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A Cooperative Approach to Multi-Level Multi-Disciplinary Aircraft Optimization

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Knowledge for Tomorrow

DLR

Outline

➤ Motivation

➤ Optimization problem

➤ Derivative-free optimization (DFO)

➤ Gradient-based optimization (GBO)

➤ Conclusion

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➢ **Motivation**

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Motivation

➢ Large increase in air travel expected in the following decades
  ➢ Supra-national calls (e.g. EU's Flightpath 2050) for decrease of aircraft emissions and noise, increase of availability and safety, *increase of multi-disciplinarity in design*...

➢ DLR project **Digital-X**:
  ➢ Computer-based design and virtual flight testing
  ➢ Multiple disciplines (nine DLR institutes involved)
  ➢ Multiple fidelity levels (from conceptual to PDE-based simulations)

➢ Multi-disciplinary optimization **in context of**:
  ➢ Use of established in-house and third-party tools and validated disciplinary methods
  ➢ Hands-on cooperation between DLR institutes
  ➢ Provision of optimization processes for in-house aircraft design research
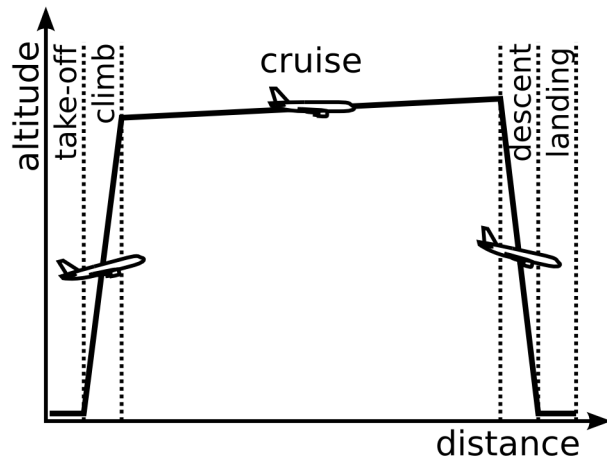
Keep in mind the context!

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Optimization problem

http://www.airliners.net/photo/Lufthansa/Airbus-A330-343X/2054700

➢ Minimize mission fuel burn of a long-range airliner

ODE integration…
...or simplified (from Breguet range equation):

$$m_f = m_e \left(\exp\left(\frac{R}{\frac{a}{g} \frac{1}{c_f} M \frac{L}{D}} \right) - 1 \right)$$

aerodynamics

structure

propulsion

➢ Using design parameters:
  ➢ aerodynamic: wing planform and sections shape
  ➢ structural: thicknesses of spars, ribs, and skin sections

➢ Under constraints:
  ➢ aerodynamic: lift, pitching moment
  ➢ structural: strength and buckling
  ➢ control: trim capability, stability margin
  ➢ performance: takeoff/landing distance, ferry range

Properties of the objective and constraints

➤ What is the influence of disciplinary design parameters on cost functions?

➤ For simplicity, consider *instantaneous range factor* as the objective:

$$\min_p \left(J = k \, \frac{1}{m} \frac{L}{D} \right), \quad p = \left(p_{aero}, p_{struct} \right)$$

at optimum:

$$\frac{dJ}{dp_{aero}} = 0$$

$$\frac{dJ}{dp_{struct}} = 0$$

⟶

$$\frac{1}{m} \frac{d(L/D)}{dp_{aero}} + \frac{L}{D} \frac{d(1/m)}{dp_{aero}} = 0$$

$$\frac{1}{m} \frac{d(L/D)}{dp_{struct}} + \frac{L}{D} \frac{d(1/m)}{dp_{struct}} = 0$$

direct grad.

cross grad.

➤ If cross gradients are small, we can approximate or even ignore them, and still reach a "sufficiently improved" design

➤ Perform similar analysis for every constraint

➤ Choose design parameters cleverly

Properties of the objective and constraints, cont.

grad
L/D

to aero. param.
to struct. param

grad
m

to aero. param.
to struct. param
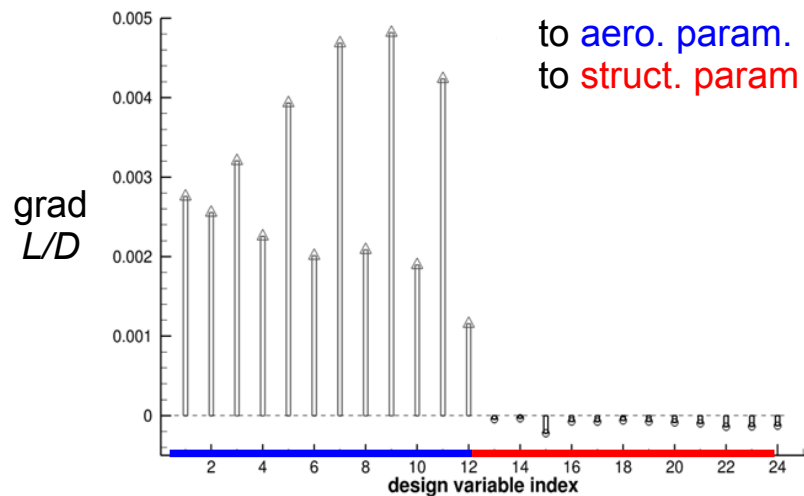
L/D polar (global influence of struct. param.)
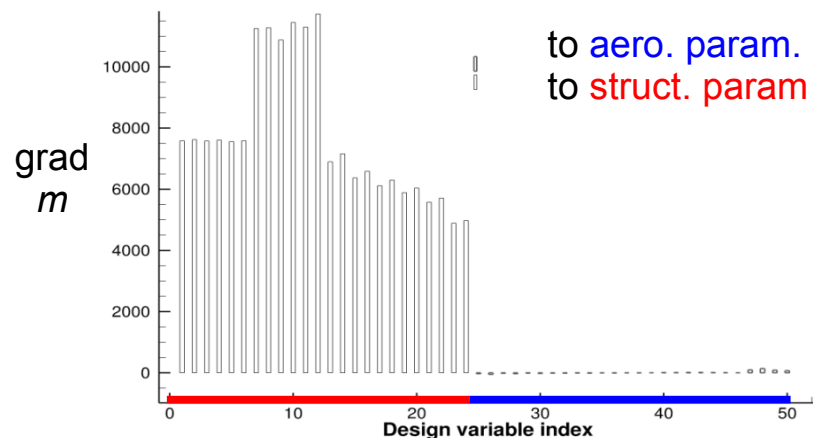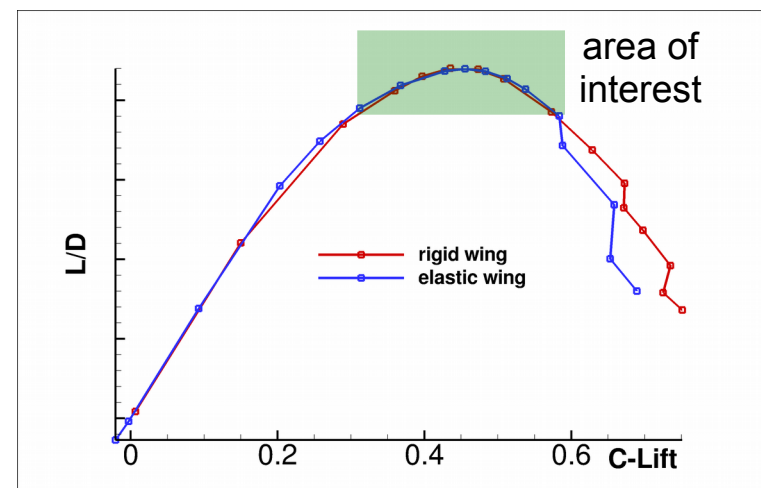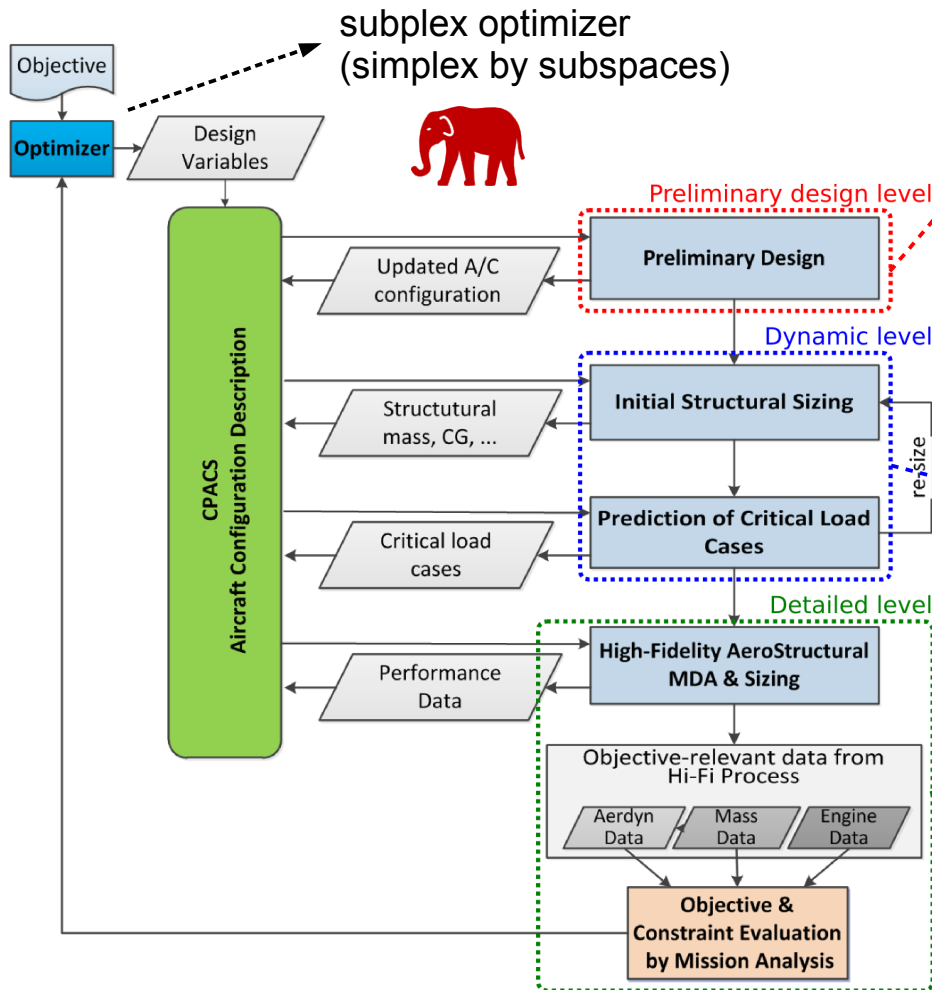

area of
interest

rigid wing
elastic wing

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➢ **Derivative-free optimization (DFO)**
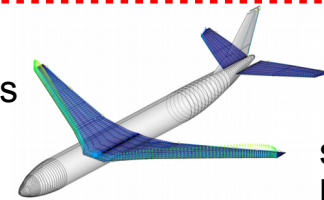➢ Gradient-based optimization (GBO)
➢ Conclusion

DFO multi-level concept

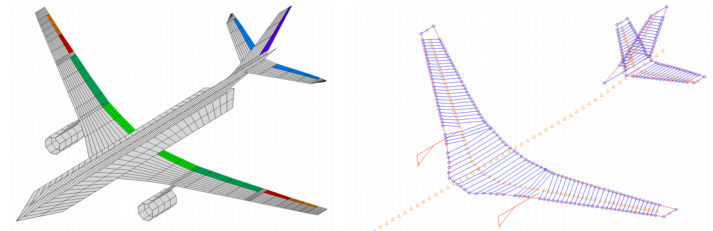$$\frac{1}{m}\frac{d(L/D)}{d\,p_{aero}} + \frac{L}{D}\frac{d(1/m)}{d\,p_{aero}} = 0$$

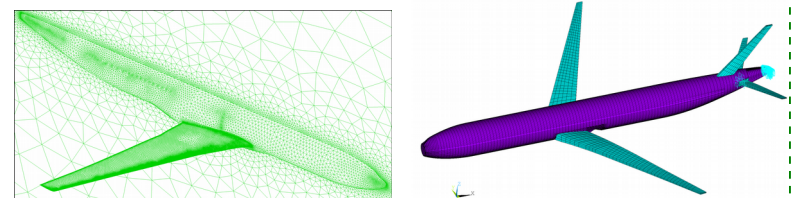$$\frac{1}{m}\frac{d(L/D)}{d\,p_{struct}} + \frac{L}{D}\frac{d(1/m)}{d\,p_{struct}} = 0$$

subplex optimizer
(simplex by subspaces)

Objective

Optimizer → Design Variables

CPACS Aircraft Configuration Description

Preliminary design level

Preliminary Design

Updated A/C configuration

isolated components

semi-empirical lifting line aero. beam struct.

Dynamic level

Initial Structural Sizing

Structutural mass, CG, ...

Prediction of Critical Load Cases

Critical load cases

resize

panel aero. (DLM), condensed FEM

steady/unsteady maneuvers, gust

Detailed level

High-Fidelity AeroStructural MDA & Sizing

Performance Data

Objective-relevant data from Hi-Fi Process

Aerdyn Data | Mass Data | Engine Data

Objective & Constraint Evaluation by Mission Analysis

PDE aero. (RANS), shell FEM w/internal struct.

static-aeroelastic perf., fully-stressed design

Optimization problem for DFO

➢ Optimize wing outer shape and wing-body-tails structure
   w.r.t. mission fuel burn

➢ Wing-body-tails geometry: Airbus XRF-1 baseline, metal structure

➢ 56 critical load cases; steady, unsteady and gust

➢ 1 performance point (Ma=0.83, CL~0.50 changes with mass)

➢ 9 wing planform and section parameters:
   aspect ratio, sweep, taper ×2, twist ×3, airfoil thickness ×2

➢ Wing area constant (by being independent parameter)

➢ Stability margin constant (by tail size and wing position update)

➢ Landing/takeoff distance roughly constant (by constant wing area and
   reducing structure mass)

➢ Lift matches mass (by flow solver internal iteration)

➢ 624 structural thickness parameters (wing, body, tails)

➢ Buckling and strength failure factors

➢ 56×624×2 structural constraints (by fully-stressed design)

Implementation and execution aspects for DFO

➢ Disciplinary tools running on servers at respective DLR institutes

➢ RCE (Remote Component Environment) for assembling and running the process over the network
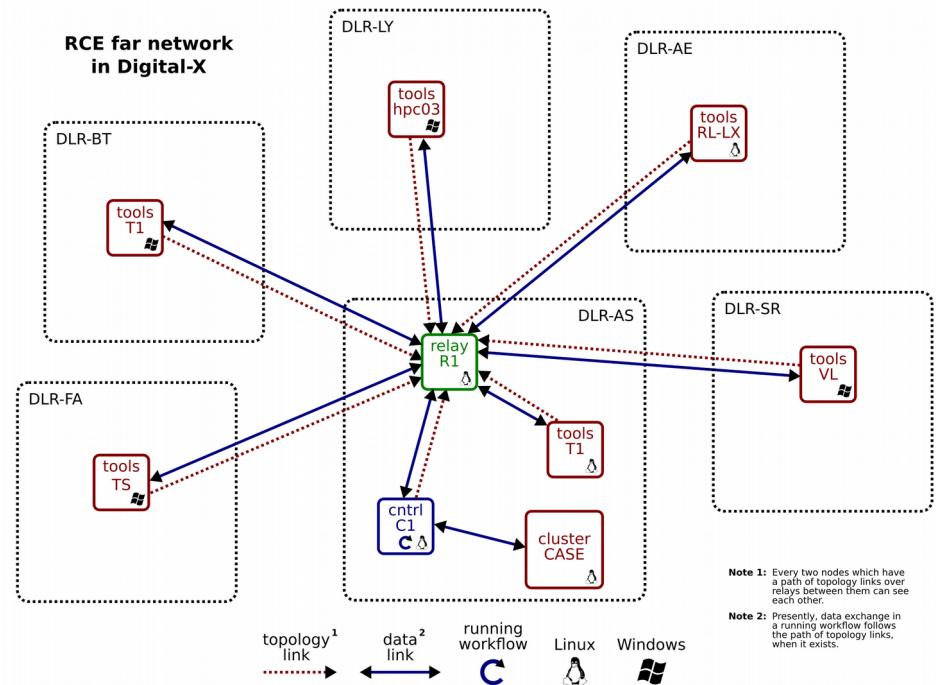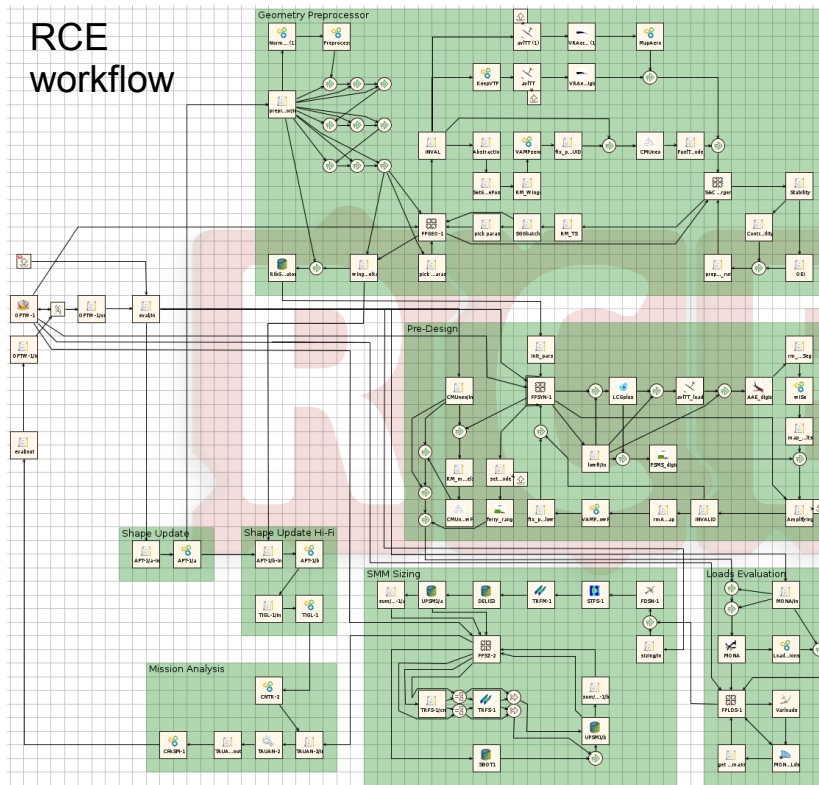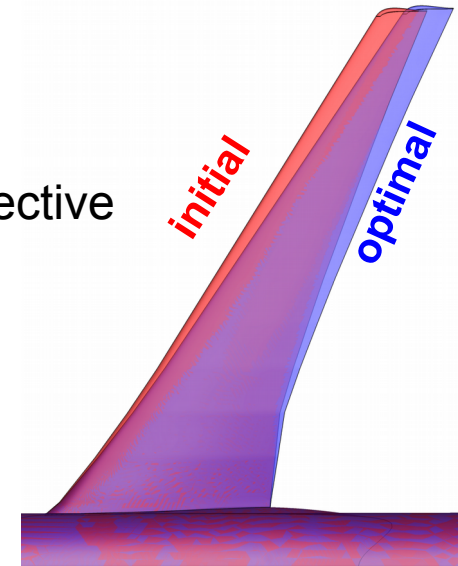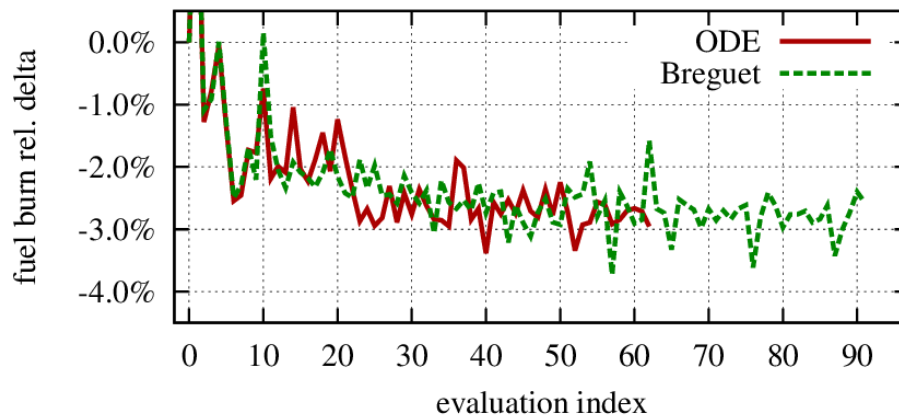

➢ 28 hours *single evaluation* run time

➢ 80-120 evaluations needed (est.)

➢ **4 months** *optimization* run time

DFO results

➢   *...still running*

➢   Results from the high-fidelity level alone

  ➢   Tested ODE- vs. Breguet-based fuel burn objective

➢   Fuel burn reduction: 3.6%

➢   18/12 hours evaluation ODE/Breguet

➢   **45 days** for optimization (*clean*)

➢   ODE- and Breguet-based
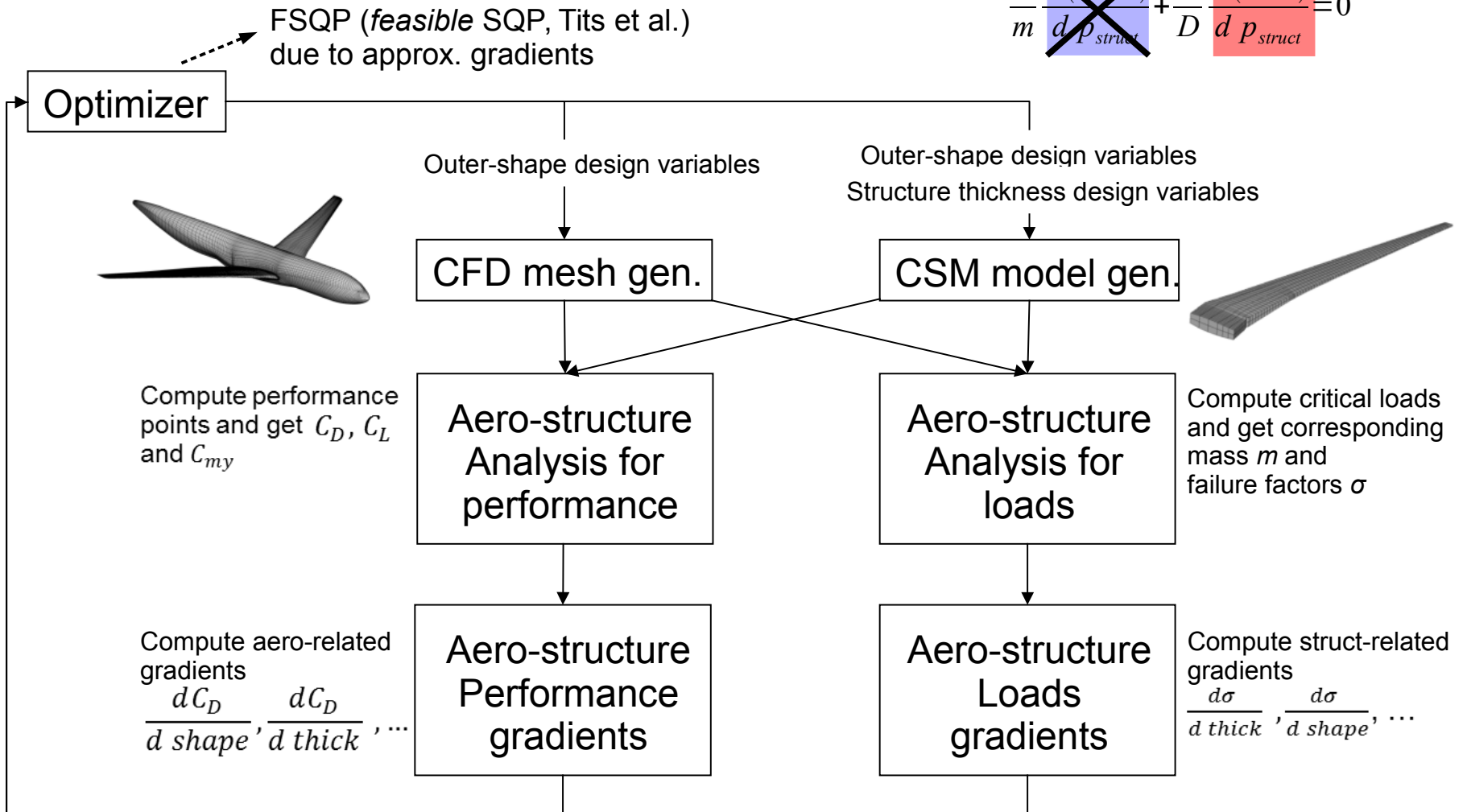final designs practically identical
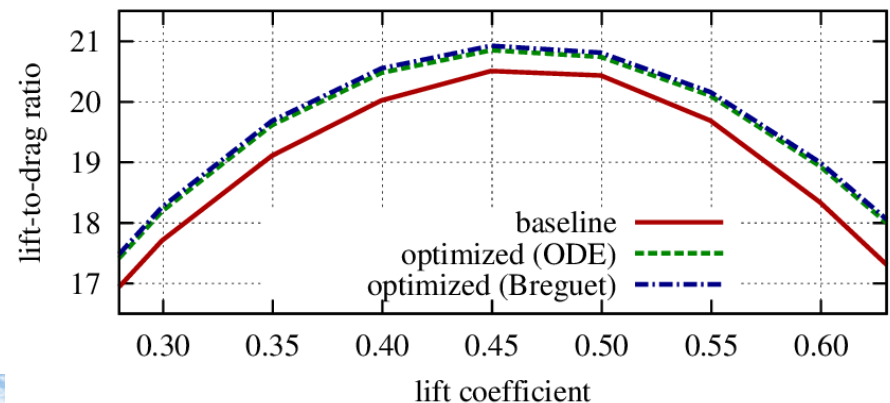
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GBO high-fidelity concept

$$\frac{1}{m}\frac{d(L/D)}{d\,p_{aero}} + \frac{L}{D}\frac{d(1/m)}{d\,p_{aero}} = 0$$

$$\frac{1}{m}\frac{d(L/D)}{d\,p_{struct}} + \frac{L}{D}\frac{d(1/m)}{d\,p_{struct}} = 0$$

FSQP (*feasible* SQP, Tits et al.)
due to approx. gradients

Optimizer

Outer-shape design variables

Outer-shape design variables
Structure thickness design variables

CFD mesh gen.

CSM model gen.

Compute performance
points and get C_D, C_L
and C_{my}

Aero-structure
Analysis for
performance

Aero-structure
Analysis for
loads

Compute critical loads
and get corresponding
mass m and
failure factors σ

Compute aero-related
gradients
$\dfrac{dC_D}{d\,shape}, \dfrac{dC_D}{d\,thick}, \cdots$

Aero-structure
Performance
gradients

Aero-structure
Loads
gradients

Compute struct-related
gradients
$\dfrac{d\sigma}{d\,thick}, \dfrac{d\sigma}{d\,shape}, \cdots$

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Optimization problem for GBO

- ➢ Optimize wing w.r.t. Breguet range factor
- ➢ Wing-body geometry: Airbus XRF-1 baseline, metal structure
- ➢ RANS for aerodynamics, FEM for structure
- ➢ 7 critical load cases; 2.5g, -1g
- ➢ 5 performance points; 1 design + 4 near off-design (Ma=0.83, CL=0.50)
- ➢ 360 airfoil-shape parameters: free-form deformation (FFD) control points
- ➢ Planform constant (by FFD c.p. only z-coord.)
- ➢ LE radius constant (by linking FFD c.p.)
- ➢ Lift constant (by flow solver internal iteration)
- ➢ Pitching moment constant (by optimizer)
- ➢ 348 structural thickness parameters
- ➢ Buckling and strength failure factors
- ➢ 348×7×2=4872 structural constraints (by optimizer)

GBO results

➢ Range factor reduction: 6%

➢ Optimization run time **80 hours**, using 8×24 cluster cores
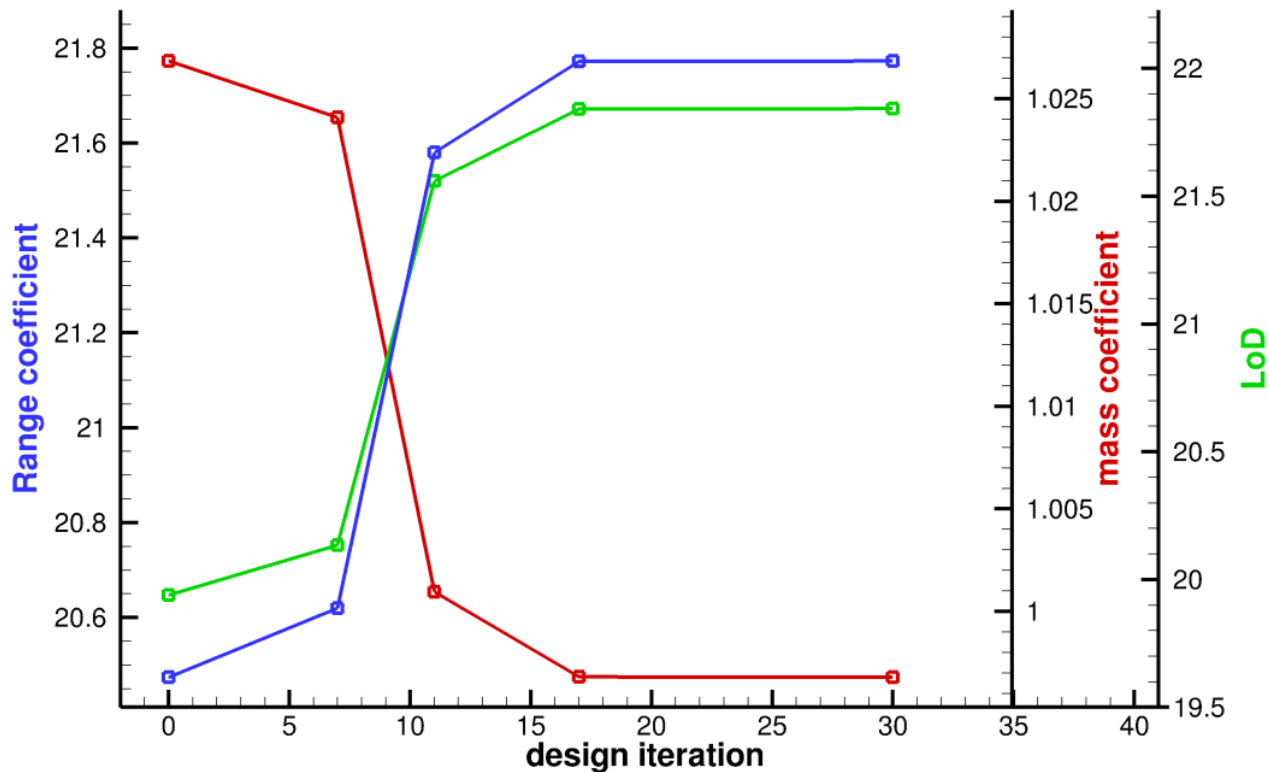
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Conclusion and Outlook

➢ Demonstrated employment of established disciplinary evaluation methods in a multi-disciplinary optimization context

➢ Demonstrated direct cooperation of experts from multiple disciplines in establishing and running optimization process

➢ Follow-on project: **VicToria**

➢ Include more subsystems (flutter-free design, active engines...)

➢ Increase cross-subsystem and cross-level consistency

➢ Reduce process run times

➢ DFO in two phases: overall aircraft design, detailed subsystem design

➢ GBO with cross-disciplinary sensitivities

Thank you for your attention!

DFO results, cont.

➢ Spanwise load distribution more inwards → smaller wing mass

➢ Shocks more forward, slightly weaker → better lift-to-drag ratio