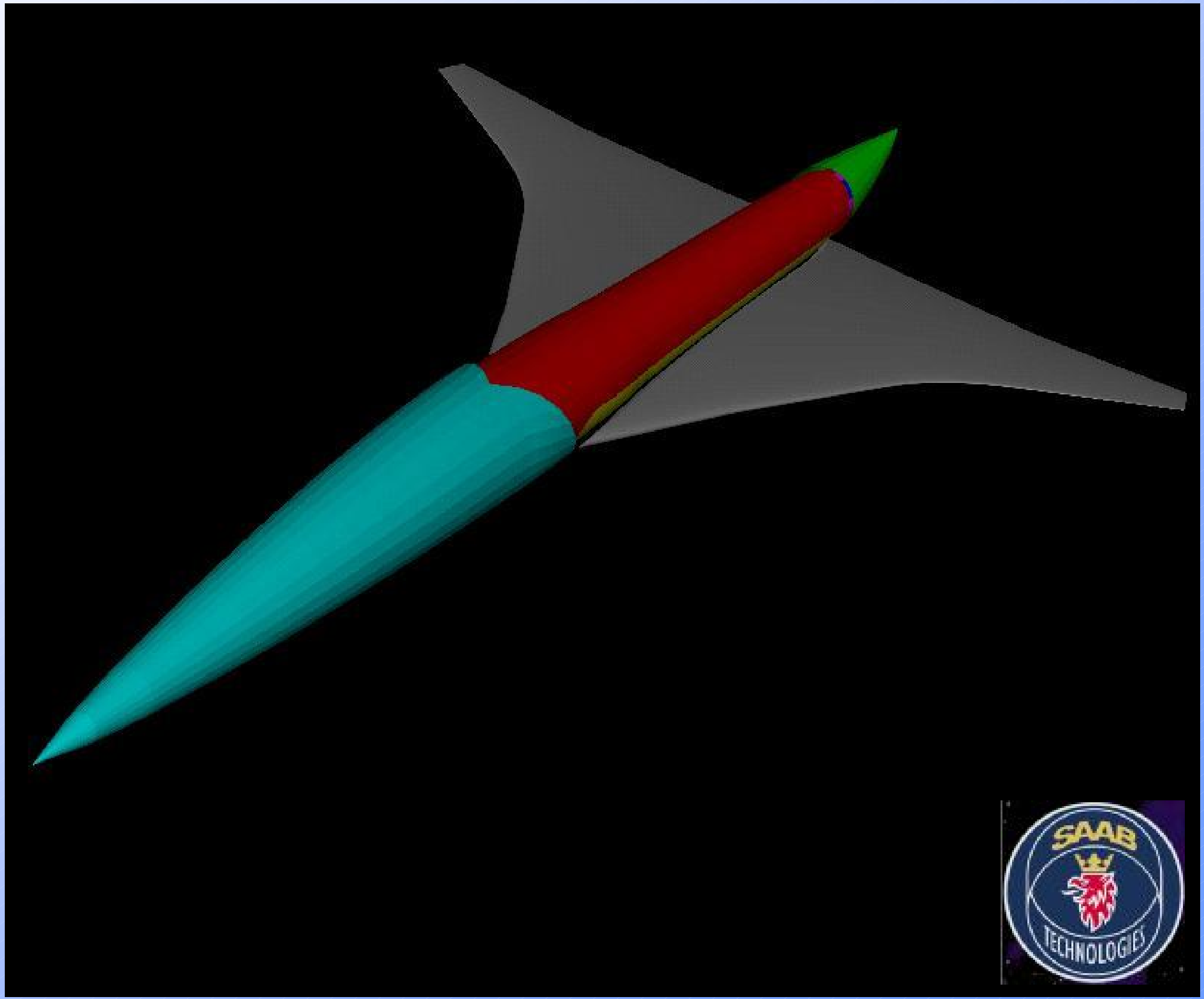
RAE2822 Drag minimisation - Results



$C_m(\alpha_1, M_1) \simeq C_m^t(\alpha_1, M_1)$ - variation of $\pm 2\%$ allowed

Optimisation in Aeronautics

Supersonic Commercial Aircraft - Drag minimisation



Supersonic Commercial Aircraft - Test case definition

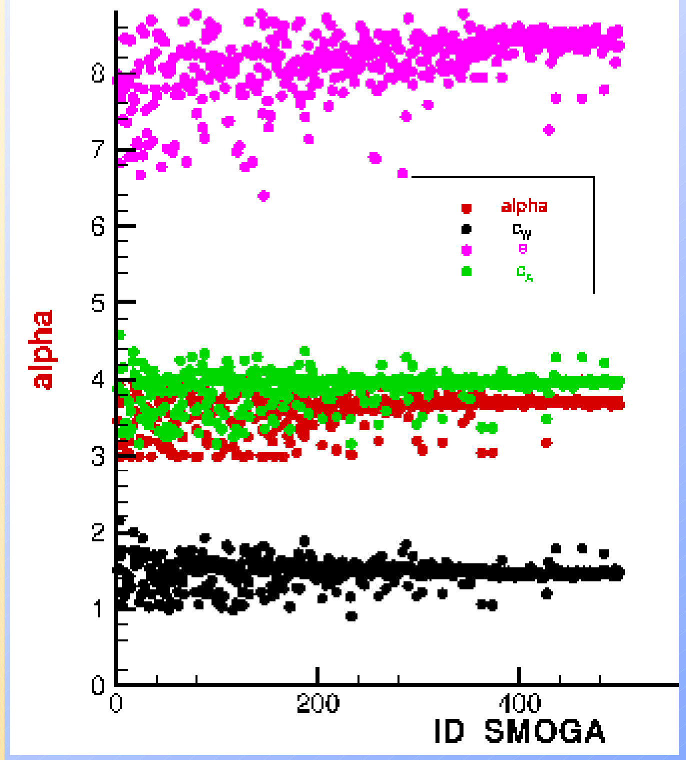
M=2.0, free angle of attack, Euler solution

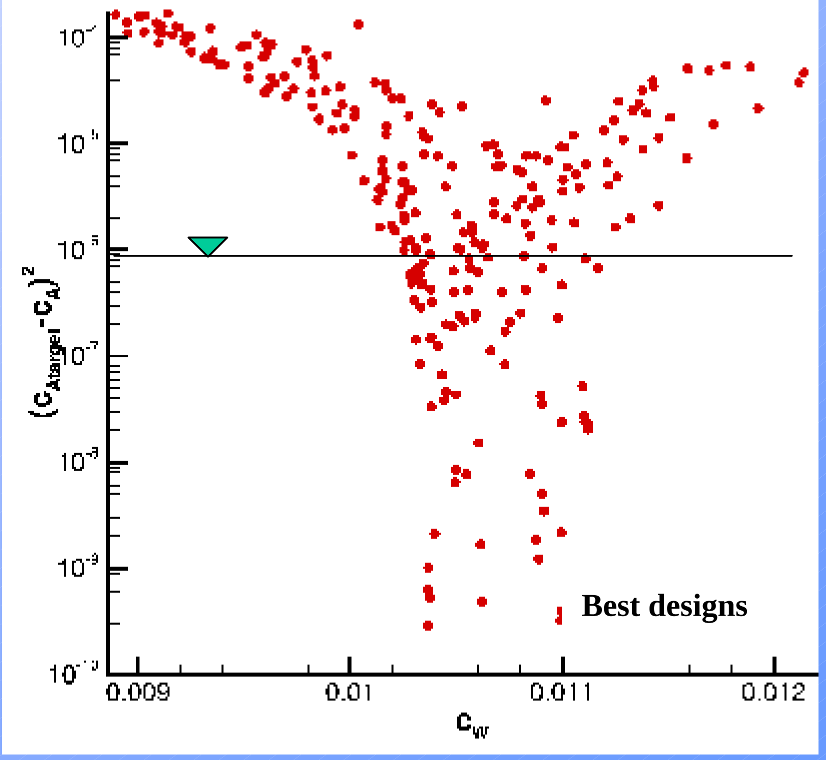
Parameterisation with ICEM's COMAK tool
Coupled to ICEM HEXA for grid generation

Objective	**Minimum drag**
Design parameters	Defining fuselage contraction, angle of attack, asymmetric wing profiles at four spanwise positions, twist at four spanwise positions, 25 parameters in total
Constraints	Pitching moment coeff. (about –0.029), location and range of fuselage contraction, minimum fuselage radius, minimum of wing spanwise profile thickness distribution, and a lift coefficient = 0.12 - to be kept in the range of 10^{-4}

Supersonic Commercial Aircraft - Convergence and objective space

Initial population: $\mu = 50$
Number of generations: $T = 10$





Design network

2-point airfoil

Drag minimisation on RAE2822

SCT drag minimisation

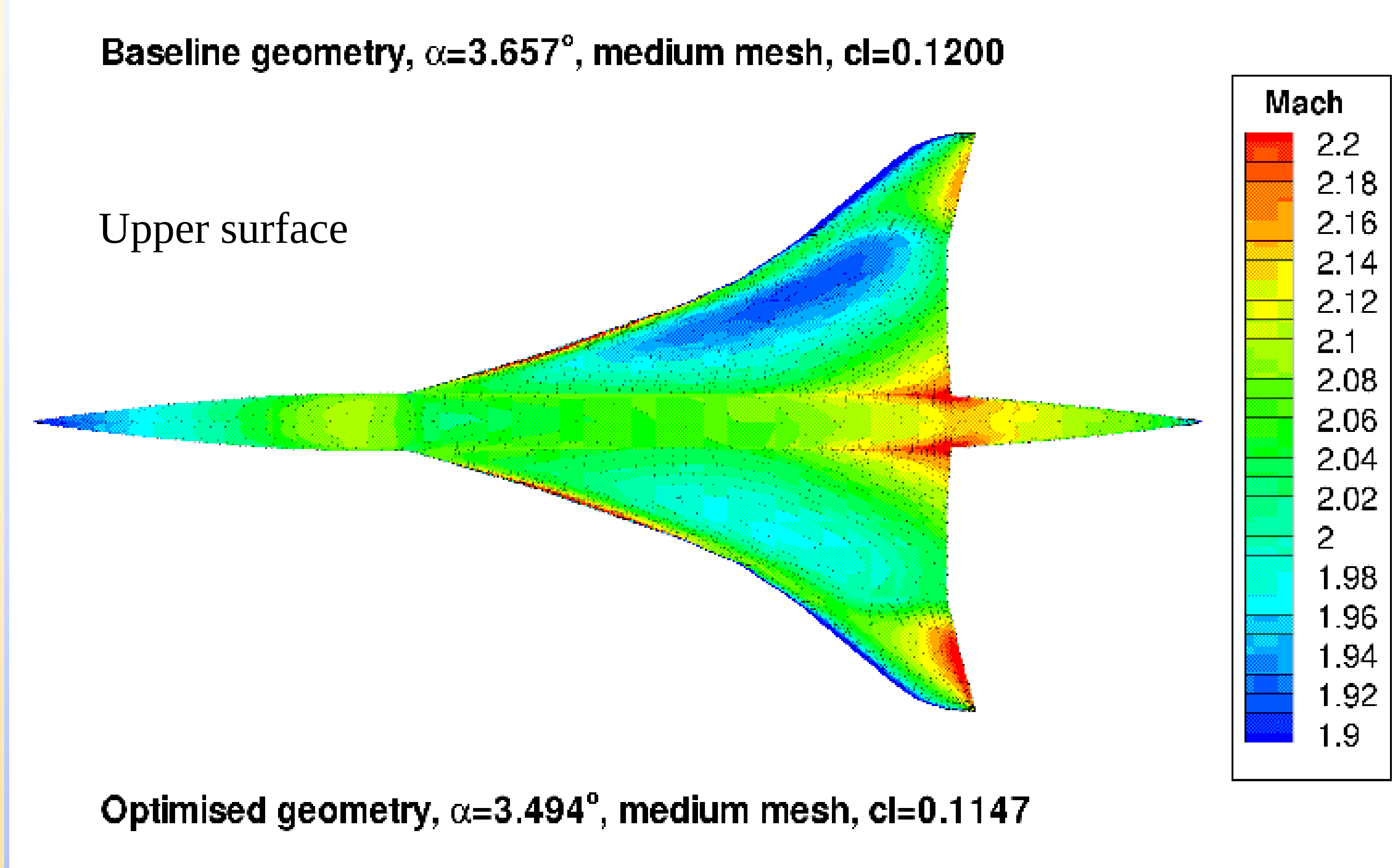
Hale – Loiter time

Robust Design

Conclusions

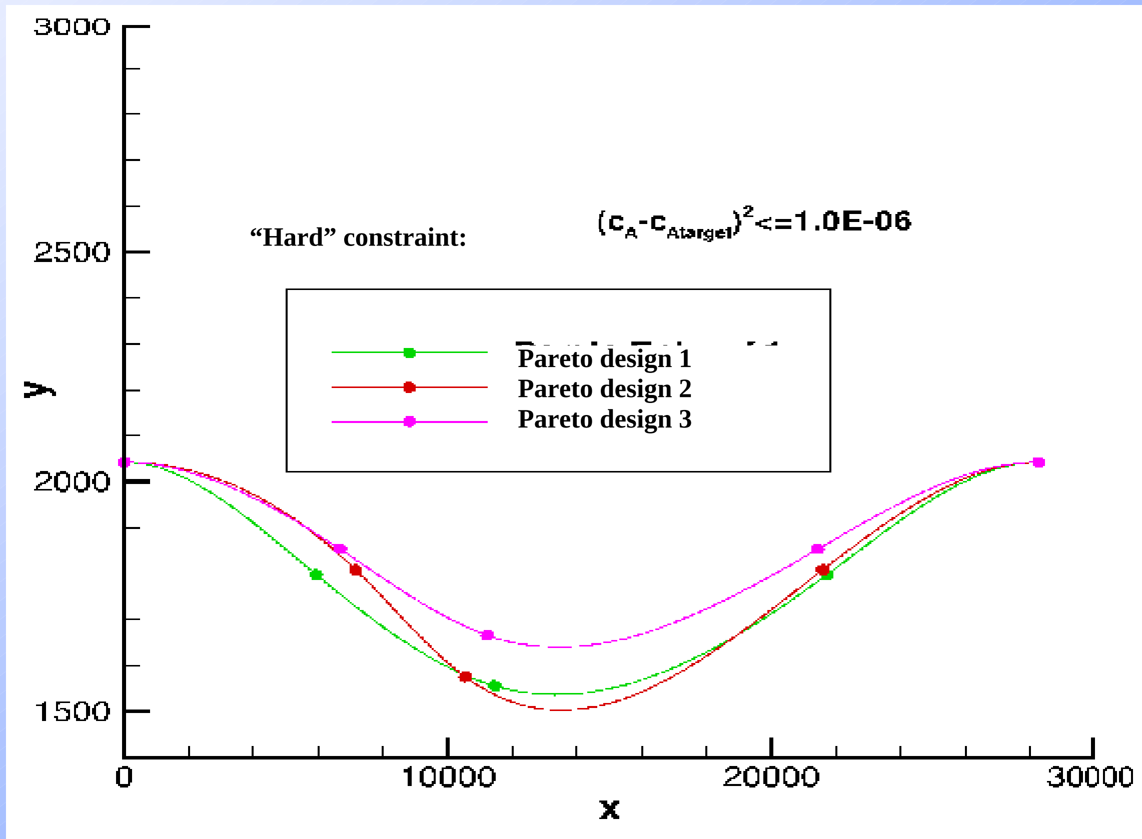
Optimisation in Aeronautics

Supersonic Commerical Aircraft - Baseline & Optimum



Supersonic Commercial Aircraft

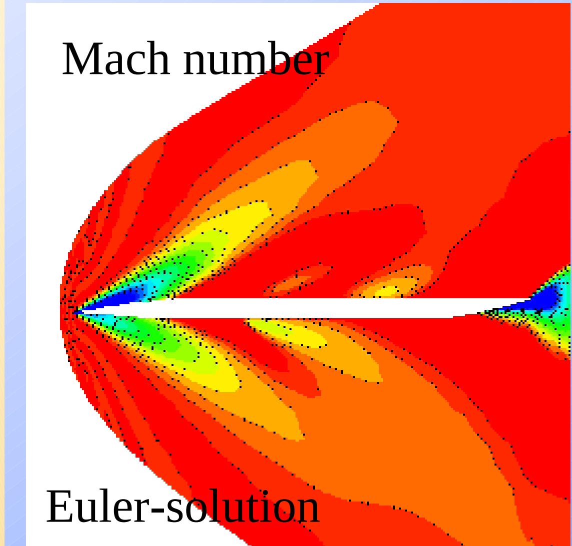
Fuselage contractions, Optimiser SMOGA

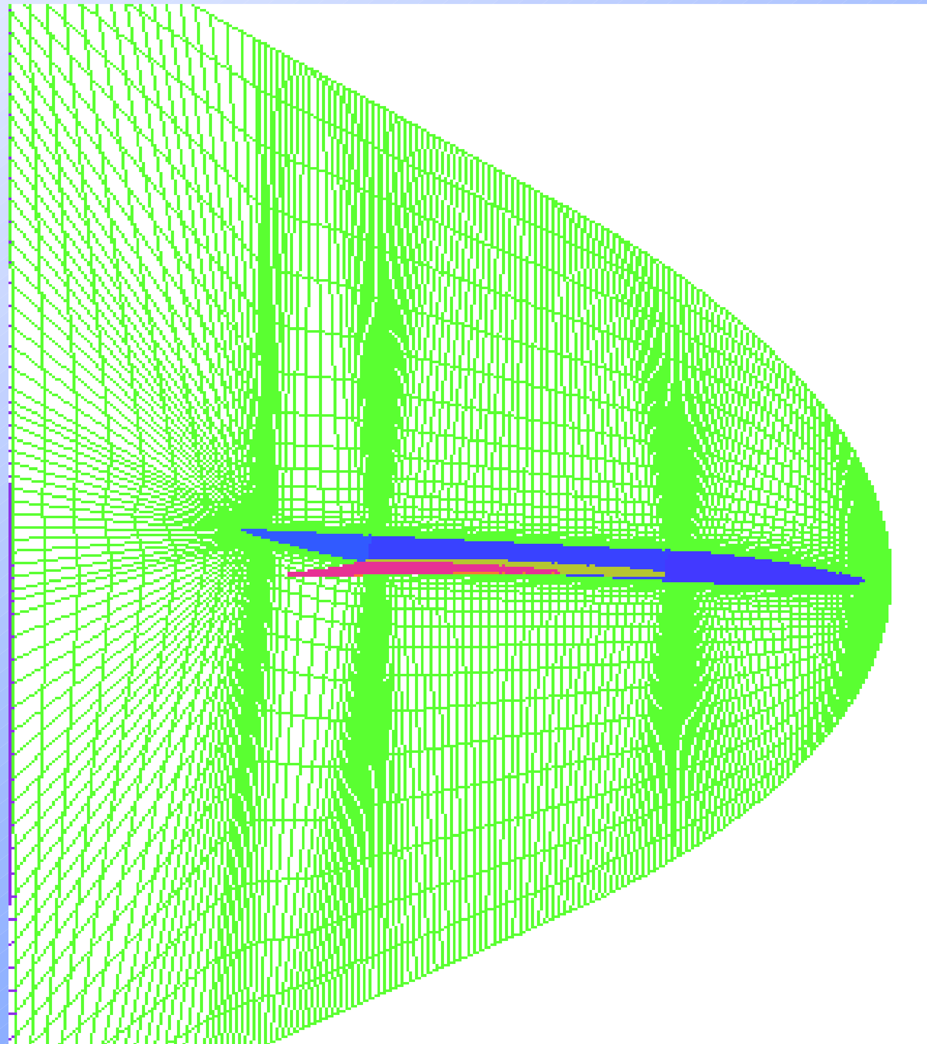


Supersonic Commerical Aircraft - Mesh and solution

- Design network
- 2-point airfoil
- Drag minimisation on RAE2822
- **SCT drag minimisation**
- Hale – Loiter time
- Robust Design
- Conclusions

"Fine" grid with
617,000 grid points





Optimisation in Aeronautics

Design network

2-point airfoil

Drag minimisation on RAE2822

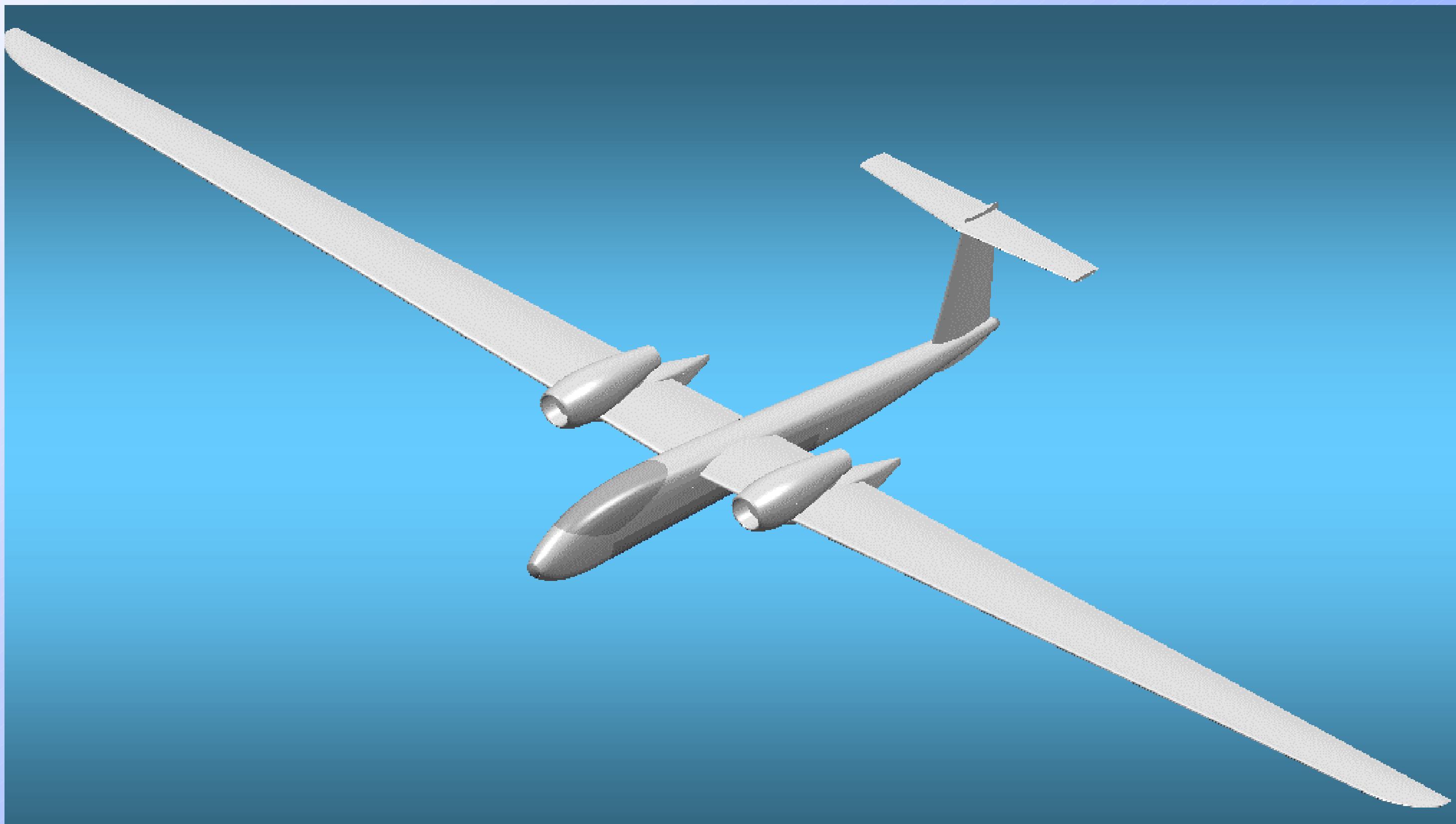
SCT drag minimisation

Hale – Loiter time

Robust Design

Conclusions

Optimisation of loiter-time for a „Hale“ A/C



a preliminary design example

Optimisation of loiter-time for „Hale“

Task/Objective

Computation of **maximum loiter time** as a function of wing-chord, profile thickness, Mach number, wing weight and the resulting drag.

According to Ma, altitude, weight and Wing-area, a “design lift coefficient” is derived – from which the drag coefficient of the optimal profile (turbulent flow) is computed.

Design variables

Mach number at start of loiter
Wing area [m**2]
Relative wing thickness [-]
Altitude at start of loiter is fixed (15km and 16 km, 17 km “not met” according to selected engine)
Wing span [m] – we have changed upper bound in different runs (!)

Optimisation in Aeronautics

Optimisation of loiter-time for „Hale“

Design network

2-point airfoil

Drag minimisation on RAE2822

SCT drag minimisation

Hale – Loiter time

Robust Design

Conclusions

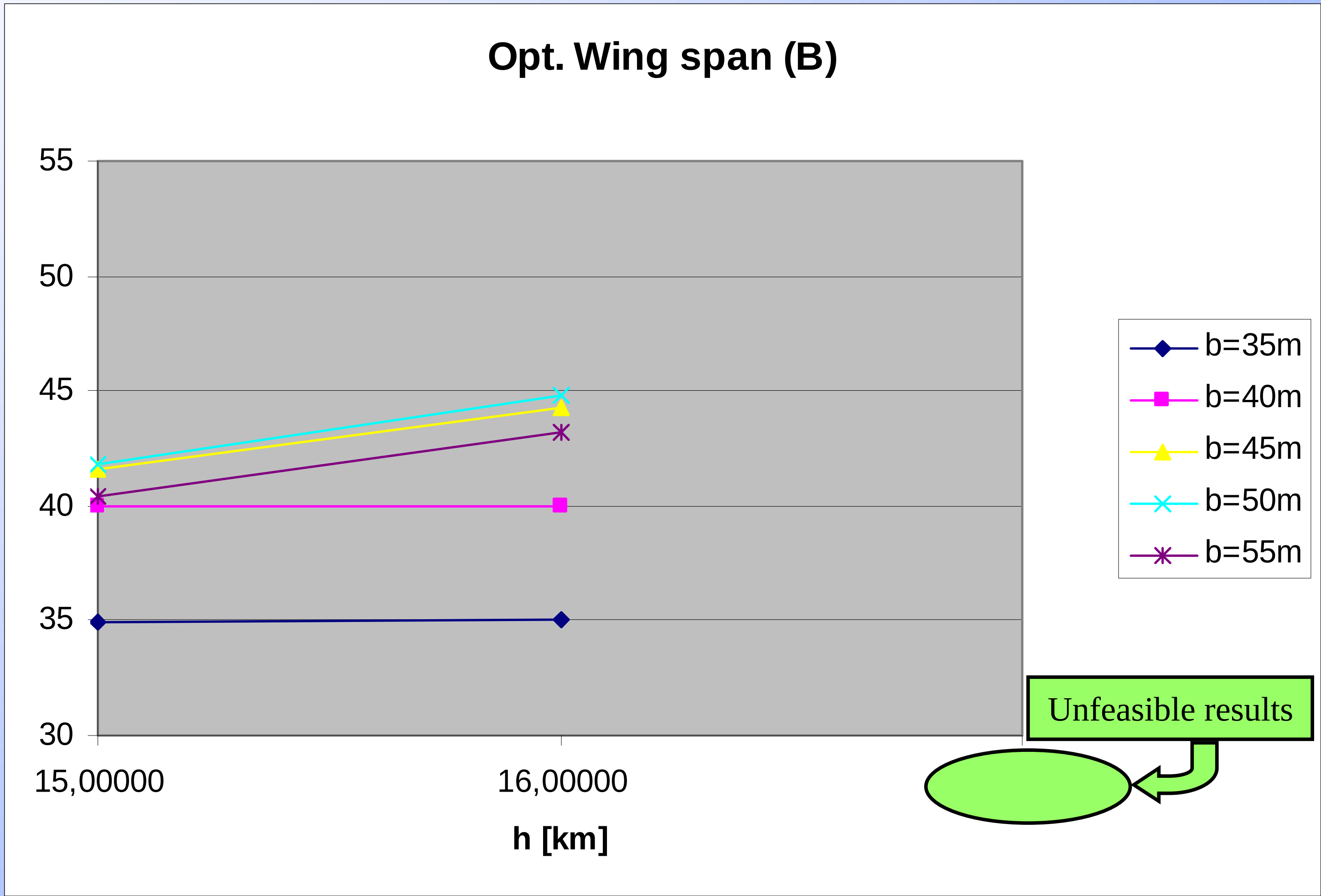
Constraints

Drag < thrust for the given engine
Critical Mach number
Max. take-off weight
Max. drag: to be lower than max. thrust
Wing thickness > 0.24

Optimiser

DES (single objective ES)
[additional GA and NLPQLP runs]

Optimisation of loiter-time for „Hale“



Design network

2-point airfoil

Drag minimisation on RAE2822

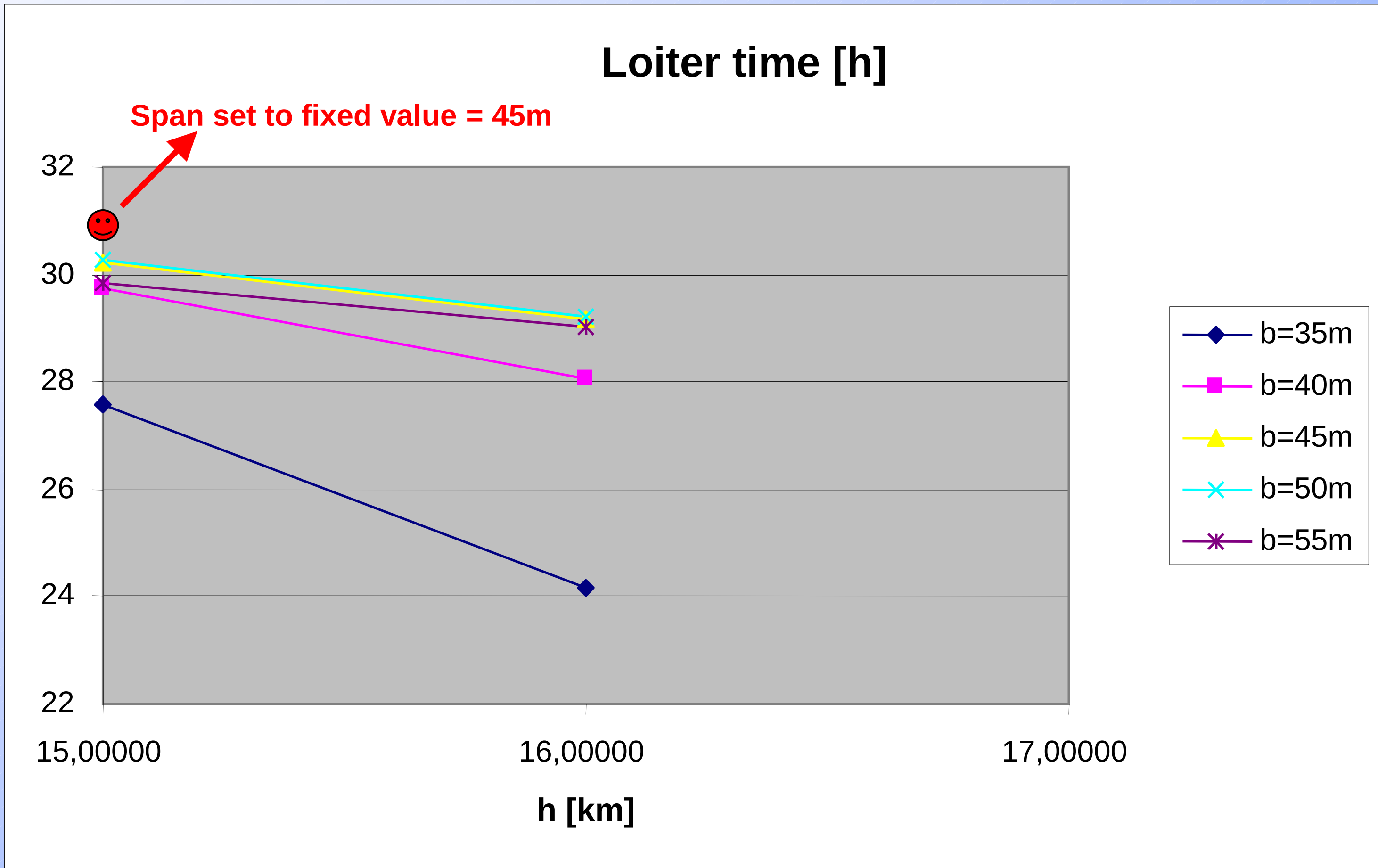
SCT drag minimisation

Hale – Loiter time

Robust Design

Conclusions

Optimisation of loiter-time for „Hale“



Design network

2-point airfoil

Drag minimisation on RAE2822

SCT drag minimisation

Hale – Loiter time

Robust Design

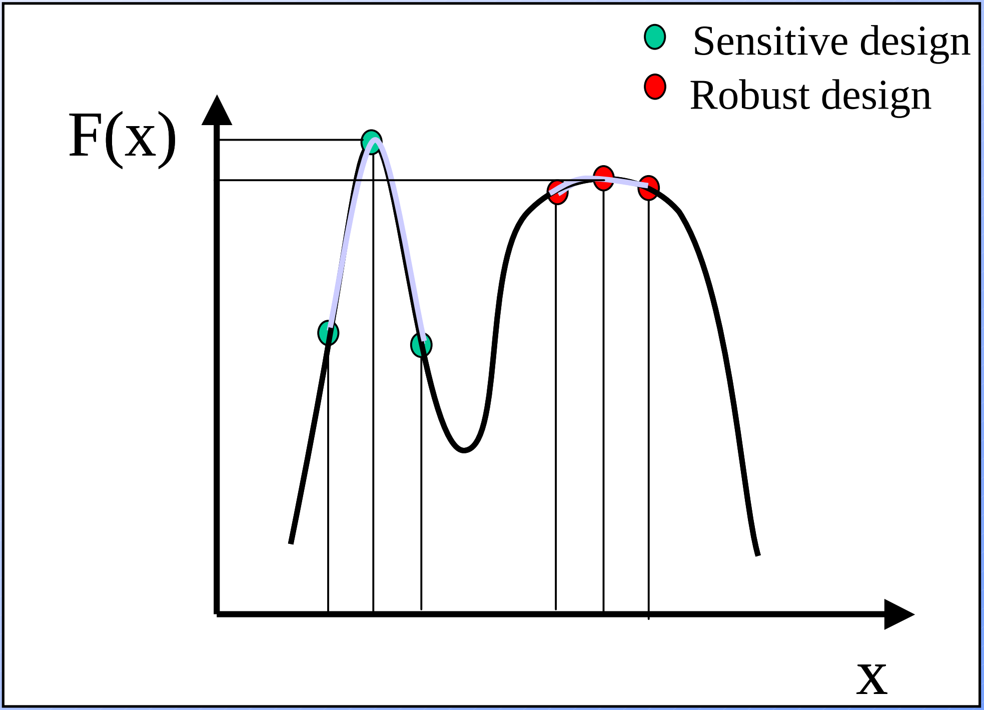
Conclusions

Optimisation of loiter-time for „Hale“ Conclusions

- As mentioned, the “fixed-span” optimisation turned out to be an extremely “peaky” optimum, i.e., in the close vicinity of this design no other can be found.
- Using an NLPQLP (SQP) method resulted in completely non-feasible solutions around the B=45m goal, because
- a collision between max. take-off weight and wing thickness occurred; either thickness or take-off weight were violated and small changes in the constraints gave rise to completely different solutions.
- Thus we must find another way to (maybe) reach the B=45m goal – if it is then one: **Robust design**

Robust design

- It has been seen that the **best solution is NOT identical to the best average solution** (an averaged variables distribution)
- Thus two additional objectives are to be employed: **Maximise average function inside the variables** distribution and **minimise standard deviation** – leading to multi-objective optimisation



=> Topic of current research

Courtesy of L. Padovan, ESTECO

Design network

2-point airfoil

Drag minimisation on RAE2822

SCT drag minimisation

Hale – Loiter time

Robust Design

Conclusions

~~Conclusion~~

We are far from being self-satisfied and have hopefully stressed advantages and open questions in equal shares.

- What problem to optimise?
- How can a known problem be optimised?
- What parameterisation to use?
- Taking new mesh generation or mesh movement, and
- how does the mesh quality influence the optimum?
- Which analysis method to apply ?
- Definition of constraints correct?
- Objective functions? (combined or separate, i.e. multi-objective) (even combined objectives AND constraints)
- What optimiser to choose ?
- Robust design needed ?