APPLICATION OF AERODYNAMIC AND AERO-STRUCTURAL OPTIMIZATION FOR ENERGY EFFICIENT AIRCRAFT

Institute of Aerodynamics and Flow Technologies

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Contributions from:

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Institute of Aeroelasticity: T. Klimmek, W. Krüger

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OF THE INTERNATIONAL COUNCIL
OF THE AERONAUTICAL SCIENCES
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ICAS 2022 SWEDEN

DLR

Outline

- Motivation
- Methods
- MDO: High Aspect Ratio Wing
- MDO: Powered Aircraft
- Conclusion and Outlook

MOTIVATION

Motivation: Energy-Efficient Aircraft

- Today's aircraft are very matured
- EU Green Deal: climate-neutral, silent aviation

Laminar A/C (All)
Aspect Ratio 12-15
UHBR-Engines
Sensors & AI

* Source:
Beck, Landa, Seitz, Boermans, Liu, Radespiel
Drag Reduction by Laminar Flow Control
Energies 2018, 11, 252.

- DLR has adapted and extended aeronautical strategy
- Digitalization, MDA/O and energy-efficient aircraft are key elements

Motivation: Energy-Efficient Aircraft

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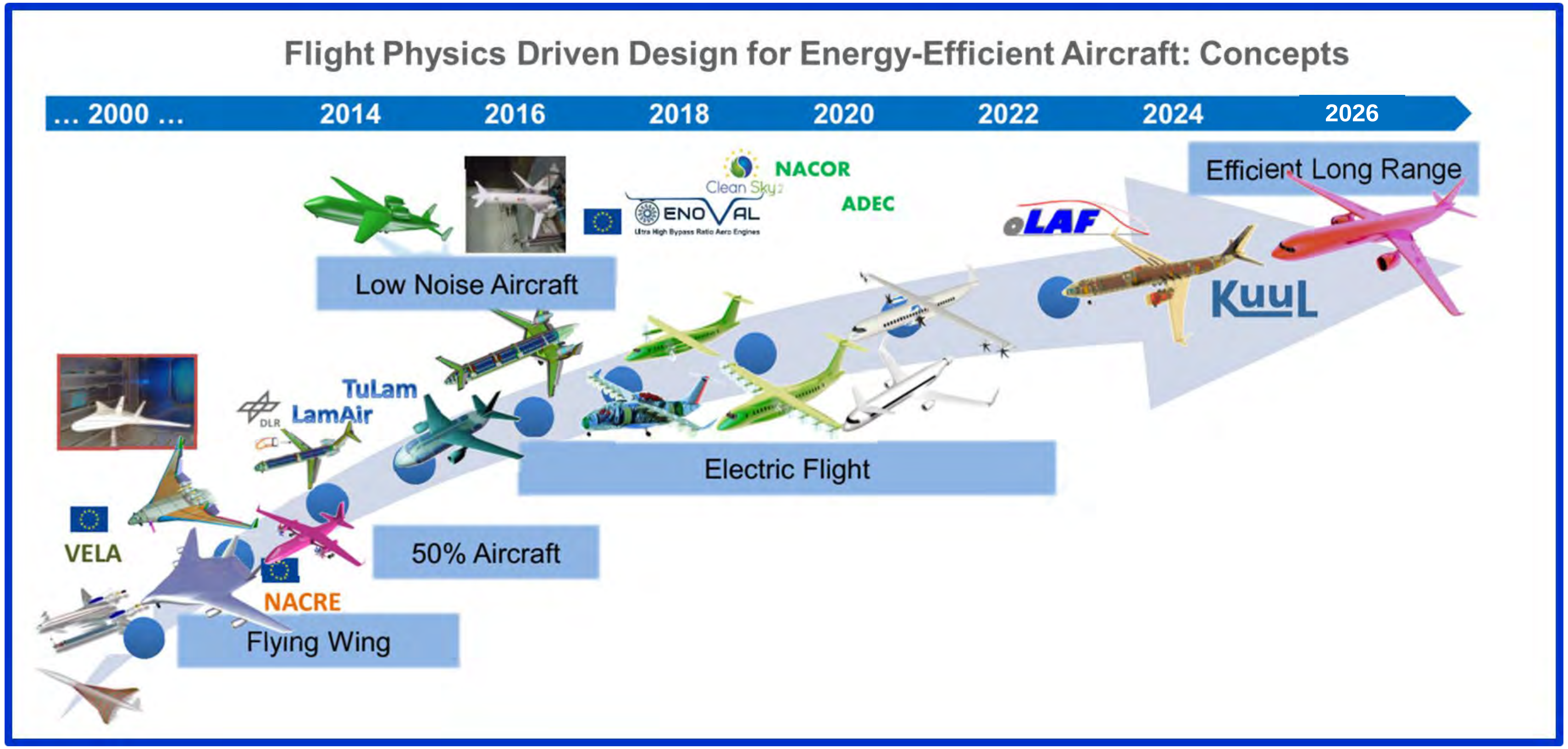

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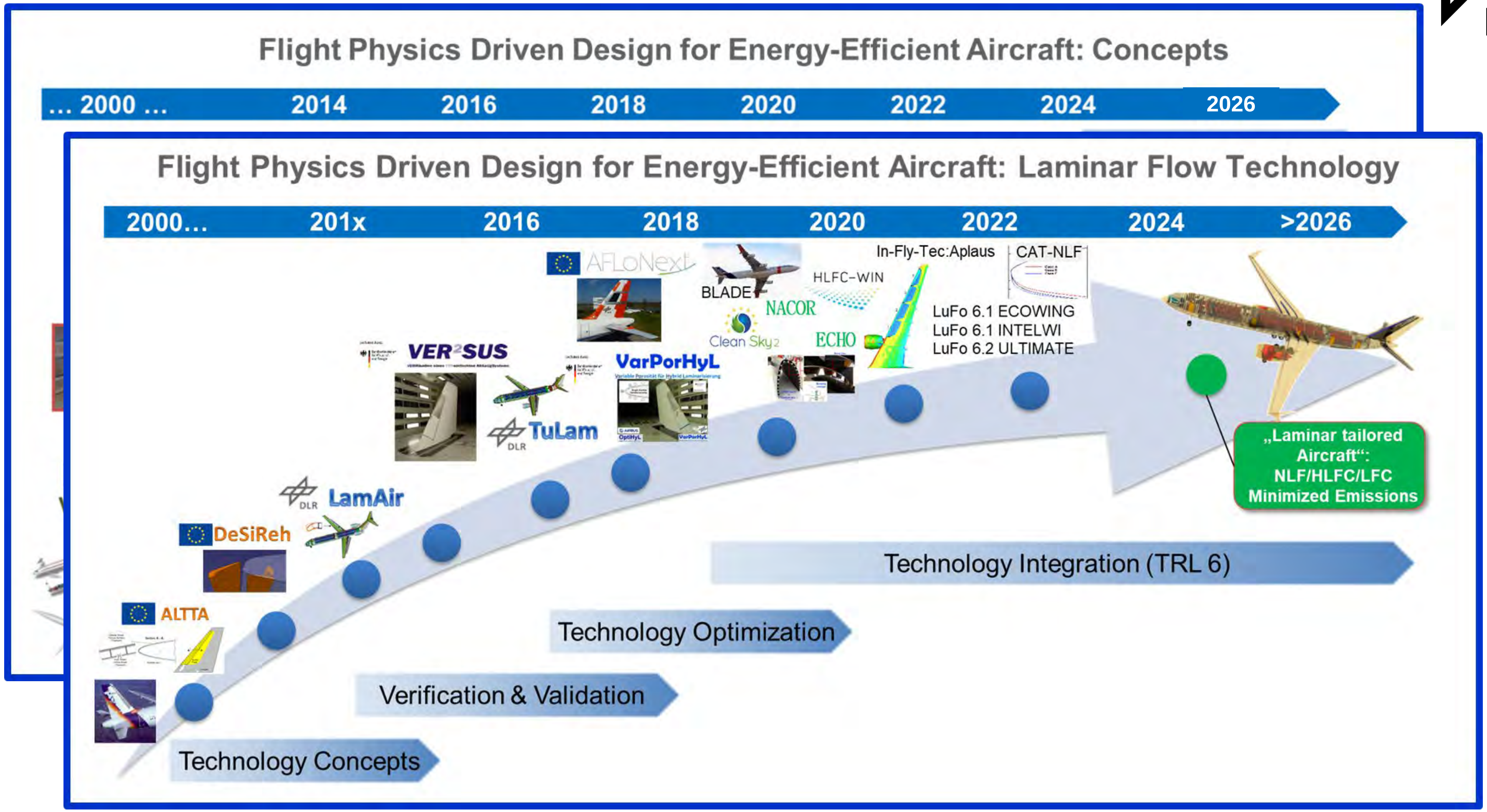

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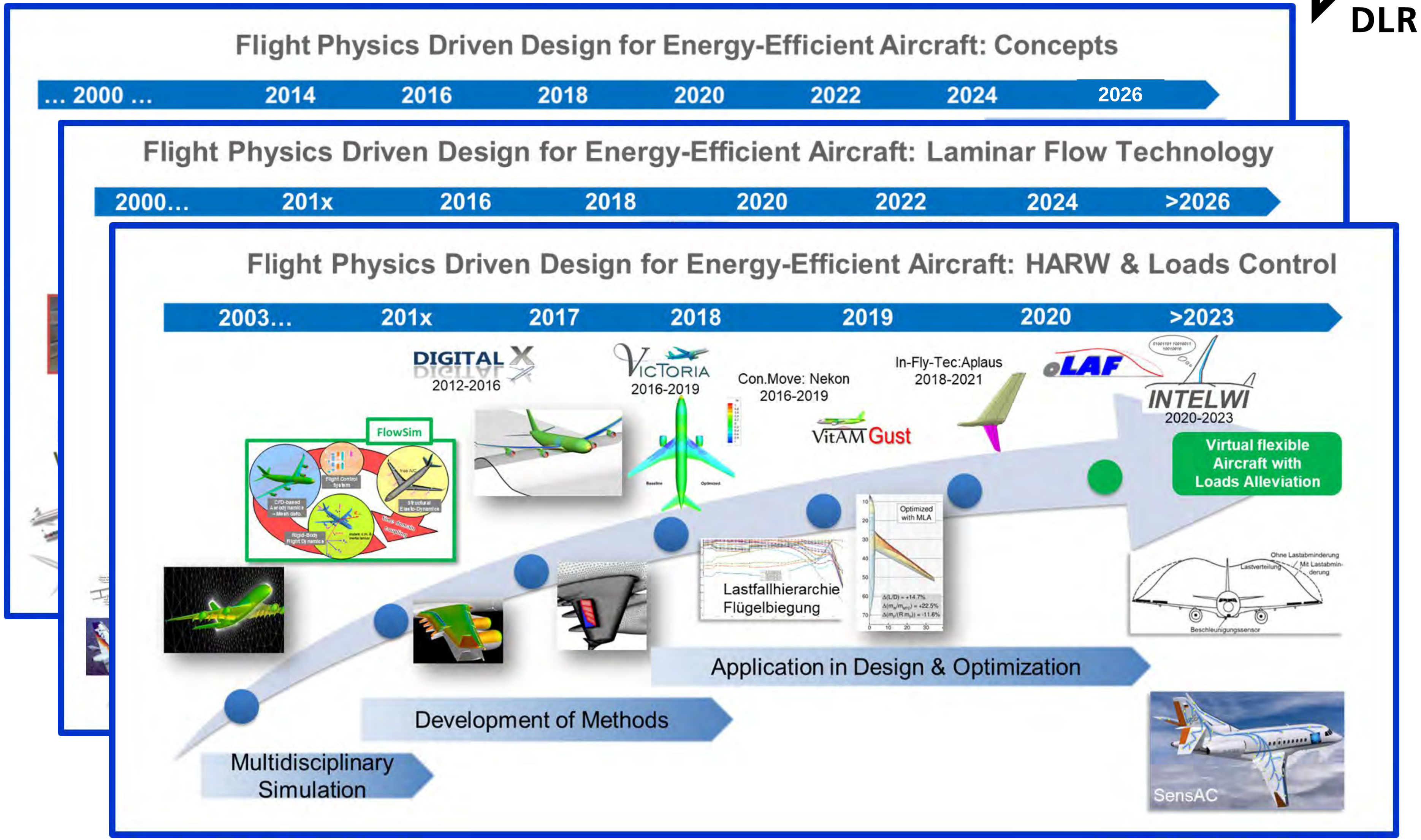

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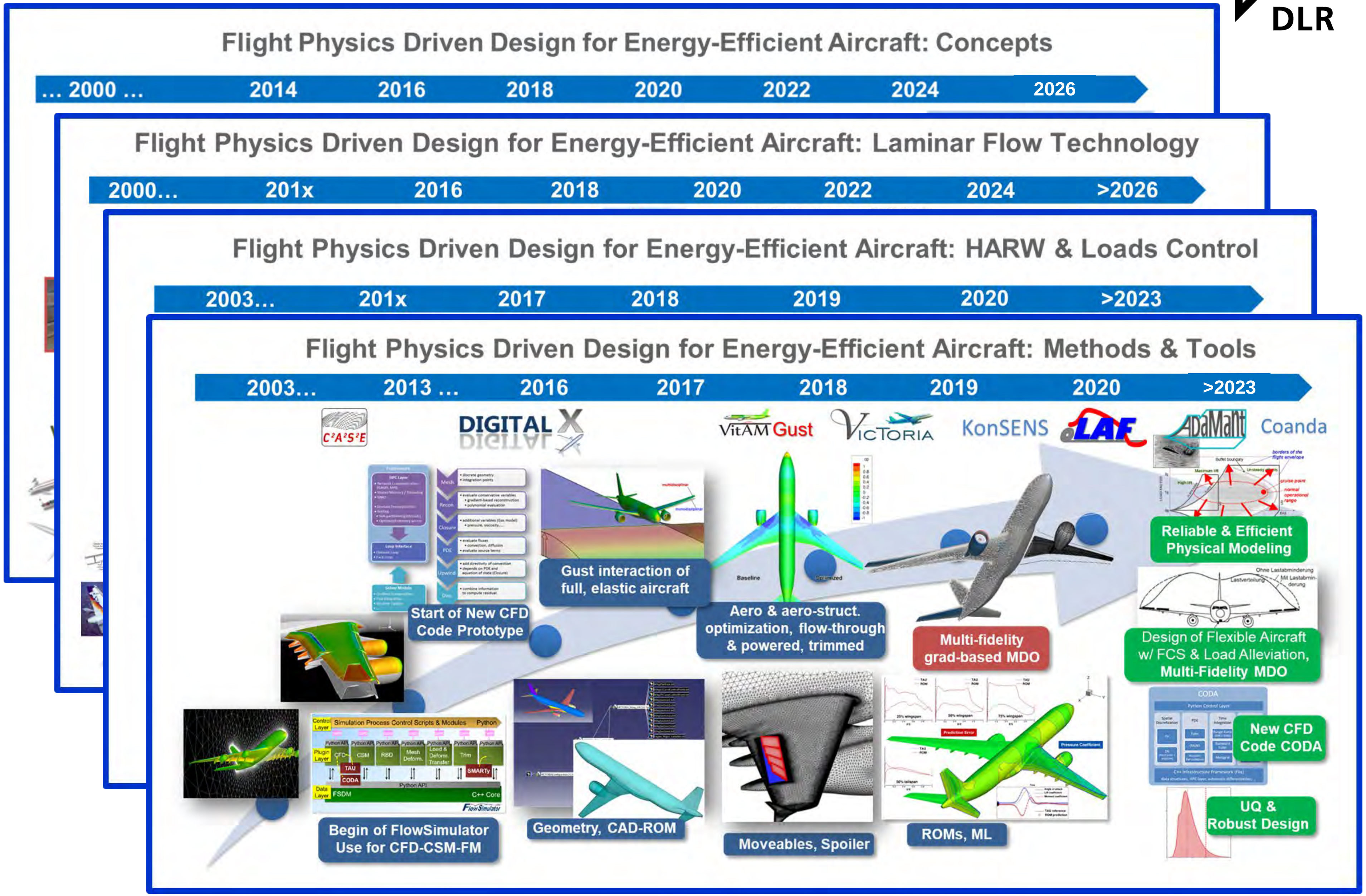
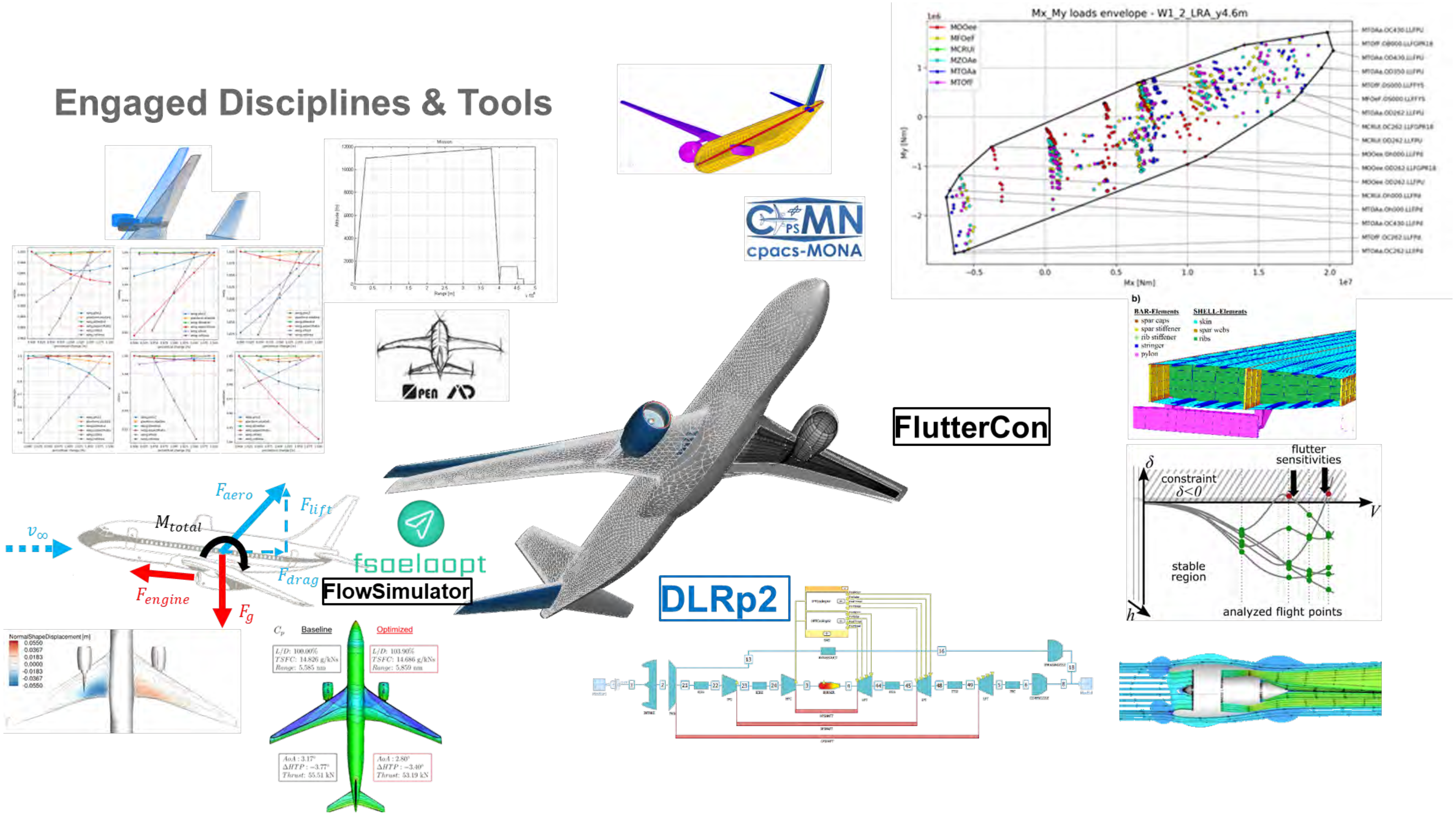


METHODS

Methods

Development & Application of MDA/O Processes



Methods
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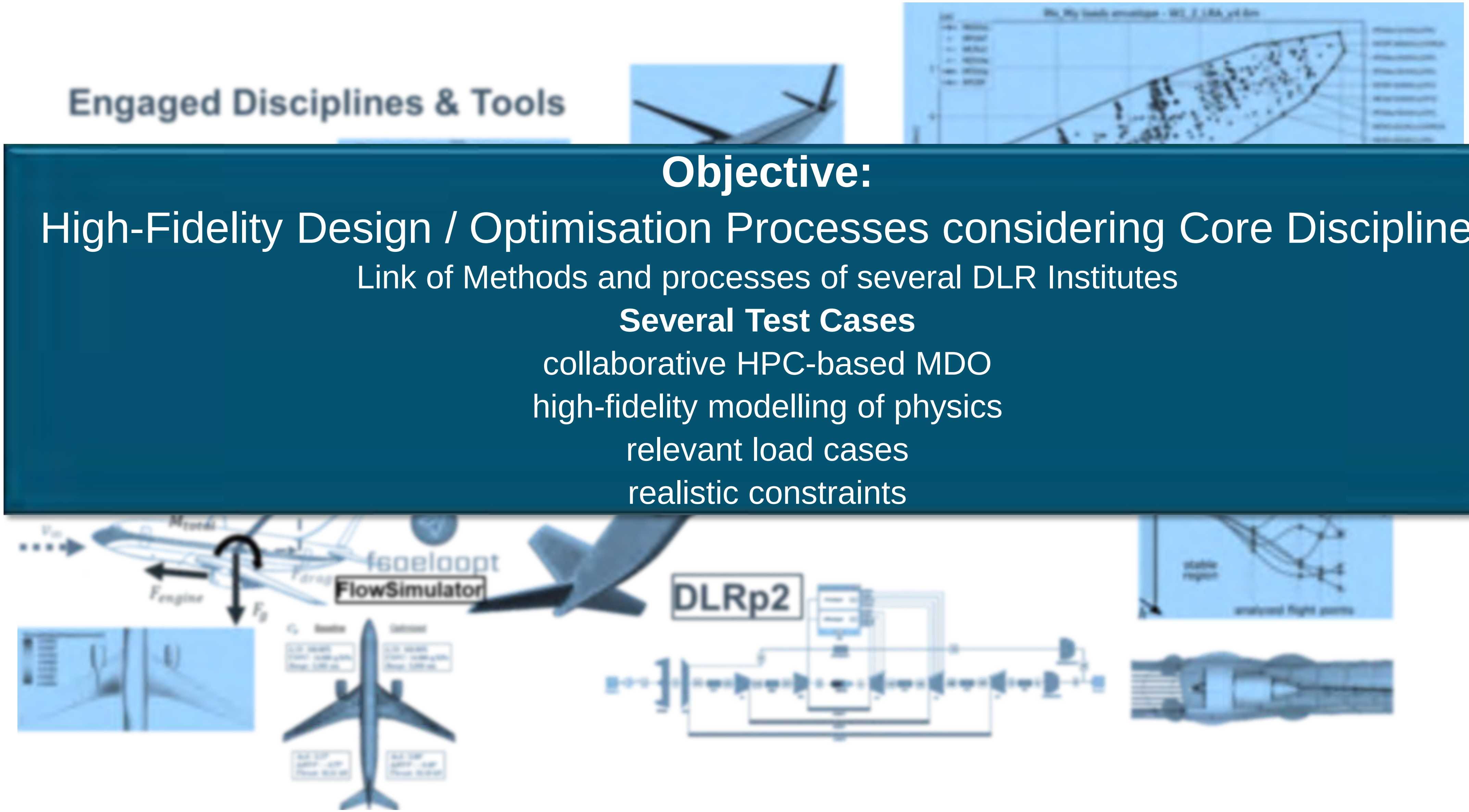


Objective:

High-Fidelity Design / Optimisation Processes considering Core Disciplines

Link of Methods and processes of several DLR Institutes

Several Test Cases

collaborative HPC-based MDO

high-fidelity modelling of physics

relevant load cases

realistic constraints

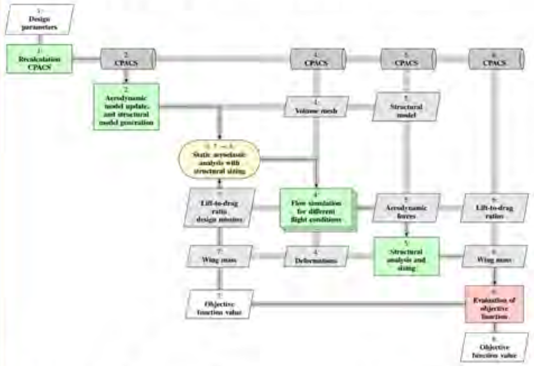
Methods

Development & Application of MDA/O Processes

DLR

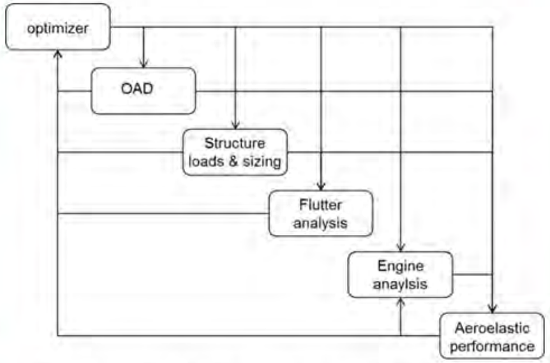
Explore and evaluate highly parallel „multi-level“ MDO strategies, addressing different needs w.r.t. run-time, problem definition & setup time, computational rescources and fidelity

Integrated Aero-Structural Wing Optimization



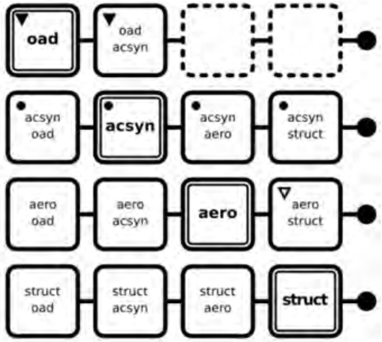
- Global, **gradient-free** optimization, sequential
- Commercial hi-fi tools, TAU
- CFRP modeling & sizing
- Constraints
- **Highly flexible wing**
- **Loads alleviation**

Multi-Fidelity Gradient-Based Approach



- Cross-disciplinary sensitivities
- Direct handling of constraints (e.g. flutter)
- **Quick trade studies**

Many Discipline Highly-Parallel Approach



- Synthesis of disciplinary optimization
- Simultaneous, interleaved execution, „one-shot“ appr.

- Comprehensive set of design load cases, many design parameters
- Powered, trimmed a/c, aluminum

T. Wunderlich: AIAA 2020-3170

M. Abu-Zurayk: AIAA 2020-3167

C. Ilic: AIAA 2020-3169

DLR

MDO: HIGH ASPECT RATIO WING

MDO: High Aspect Ratio Wings

LuFo-6.1 Project INTELWI

"Investigations of high aspect ratio, load adaptive, ultra-efficient and intelligent wings"

Supported by:
Federal Ministry for Economic Affairs and Climate Action
on the basis of a decision by the German Bundestag

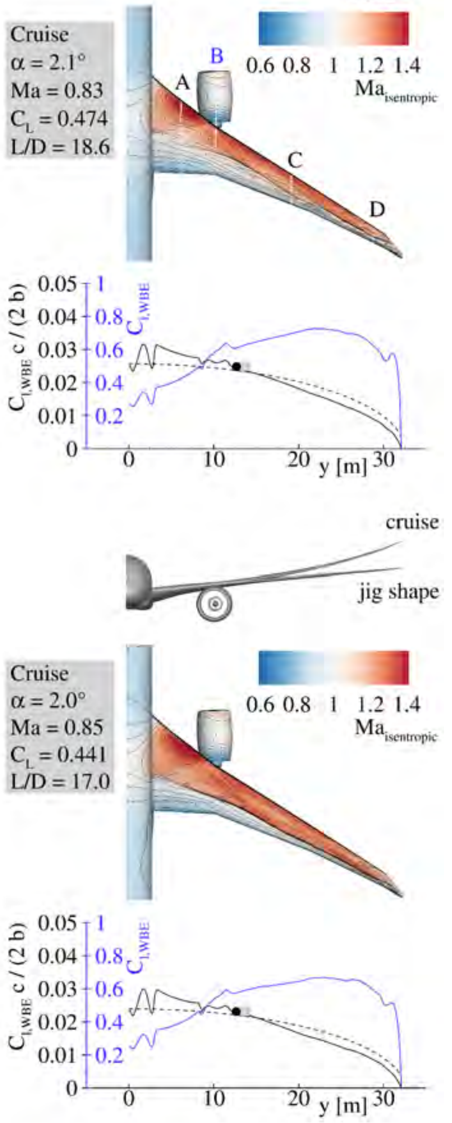
DLR

Objectives

- Development of MBSE-architectural frameworks on OAD-level with technologies for load alleviation
- Development and flight physics analysis of technologies for load alleviation, buffet control, flight control and wing structures
- Design of a long range passenger aircraft with high aspect ratio, load adaptive, ultra-efficient and intelligent wing
- Plan form, aspect ratio pre-defined

Status and Results

- First version of OAD process with maneuver load alleviation
- Combined aero-structural wing and inverse wing airfoil design of the reference aircraft (planform with aspect ratio of 12.4)
- Multipoint optimization of flight performance using control surface deflections



MDO: High Aspect Ratio Wings

DLR Project oLAF "optimally Load-Adaptive Aircraft"

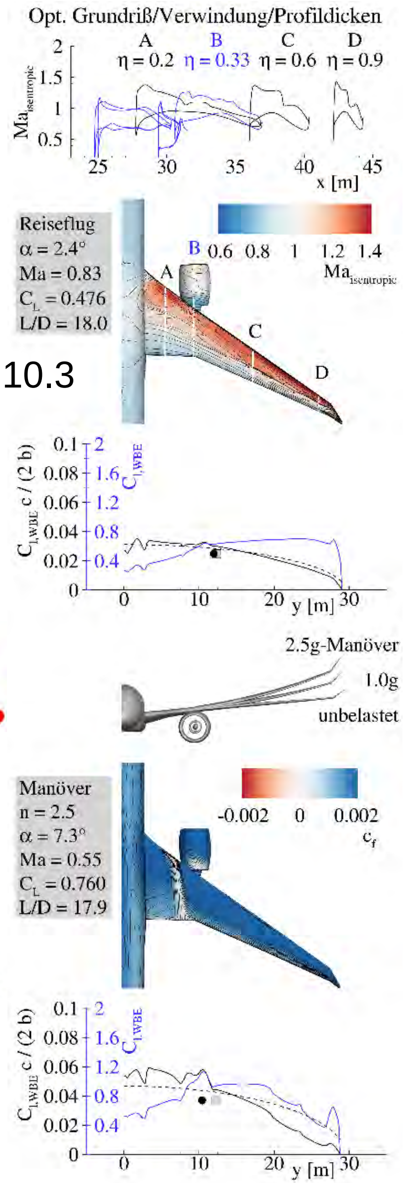
Objectives

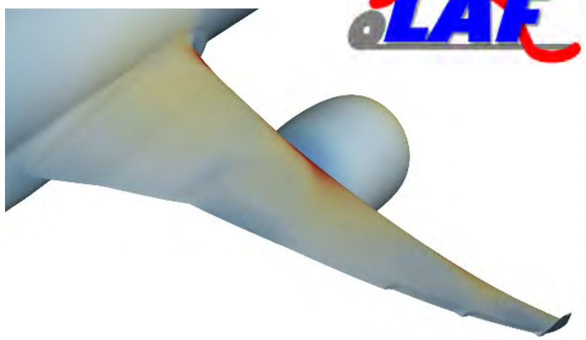
- Development of a multi-fidelity aircraft design and optimization process with integrated load adaptation
- Development and assessment of innovative concepts and technologies for load alleviation
- Design of an optimally load-adaptive aircraft and quantification of potential for efficiency improvement
- Plan form as a result

Status and Results

- Second design loop of the reference aircraft with state-of-the-art load alleviation
  - Overall aircraft design
  - Aero-structural wing optimization (planform, twist and airfoil thickness)
  - Detailed aerodynamic design and optimization (airfoil design)
  - System design
  - Load analysis and aeroelastic design
  - Detailed structure design and sizing
- Preparation phase for the selection of developed load alleviation technologies for the design of the optimally load adaptive aircraft
- Ongoing work on the design and optimization process development

AR = 10.3





MDO: High Aspect Ratio Wing

Potential of highly flexible composite wing and maneuver load alleviation on specific fuel consumption?

- Effect on wing geometry ?

Global Multidisciplinary Optimization with RANS-based CFD (TAU) and CSM (Nastran)

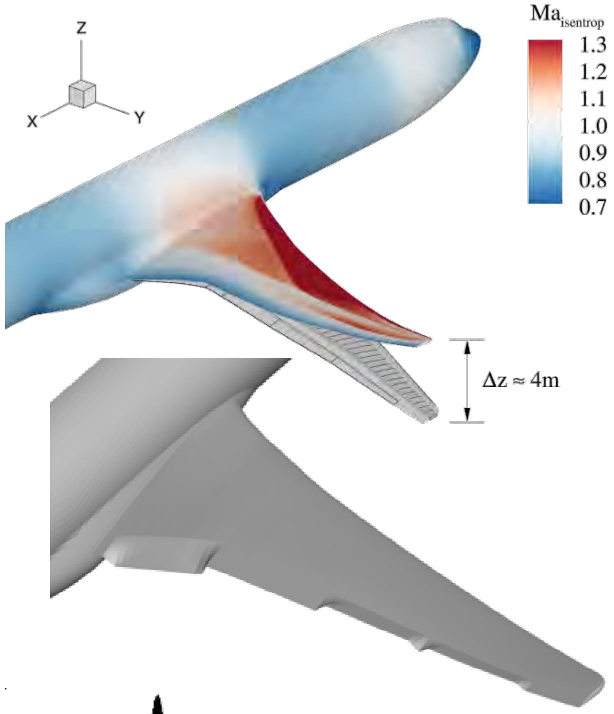
- Setup reference configuration: similar Airbus XRF-1 with optimized twist
- Optimizations for conventional stiffness
- Optimizations for increased strain allowable (planform, twist- and thickness distribution)
- Introduction of active maneuver loads alleviation
  - Optimizations for conventional stiffness
  - Optimizations for increased strain allowable

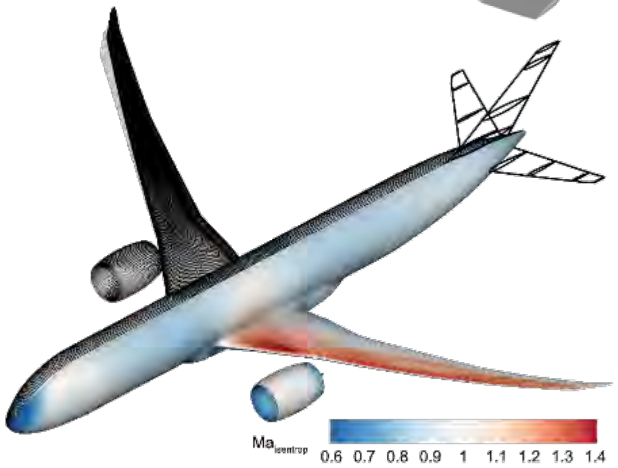
Maneuver Load Alleviation

- Trailing edge control surfaces (inner, outer, aileron)
- Lift re-distribution, shift towards inner wing, wing movement → impact HTP (handbook)

Flexible Wing

- Increased strain allowable: 3500µm/m → 5000µm/m
- Modified stringer concept





MDO: High Aspect Ratio Wing

Objective Function

- Minimization of combined fuel consumption per payload and range (3 missions)

Reference Configuration

- Generic long range aircraft similar to Airbus XRF1

Design Parameter (17 + 6 for MLA)

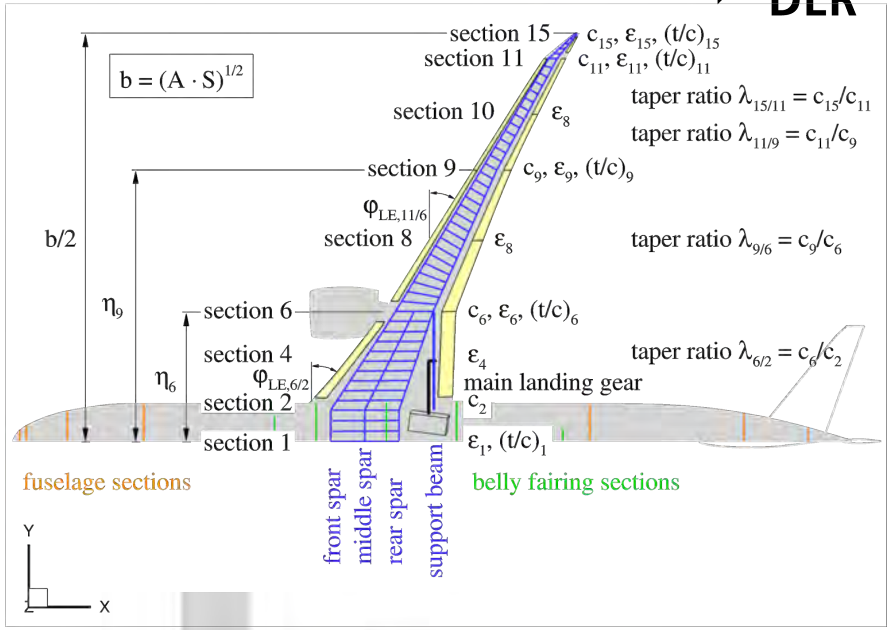
- Wing area, Aspect ratio, Leading edge sweep angle
- Taper ratios (inner, middle, outer wing)
- Twist (5 sections) and Thickness distributions (4 sections)
- Position of rear spar inner wing
- Moveables chord length, deflections

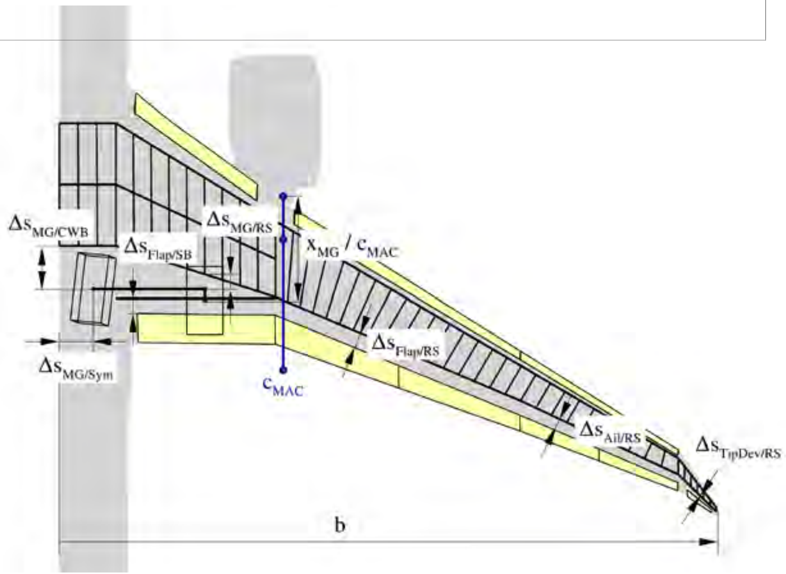
Constraints

- Max. take-off mass = constant
- Fuselage, engine masses = constant
- Leading, trailing edge specific masses = constant
- Fixed wing structural topology (spar positions, rib spacing)
- VTP/HTP sizing with volume coefficient (handbook)
- Geometric integration of landing gear and moveables
- Fixed design missions (3) and load cases (3)

Mission	Range	Ma	Payload	Weighting
Reference mission	4000 nm	0.83	40800 kg	0.6
Increased Mach	4000 nm	0.85	40800 kg	0.1
Design mission	6500 nm	0.83	$m_{MTO} - m_{OE} - m_F$	0.3

Load Case	Altitude	Ma	C_L	n_z
2.5g maneuver	0 m	0.552	0.739	2.5
-1.0g maneuver	6096 m	0.784	-0.319	-1.0
Roll maneuver	0 m	0.552	0.493	1.667





MDO: High Aspect Ratio Wing

Geometry Modelling

- Central data description (CPACS)
- Parametric CAD-Model (CATIA®)

CFD-CSM Coupling

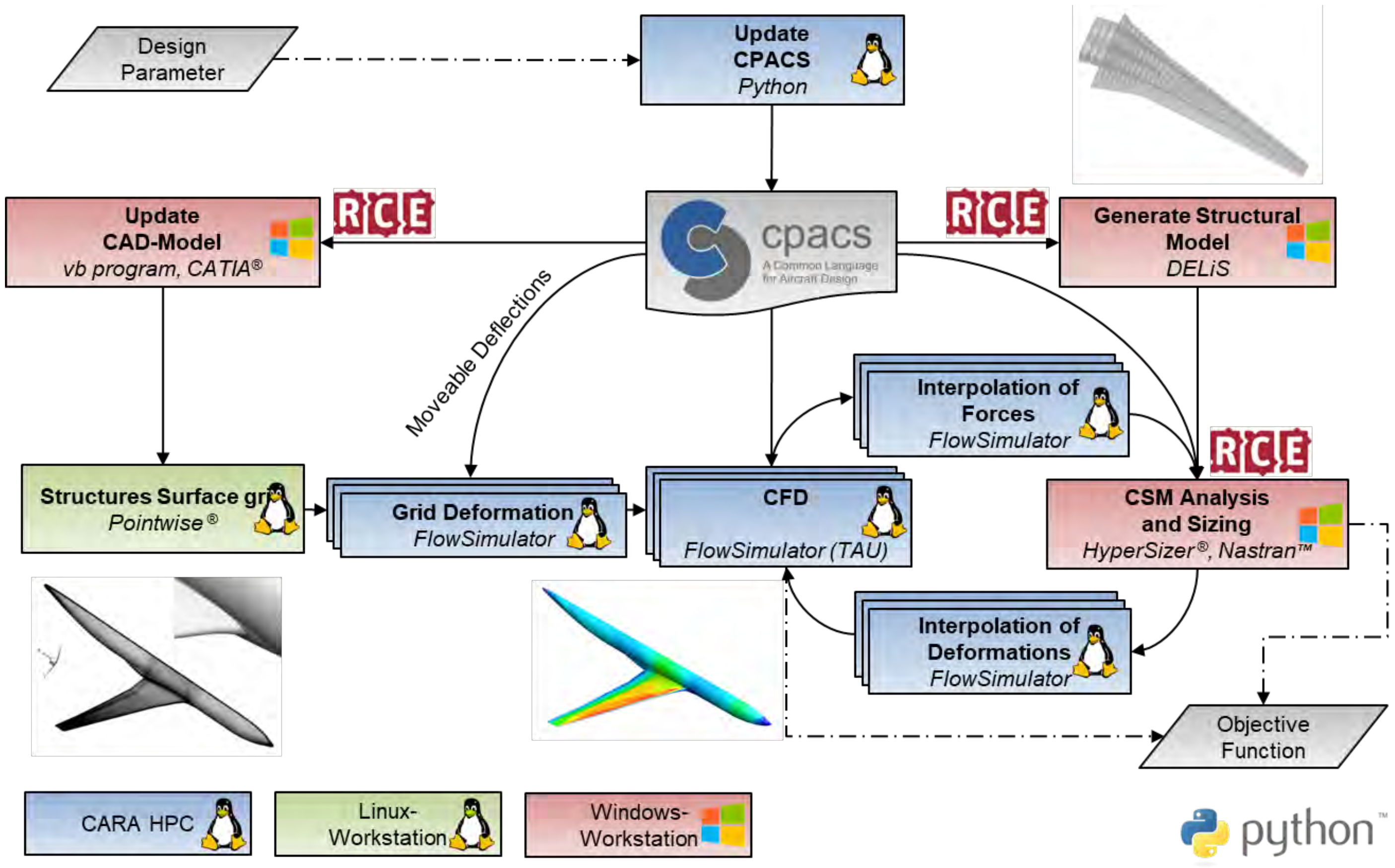
- Reynolds-averaged Navier-Stokes (DLR TAU-Code)
- Simplified moveable deflections (mesh deformation, FlowSimulator)
- CFD-CSM Coupling (FlowSimulator)

Structural Analysis and Sizing

- FEM (MSC Nastran™)
- Sizing of composite wing box (HyperSizer®)

Optimization Strategy

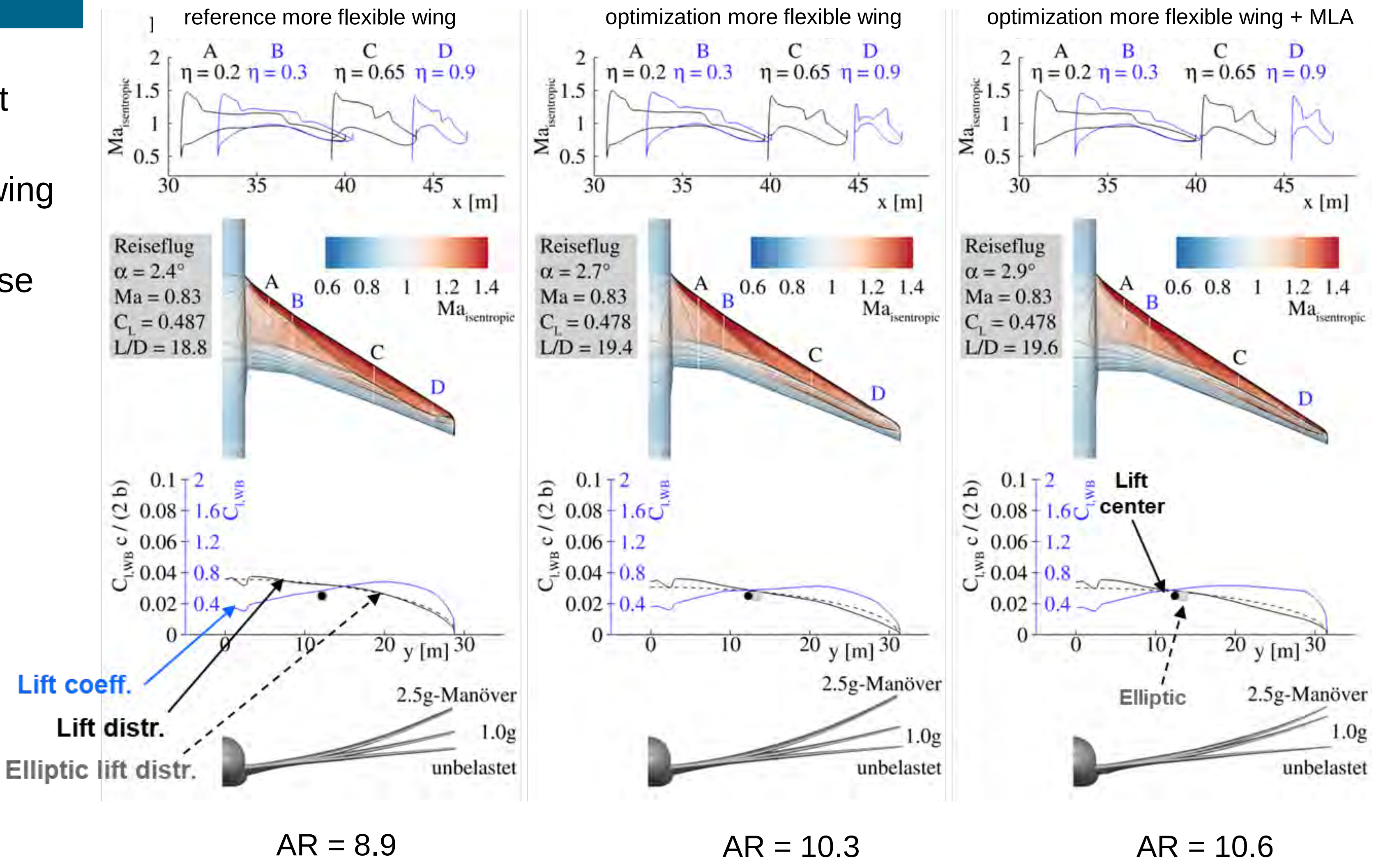
- Surrogate-based global optimization



MDO: High Aspect Ratio Wing

Aerodynamic Analysis (cruise)

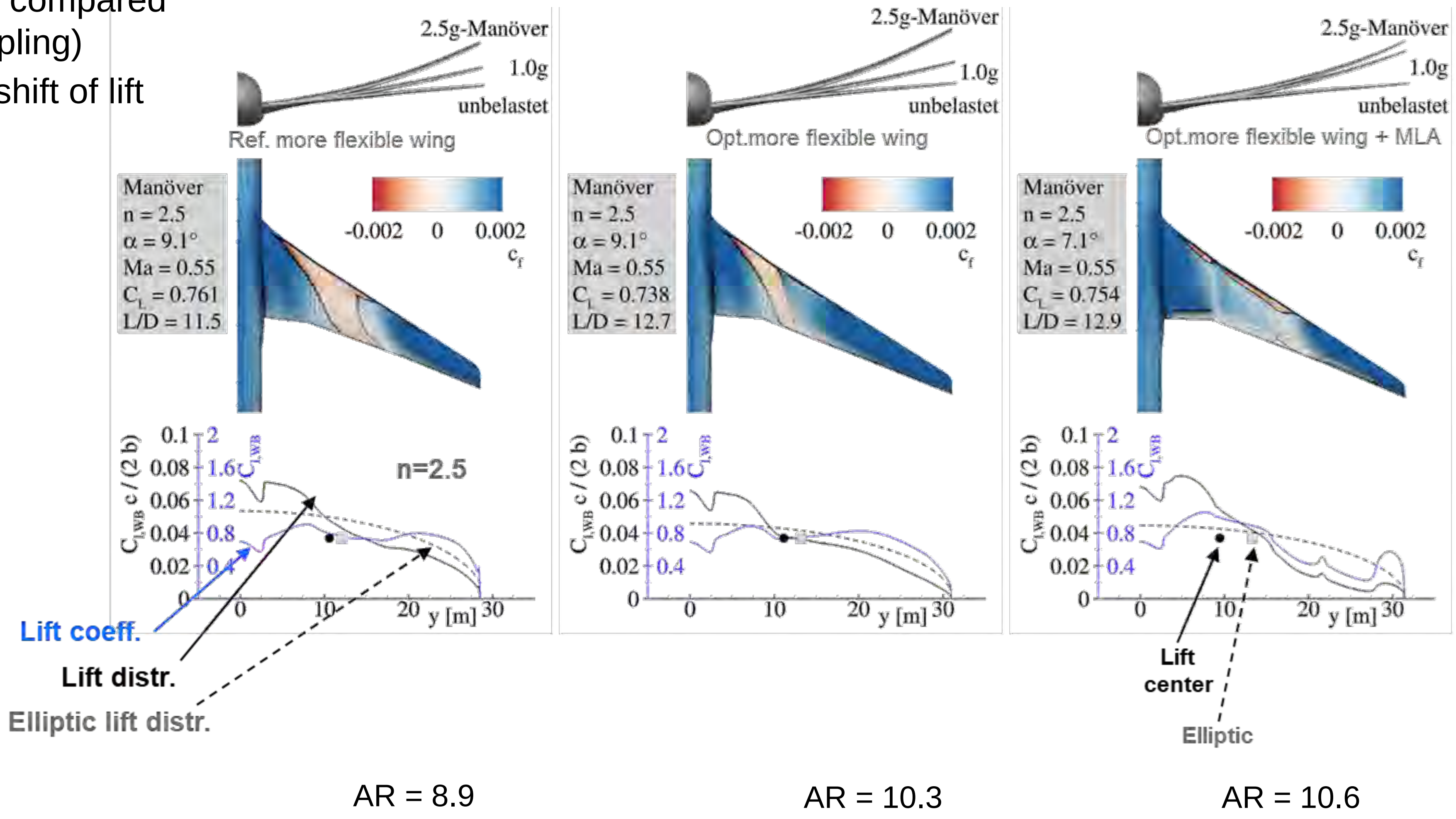
- Similar lift distribution in cruise inboard shift compared to elliptic lift distribution
- Increased lift coefficients at outer wing (increased taper ratio)
- Increased wing deformation at cruise



MDO: High Aspect Ratio Wing

Aerodynamic Analysis (maneuver)

- Lift distribution shifted inboard compared to cruise (bending-torsion coupling)
- With MLA: increased inboard shift of lift distribution



MDO: High Aspect Ratio Wing

DLR

Combined Fuel Consumption

- 2% (plan form) + 4% (MLA)
  → 6% reduction

L / D in Cruise

- 3% (plan form) + 1% (MLA)
  → 4% improvement

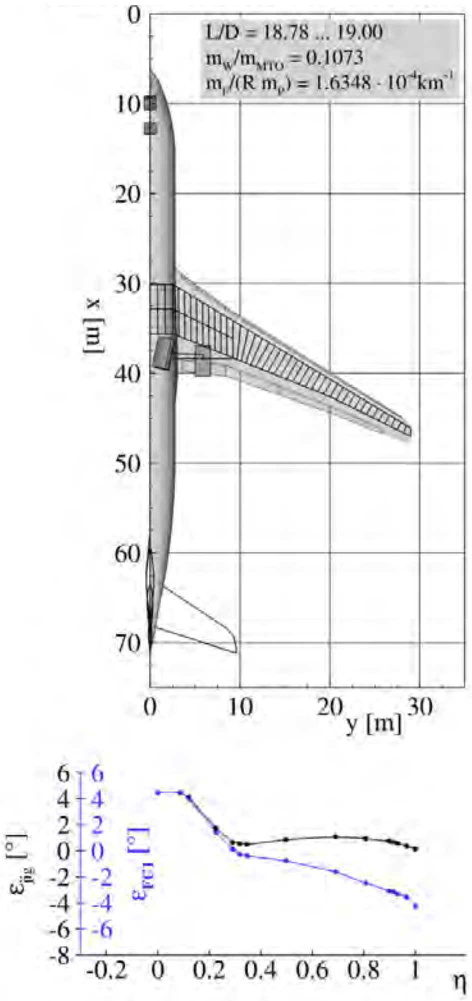
Wing Mass

- +4% (plan form), -8% (MLA, increased span)
  → 4% reduction

Wing Geometry

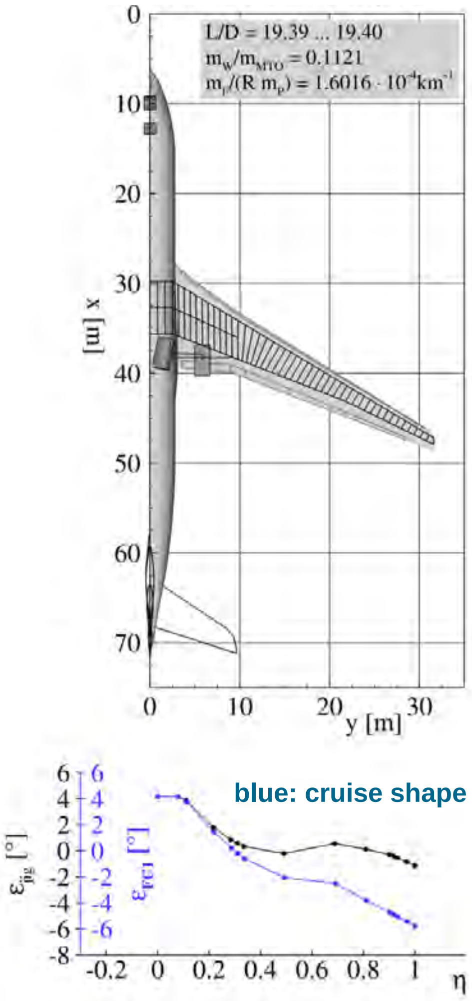
- Increased Wing Span
- Increased Taper Ratio

reference more flexible wing



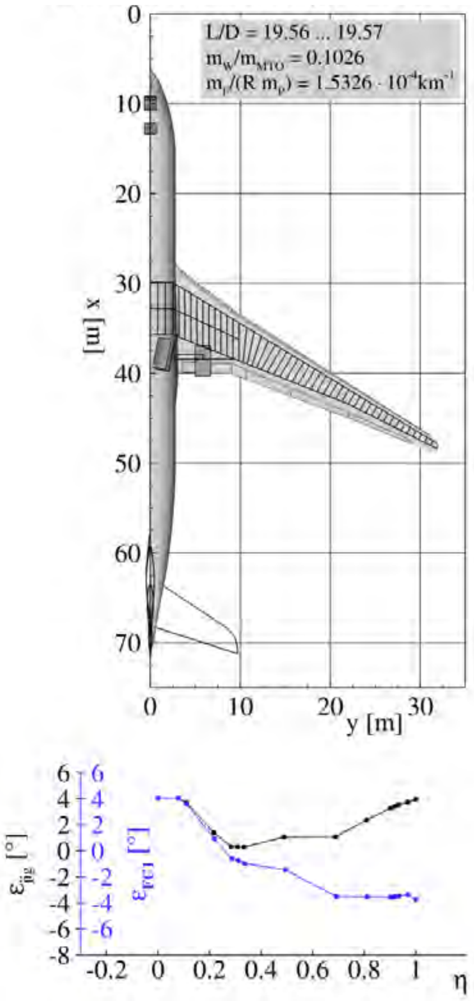
AR = 8.9

optimization more flexible wing



AR = 10.3

optimization more flexible wing + MLA



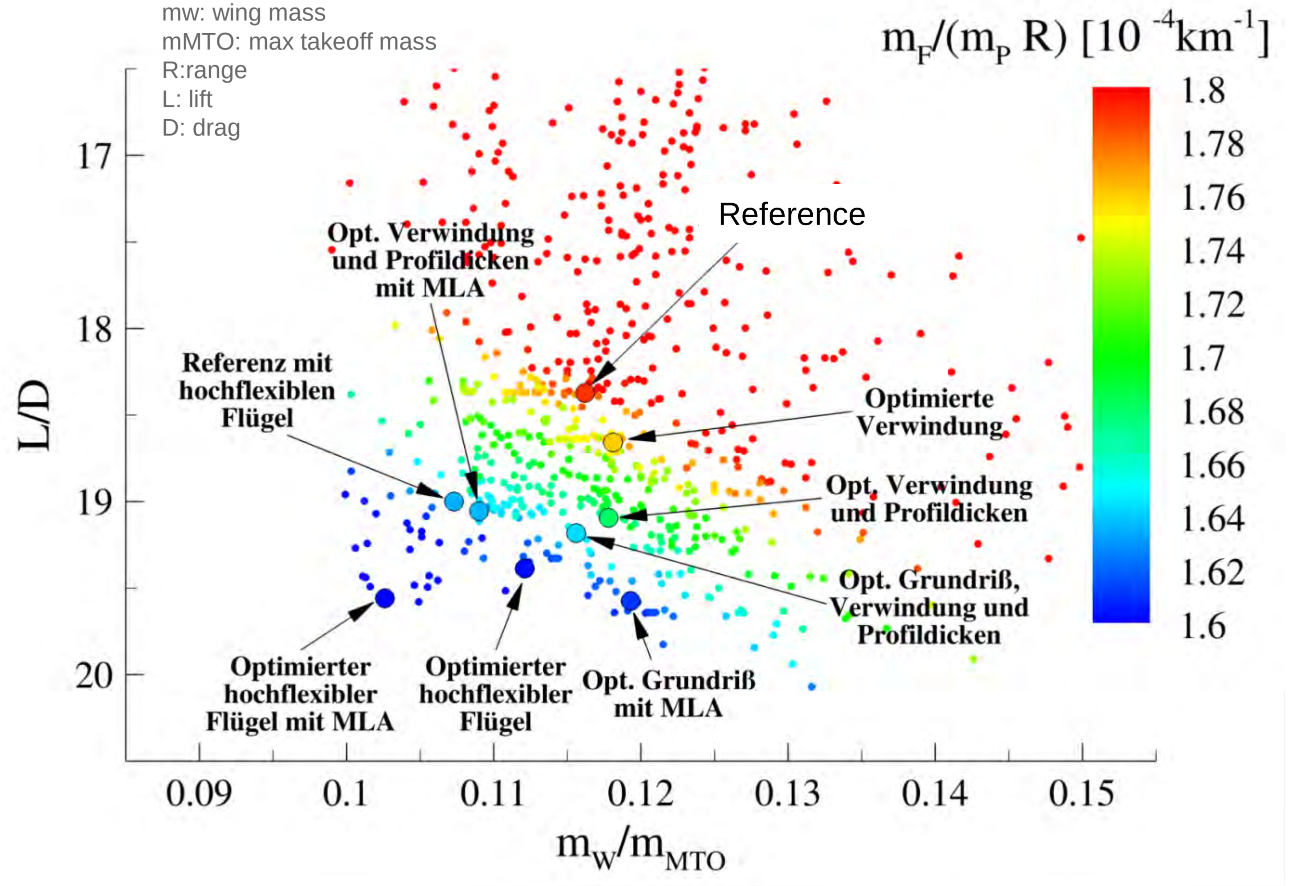
AR = 10.6

MDO: High Aspect Ratio Wing

- **Potential to reduce specific fuel consumption (3 missions)**

- Decrease relative airfoil thickness
- Wing plan form
- Highly flexible wing
- Maneuver load reduction

mp: payload
mw: wing mass
mMTO: max takeoff mass
R:range
L: lift
D: drag



MDO: High Aspect Ratio Wing

- **Potential to reduce specific fuel consumption (3 missions)**

- Decrease relative airfoil thickness
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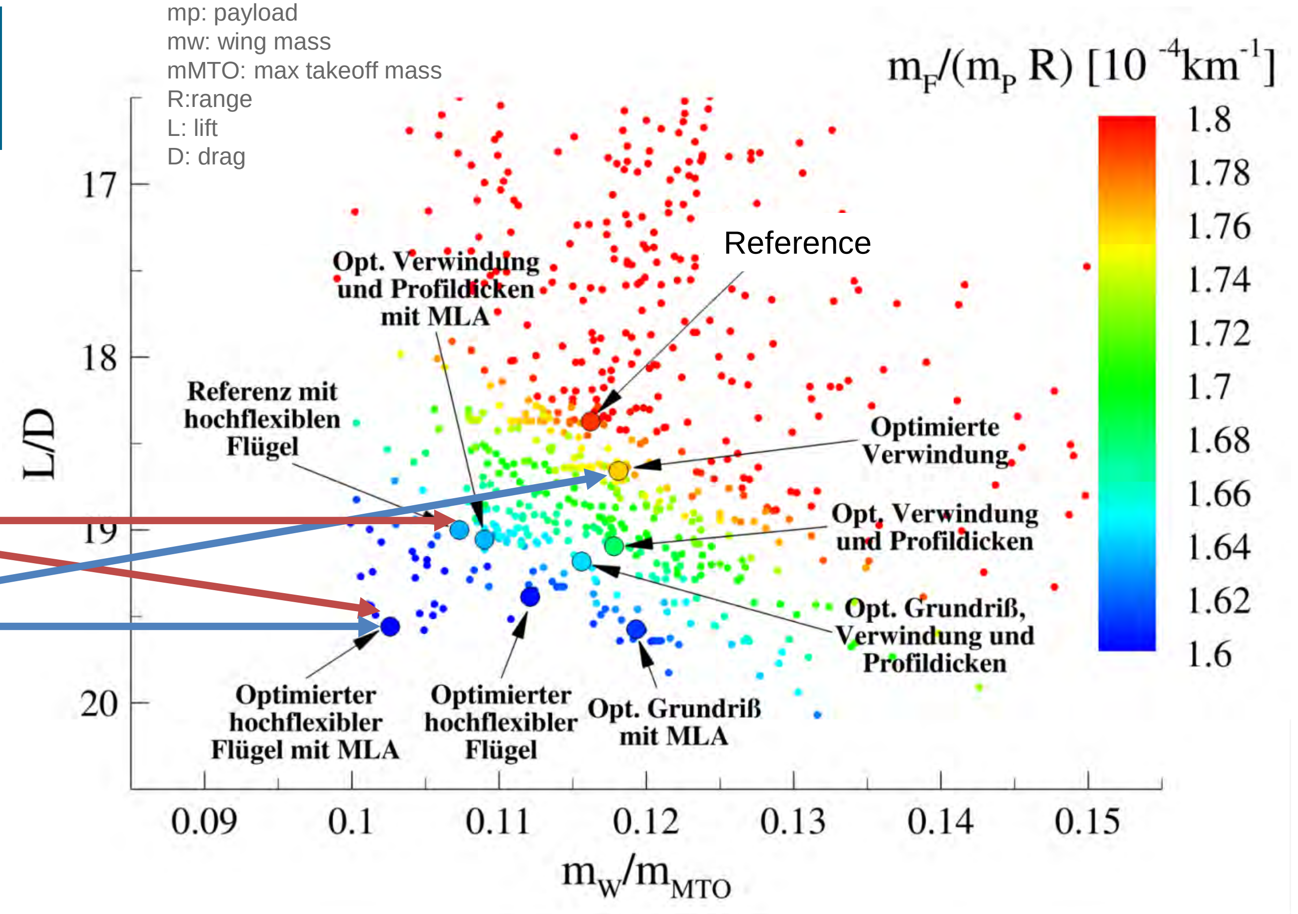
- Highly flexible wing
- Maneuver load reduction

- ≈ 6% relative to more flexible wing

- ≈ 13 % relative to Reference with optimized twist



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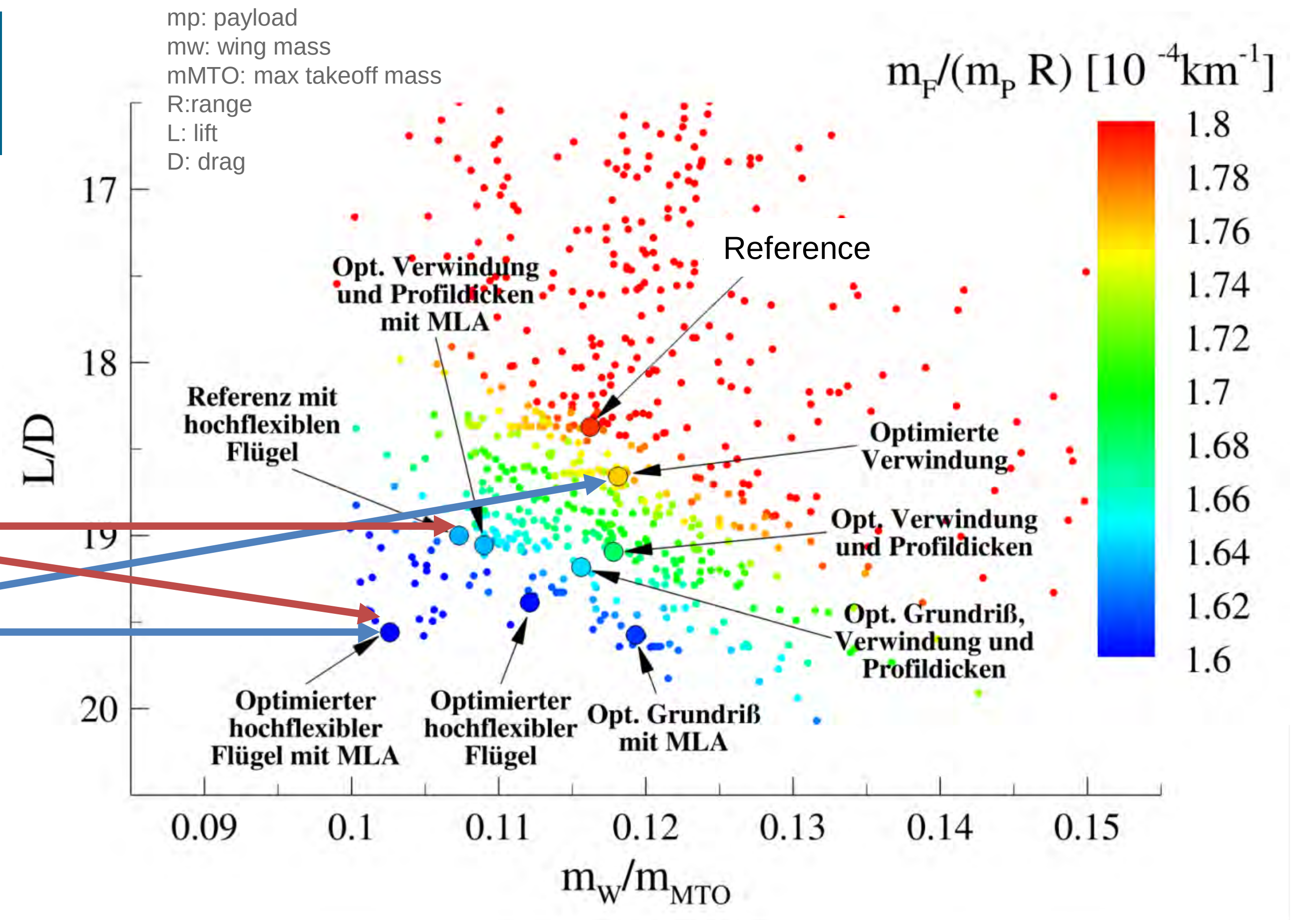


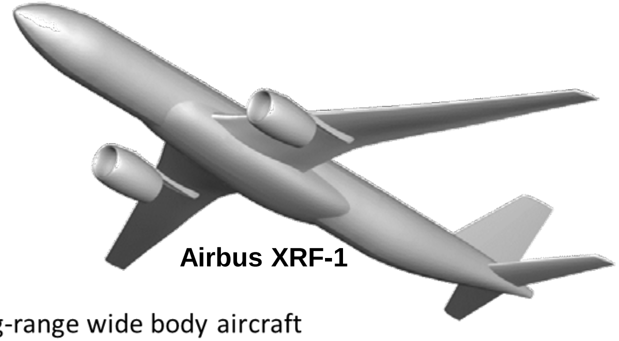
- Benefits from active load redistribution
- Landing gear and moveables integration limit design space (only 1% of the design fulfilled constraints)

MDO: POWERED AIRCRAFT

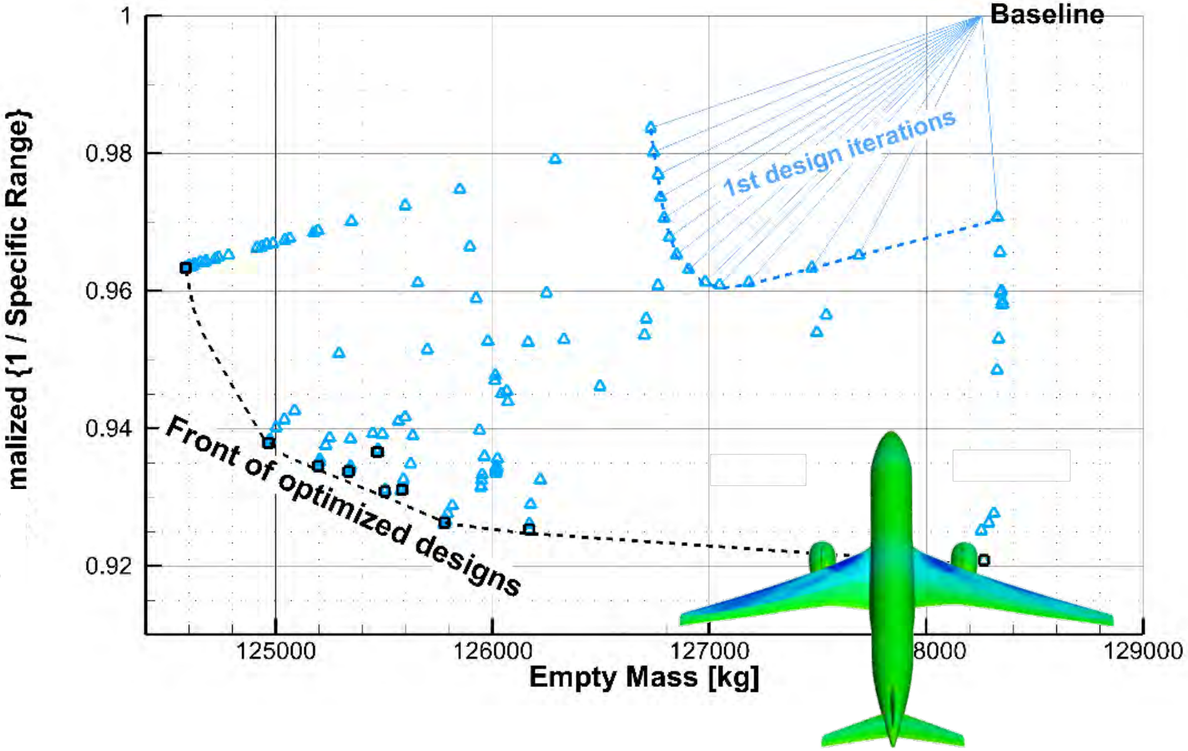
MDO: Powered Aircraft

Baseline	The full XRF-1 configuration
Objective Functions	Specific Range | Fuel Burn | Empty Mass
Optimization Algorithm	Feasible SQP
Optimization Stratigy	**Multi-point** (5 flight points) | Multi-Objective
Computational Models	CFD: 6.6M nodes | CSM: 18T nodes
Design Parameters	3 Planform | 2 chords | 11 Twists | 8 BellyFairing | 18X7:126 profiles 392 Material Thicknesses | **Total: 542**
Loads for Sizing	**6 Mass cases | 1080 load cases (low fidelity)**
OAD Constraints	Approach Speed | Take-off & Landing Field Lengths Stability Margin | Wing Span | LG Integration {Nose landing gear effectiveness | Longitudinal tip-over | Lateral tip over
Structure Constraints	Strength | Buckling >845,000 (Sequential) or ~20,000 (Concurrent)
Flight Performance Constraints	3 Trimming constraints

Performance Points / Missions					*Engine condition*
Mach 0.83 Backward CoG	Mach 0.81 Comp. CoG	Mach 0.83 Comp. CoG	Mach 0.85 Comp. CoG	Mach 0.83 Forward CoG	Powered Engine



- Generic long-range wide body aircraft
- Design Point:
  $Ma_\infty = 0.83$, h = 35,000ft, $C_L \approx 0.50$,
  design range = 5600 nm



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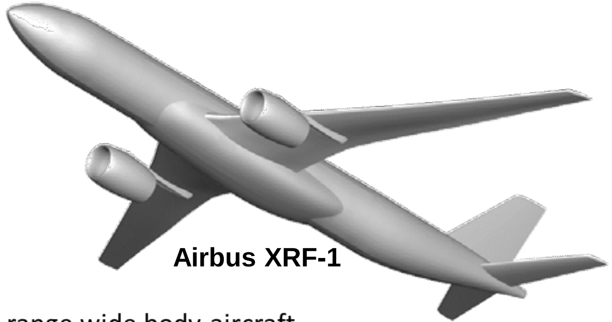

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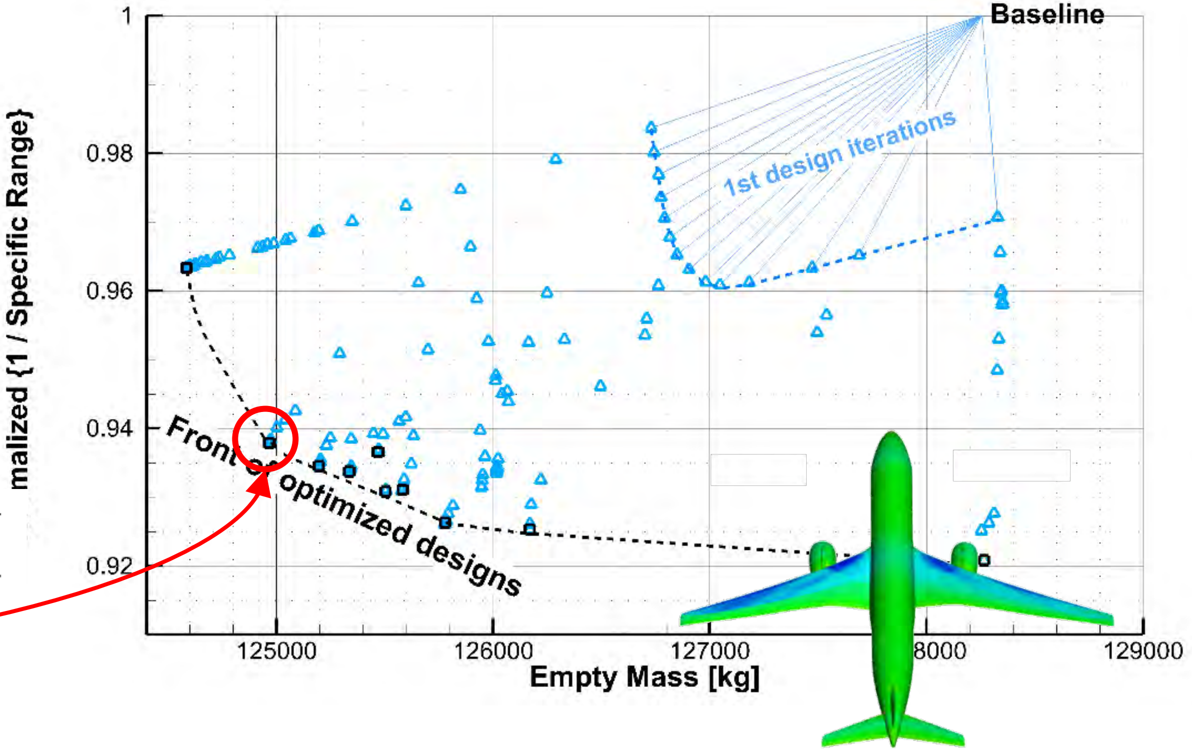

spec. fuel consumption: **≈ -6.1** %
Empty mass: **≈ -2.5 %**

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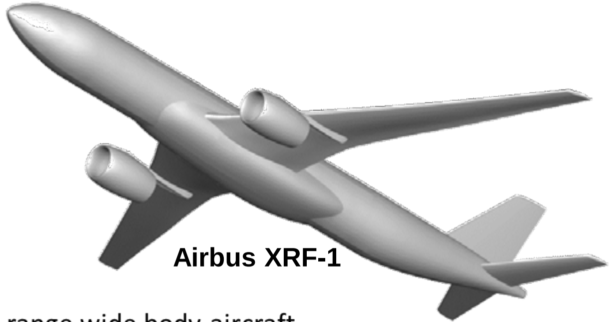

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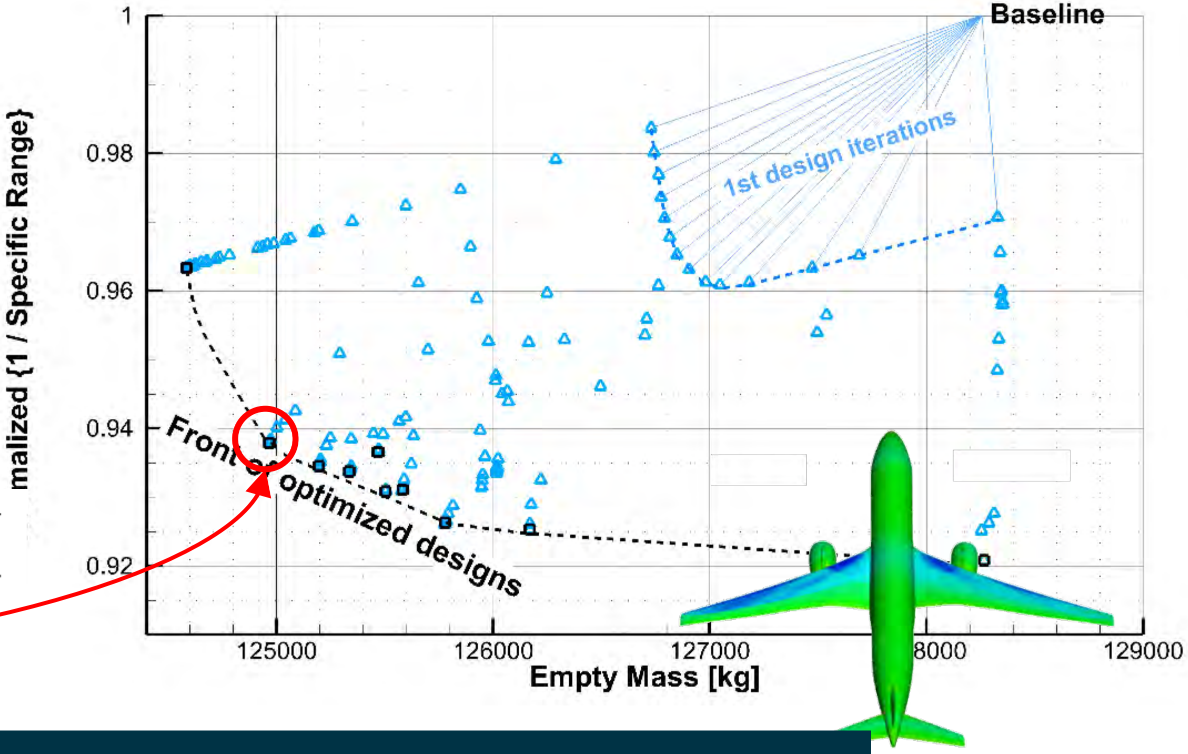


HPC Requirements:
5 flight points X **4** Cluster nodes (per flight point) X **64** cores (per node) X **14** parallel optimizations
=**17,920 cores** ; optimizations converged within **10-14 days**

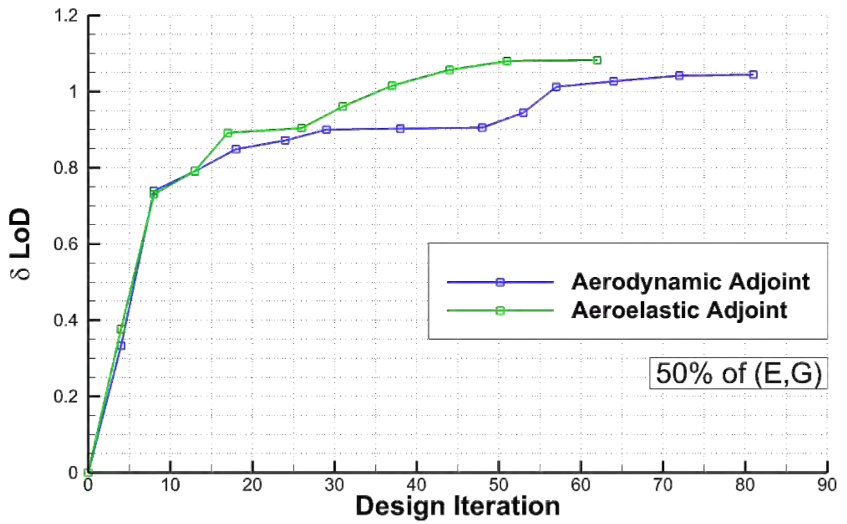
Coupled Aeroelastic Adjoint & Wing Flexibility
EU Project Madeleine

Motivation

- DLR, ONERA and AIRBUS implemented the coupled aeroelastic adjoint, employed it on the XRF-1 configuration, and realised barely any benefit, when compared to applying the aerodynamic adjoint on the flight shape

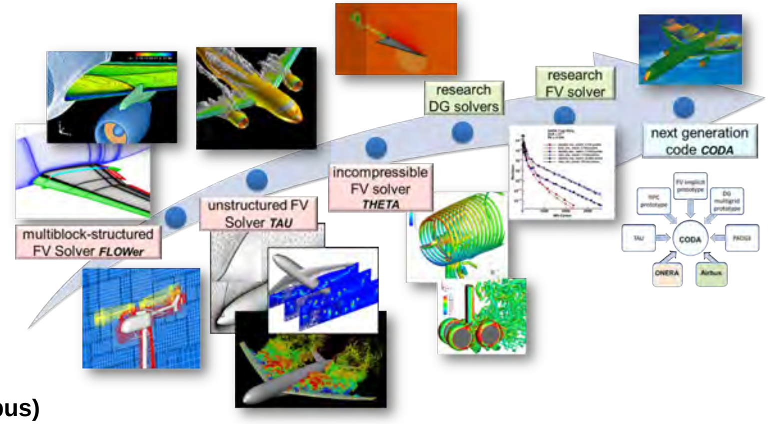
Status and Results

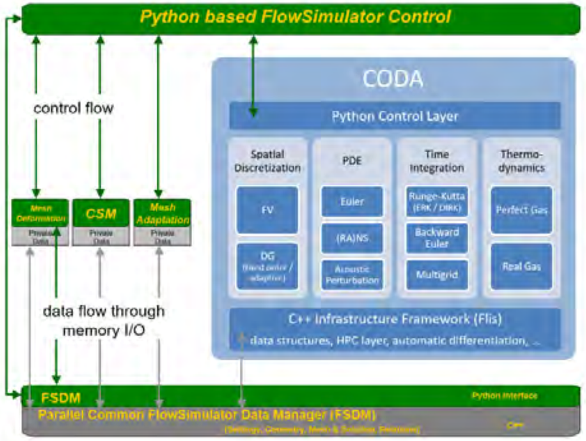
- Generate several CSM models by reducing the Young's modulus (E) and the shear modulus (G) of elasticity simultaneously until the linear theory limits are reached
- Use them in aerostructural optimizations, once while employing the aerodynamic adjoint, and once while employing the aeroelastic adjoint, always on the computed flight shape
- 100% E&G, dZ/b = 6.5% → both optimizations reach similar values
- 50% E&G, dZ/b = 10.3% → coupled aeroelastic adjoint beneficial

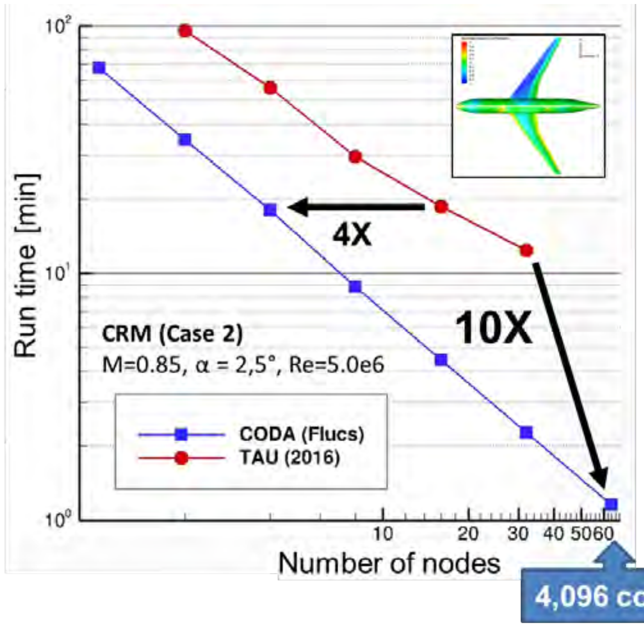


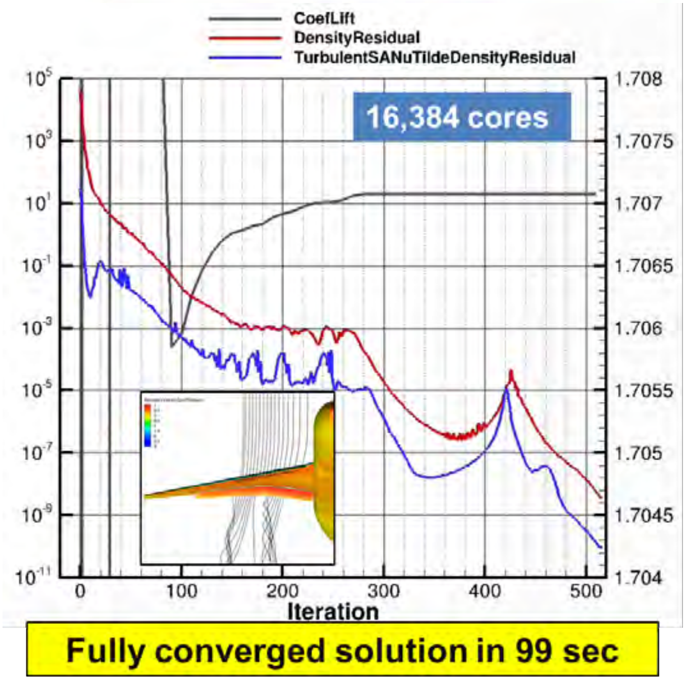
Conclusion and Outlook

- MDO Strategies and Methods
  - MDO beneficial for trade studies
  - Different needs with respect to: run-time, setup time, comp. resources and fidelity will be addressed
  - Pareto front efficiently computed >500 design variables
  - Further development and integration of FlowSimulator and CODA **(CFD for ONERA, DLR, Airbus)**
  - Native FlowSimulator Plugin (MDA/O)
  - Several new MDAO relevant features (overset, immersed BC, Rapid CFD, automatic differentiation)
  - Integration in MDA/O processes from beginning





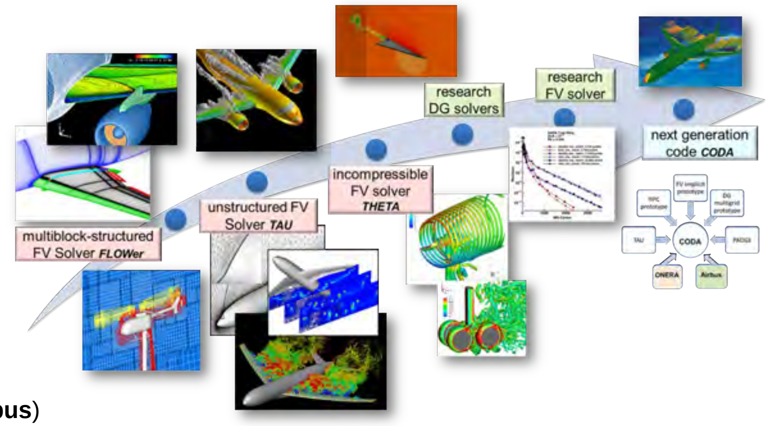


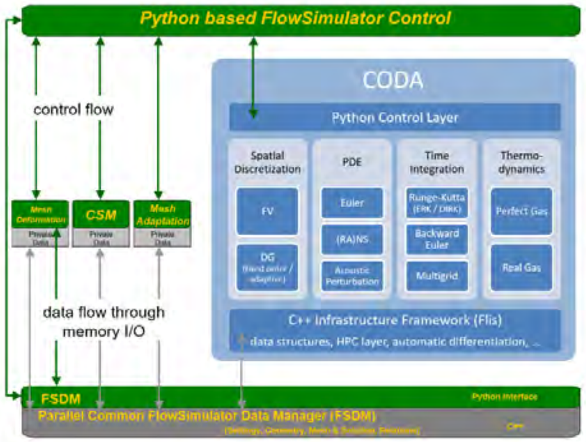


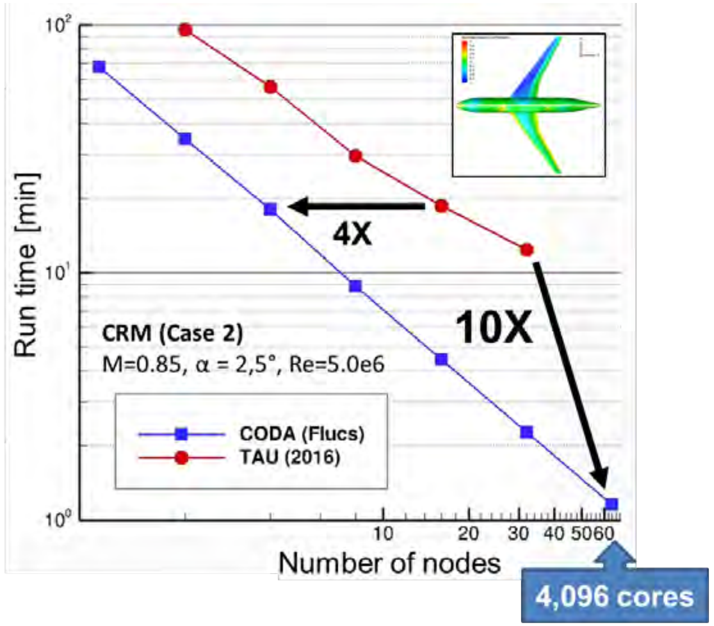
CODA is the computational fluid dynamics (CFD) software being developed as part of a collaboration between the French Aerospace Lab ONERA, the German Aerospace Center (DLR), Airbus, and their European research partners. CODA is jointly owned by ONERA, DLR and Airbus

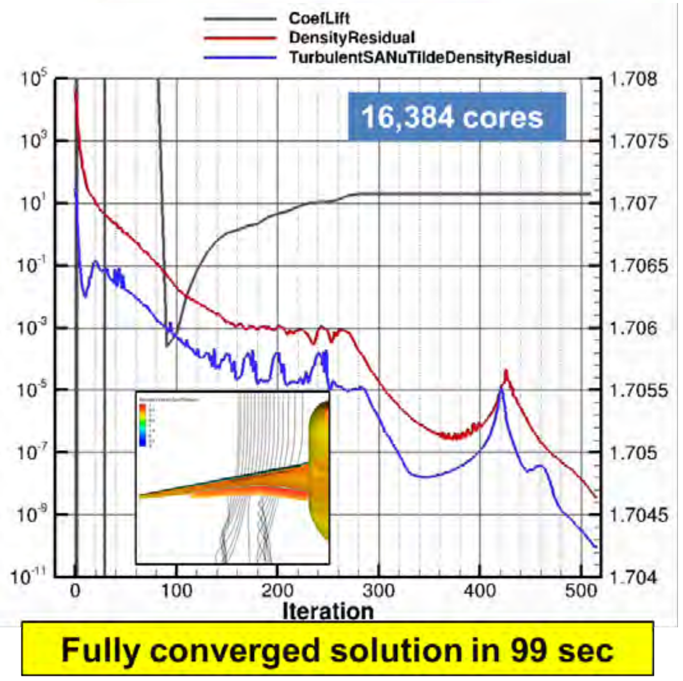
Conclusion and Outlook

- MDO Strategies and Methods
  - MDO beneficial for trade studies
  - Different needs with respect to: run-time, setup time, comp. resources and fidelity will be addressed
  - Pareto front efficiently computed >500 design variables
  - Further development and integration of FlowSimulator and CODA **(CFD for ONERA, DLR, Airbus)**
  - Native FlowSimulator Plugin (MDA/O)
  - Several new MDAO relevant features (overset, immersed BC, Rapid CFD, automatic differentiation)
  - Integration in MDA/O processes from beginning
- Energy-Efficient Aircraft
  - High aspect ratio wing investigations with relevant constraints, moveables/spoiler, high-lift aspects
  - Integration of load alleviation from conceptual to HiFi MDO
  - Integration of laminar design, transition









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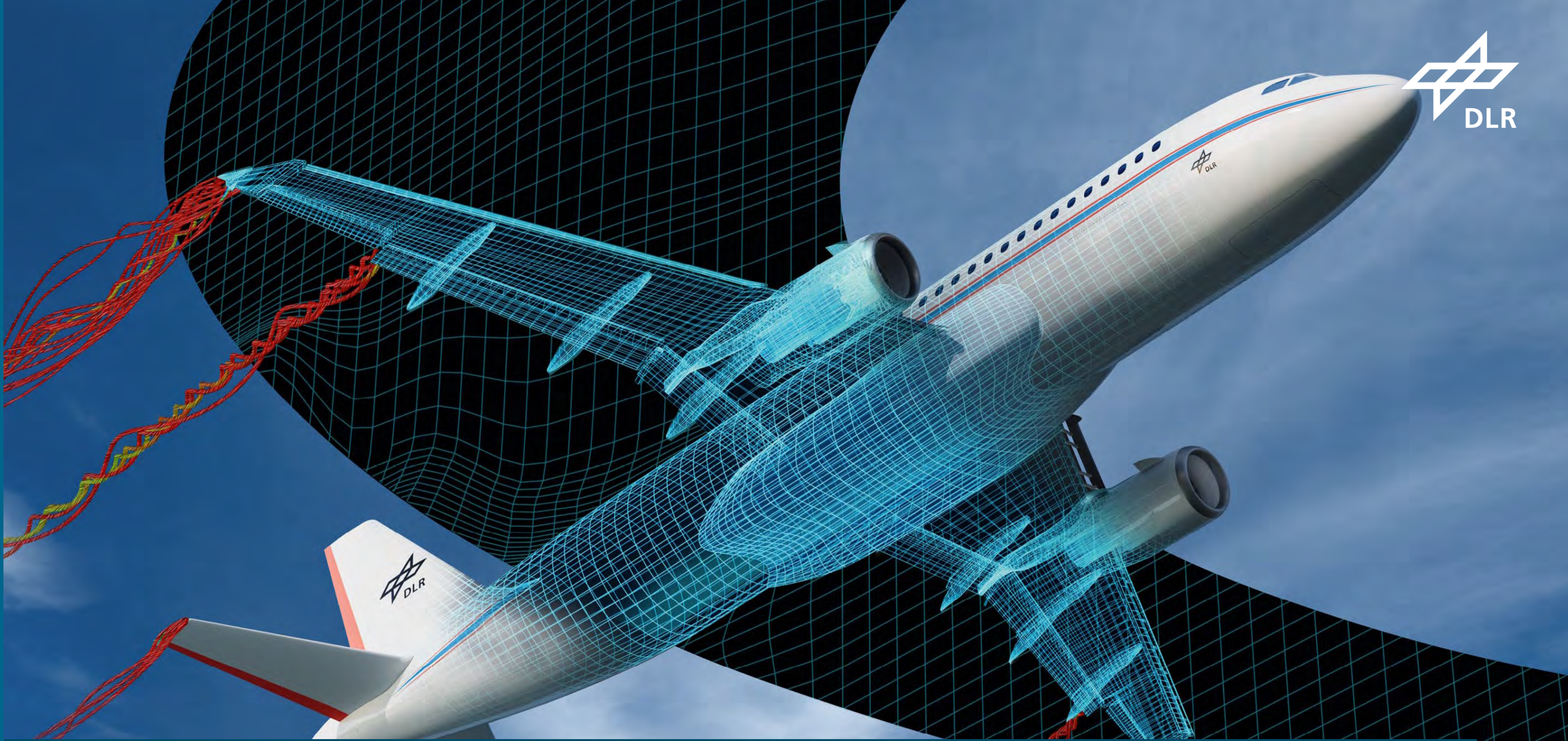

Questions ?

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