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Overview of collaborative high performance computing-based MDO of transport aircraft in the DLR project VicToria

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Outline

- Motivation
- MDO approaches
- Results
- Conclusion

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- **Motivation**
- MDO approaches
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Motivation

- DLR project **VicToria**
  - **Physics-based** overall aircraft MDO
    - Conceptual and preliminary design
    - Involvement of numerous disciplinary expert groups
    - Use of high-performance computing resources
  - **Multiple levels of fidelity**
    - From semi-empirical to RANS/FEM simulations
  - **Industry-relevant** test case
    - A twin-engine long-range airliner

VicToria

Three MDO approaches

- **Integrated aerostructural wing optimization**
  - Aerostructural wing optimization based on high fidelity simulation
  - Structural wing box sizing in the parallel static aeroelastic analysis
  - Get a better understanding of multidisciplinary interactions and of the influence of aeroelastic tailoring for more flexible wings
- **Multi-fidelity gradient-based approach**
  - Investigate several ways of employing gradients for aircraft MDO
  - High-fidelity aerodynamics-structure-propulsion coupling under overall aircraft design constraints
  - Efficient methods for computing cross-disciplinary gradients
- **Many-discipline highly-parallel approach**
  - Enable effective involvement of many disciplines
  - Combine disciplinary design subprocesses of arbitrary type: gradient-based or derivative-free optimization, or a specific design method
  - Parallelism in process execution and in process definition and assembly

DLR

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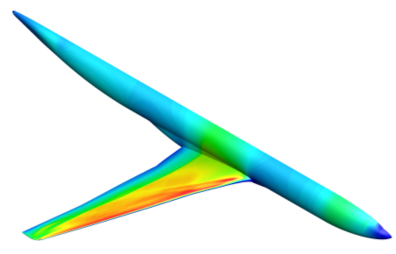
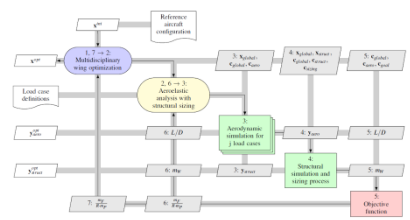
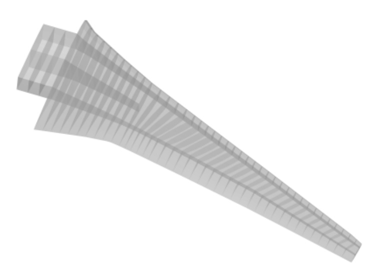
Integrated aerostructural wing optimization (1)

- Usage of a central parametric file format (CPACS)
- Realistic flow physics (RANS)
  - Transonic cruise flight (shocks)
  - Maneuver flight (shocks, flow separations)
- Wing box sizing for composite structures
  - “Aeroelastic tailoring”
- Fluid-structure coupling
  - Performance calculation for flight shape
  - Passive load alleviation for maneuver load cases
- Multi-mission/multi-point design
- Runtime of 2 h for wing analysis =>
  2 weeks for wing optimization
  (9 x 3 = 27 nodes on C2A2S2E cluster)
- Implementation for conventional aircraft configurations
- Only consideration of maneuver load cases
- Simplified control surface deflections (mesh deformation)

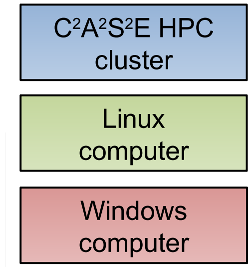


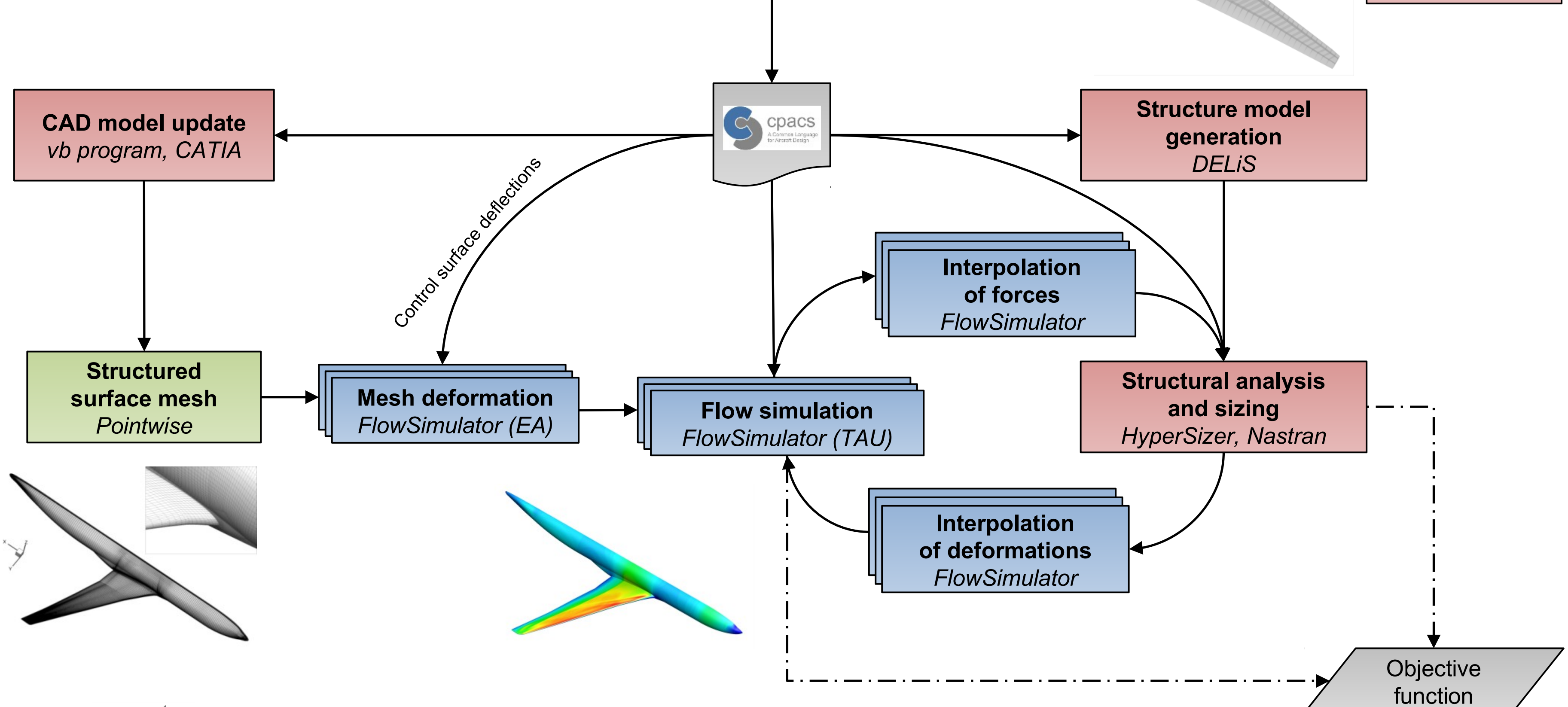




Integrated aerostructural wing optimization (2)

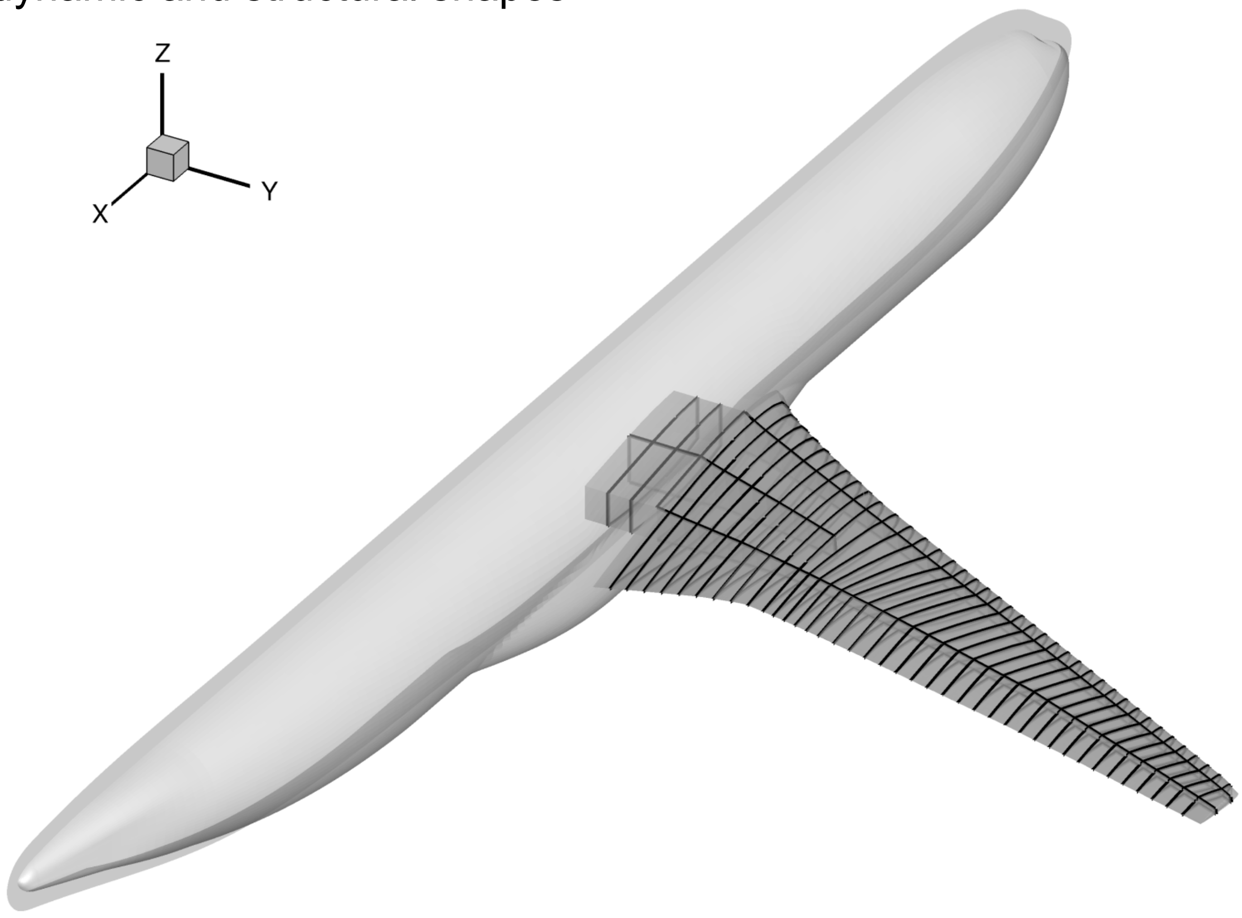
- "Online" process overview





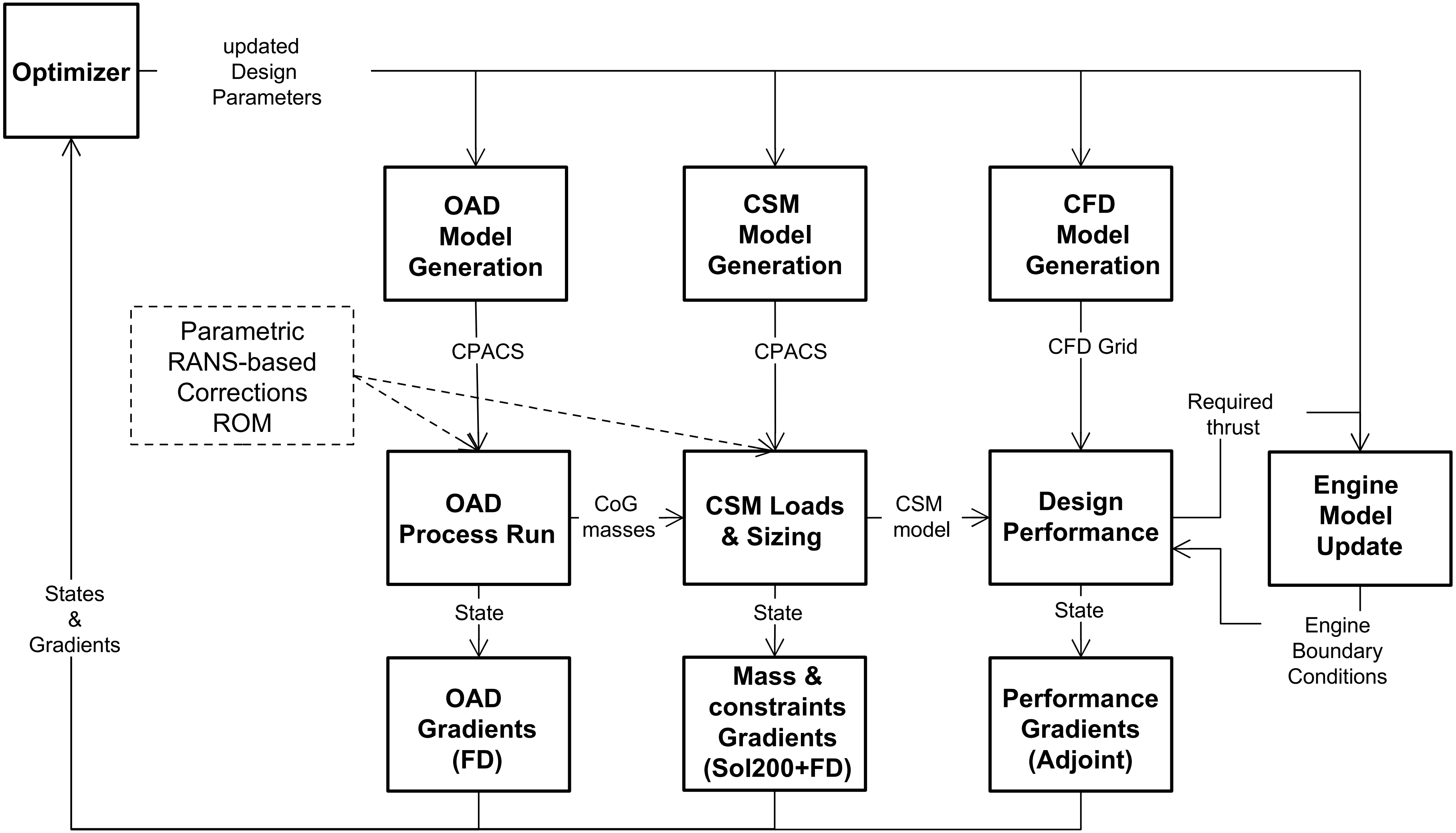
Integrated aerostructural wing optimization (3)

- Aerodynamic and structural shapes



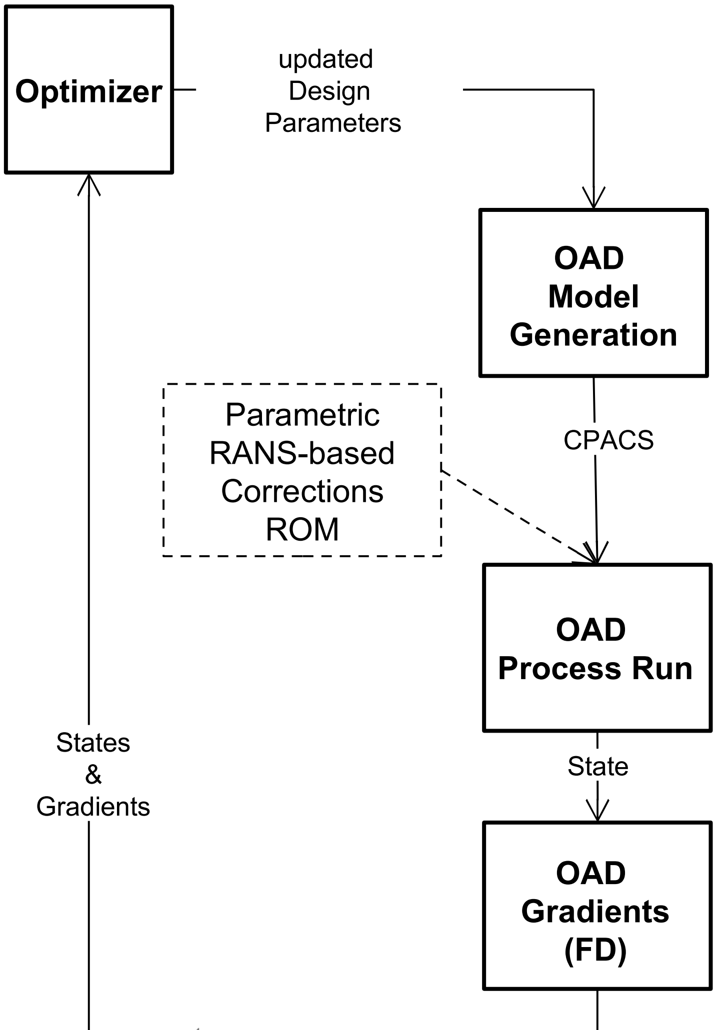
Multi-fidelity gradient-based approach (1)

- Multi-fidelity process overview

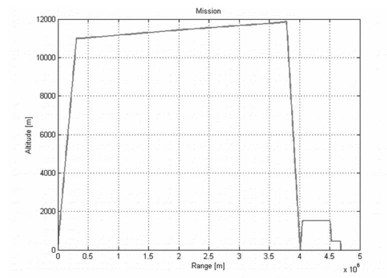


Multi-fidelity gradient-based approach (2)

- Overall aircraft design subprocess

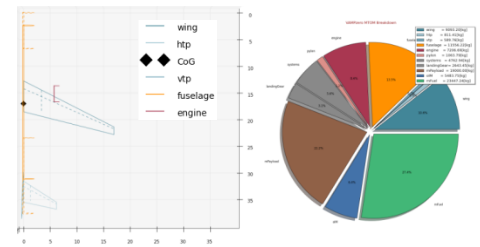


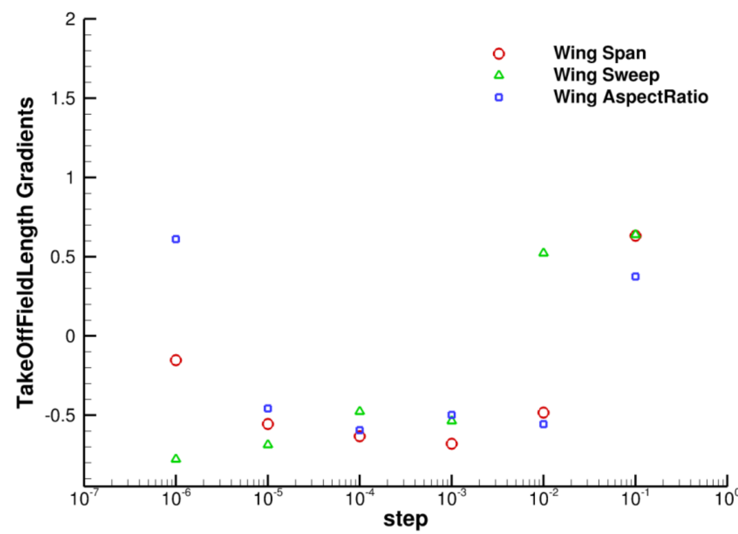
Aircraft TLAR



Mission, PAX, Mach, etc.

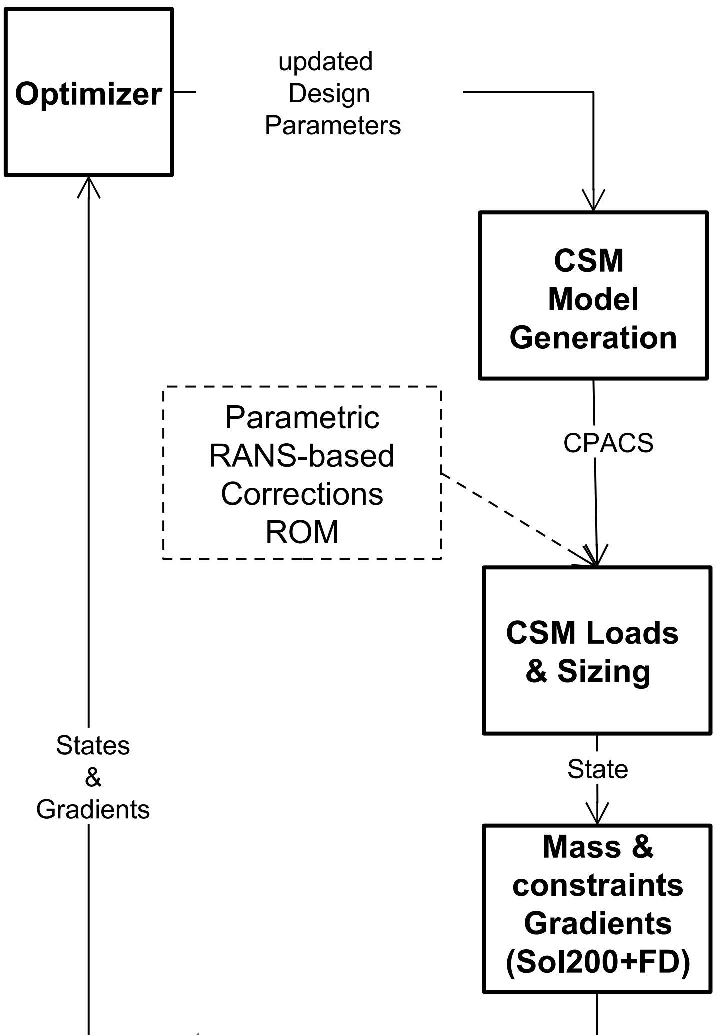
Conceptual synthesis Output

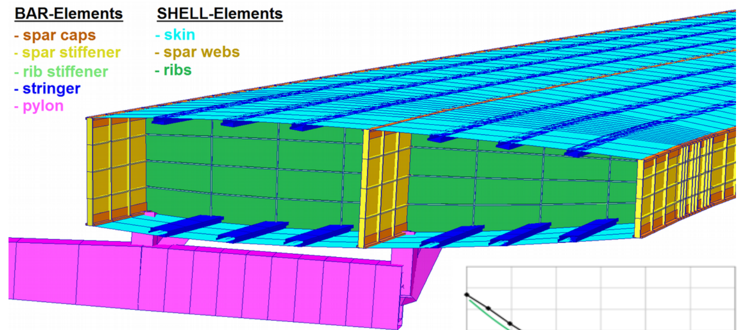


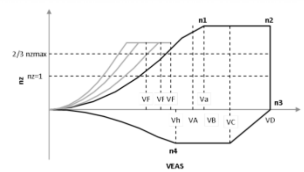


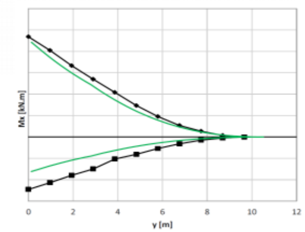
Multi-fidelity gradient-based approach (3)

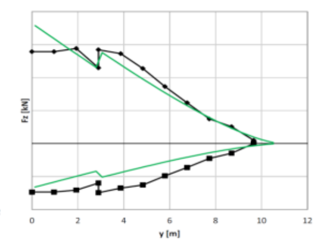
Structural subprocess

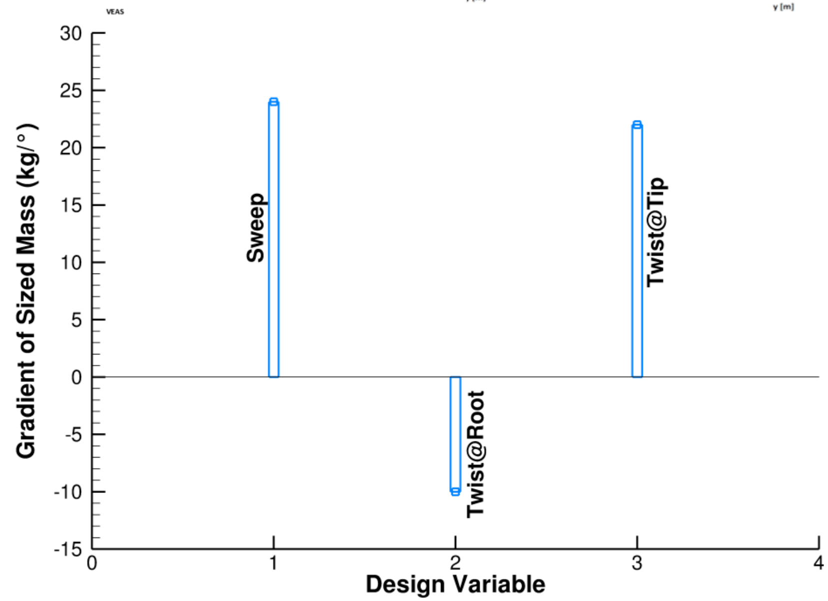












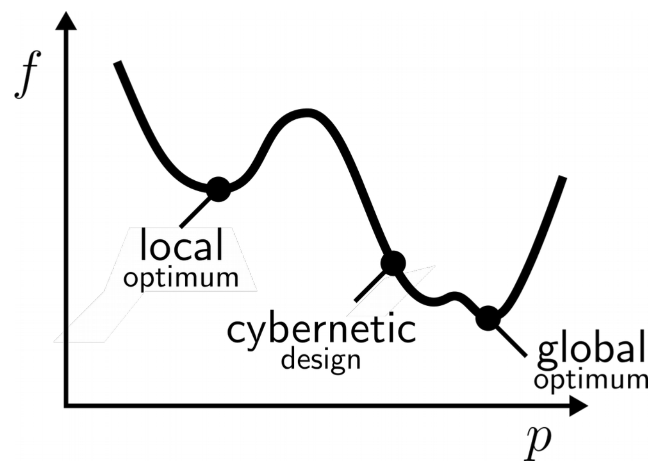
Many-discipline highly-parallel approach (1)

- Universal design equation: describes **any** design process

$$\frac{\widehat{df(w,p)}}{dp} - \lambda \frac{\widehat{dc(w,p)}}{dp} = 0, \quad c(w,p) = 0, \quad r(w,p) = 0$$

f – objective p – design parameters r – consistencies
c – constraints λ – constraint scales w – states

- Implicit approximate KKT system of complex human-machine interaction
  - "Human in the equation", **cybernetic** Jacobians



Cybernetics:
a transdisciplinary approach to modeling, analysis, and control in complex systems

Many-discipline highly-parallel approach (2)

- Design equation expanded for many disciplines and a global objective

$$i = 1 \ldots n \text{ disciplines; } \min F(f_1, f_2, \ldots, f_n);\; f_i,\; c_i,\; p_i,\; \lambda_i,\; r_i,\; w_i$$

$$\widehat{\frac{\partial F}{\partial f_1}} \widehat{\frac{df_1}{dp_1}} + \widehat{\frac{\partial F}{\partial f_2}} \widehat{\frac{df_2}{dp_1}} + \ldots + \widehat{\frac{\partial F}{\partial f_n}} \widehat{\frac{df_n}{dp_1}} - \left\{ \lambda_1 \widehat{\frac{dc_1}{dp_1}} + \lambda_2 \widehat{\frac{dc_2}{dp_1}} + \ldots + \lambda_n \widehat{\frac{dc_n}{dp_1}} \right\} = 0$$

$$r_1,\; c_1 = 0$$

$$\widehat{\frac{\partial F}{\partial f_1}} \widehat{\frac{df_1}{dp_2}} + \widehat{\frac{\partial F}{\partial f_2}} \widehat{\frac{df_2}{dp_2}} + \ldots + \widehat{\frac{\partial F}{\partial f_n}} \widehat{\frac{df_n}{dp_2}} - \left\{ \lambda_1 \widehat{\frac{dc_1}{dp_2}} + \lambda_2 \widehat{\frac{dc_2}{dp_2}} + \ldots + \lambda_n \widehat{\frac{dc_n}{dp_2}} \right\} = 0$$

$$r_2,\; c_2 = 0$$

disciplinary design

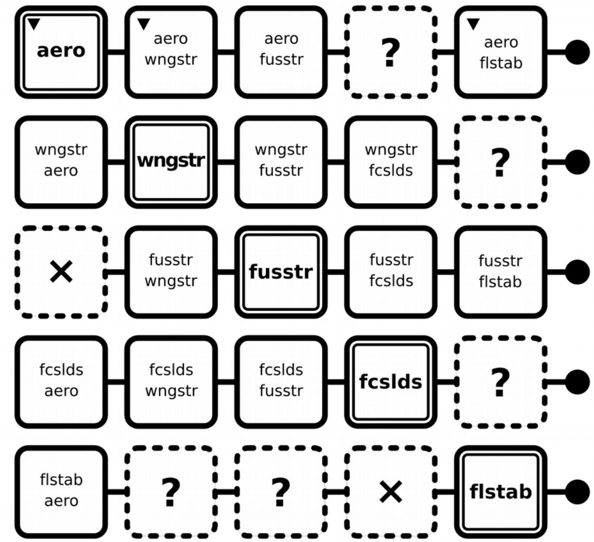
design top dependency

design interdependency

$$\vdots$$

$$\widehat{\frac{\partial F}{\partial f_1}} \widehat{\frac{df_1}{dp_n}} + \widehat{\frac{\partial F}{\partial f_2}} \widehat{\frac{df_2}{dp_n}} + \ldots + \widehat{\frac{\partial F}{\partial f_n}} \widehat{\frac{df_n}{dp_n}} - \left\{ \lambda_1 \widehat{\frac{dc_1}{dp_n}} + \lambda_2 \widehat{\frac{dc_2}{dp_n}} + \ldots + \lambda_n \widehat{\frac{dc_n}{dp_n}} \right\} = 0$$

$$r_n,\; c_n = 0$$

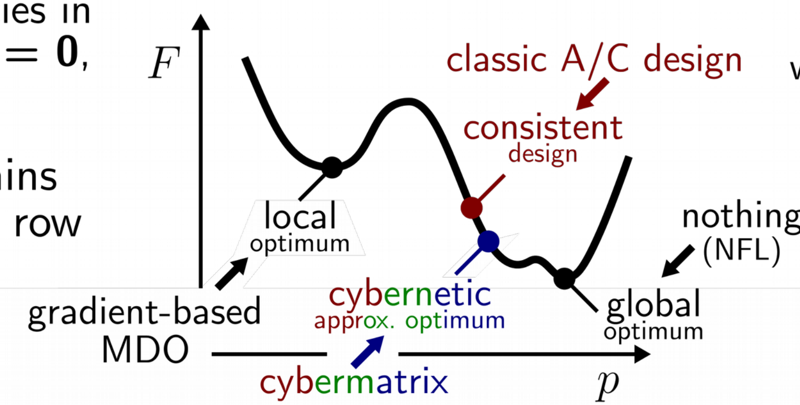


cybermatrix
working representation

N2 chart variant

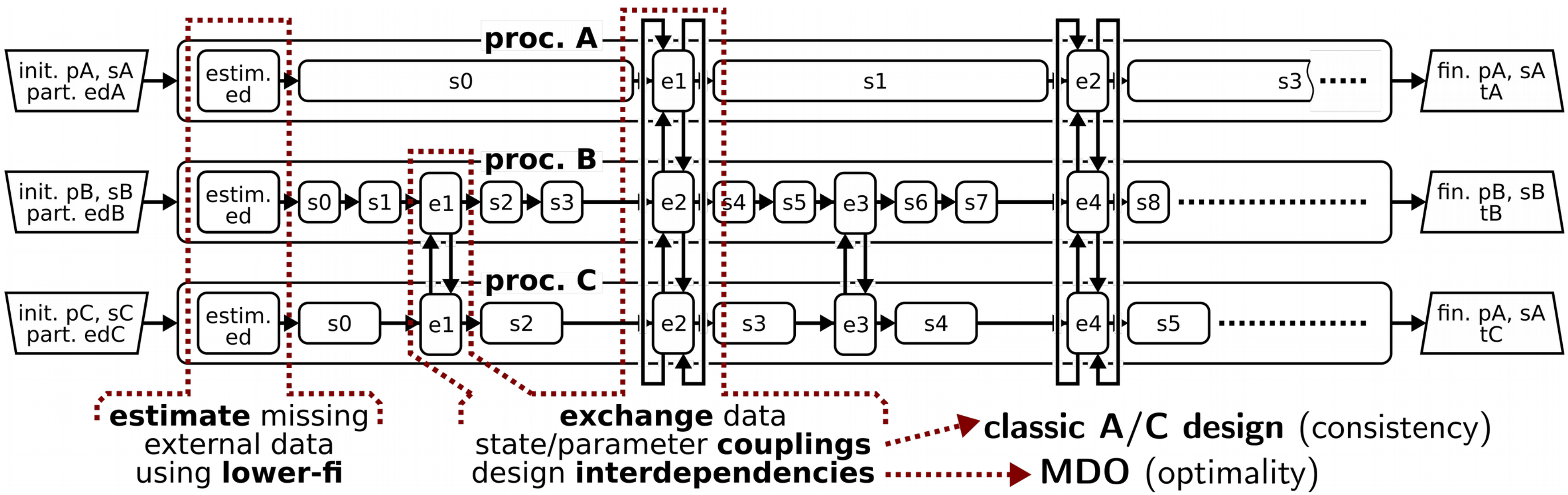
Top-/interdependencies in **classic A/C design = 0**, **MDO ≠ 0**

Every **actor** maintains full **control** of own row



Many-discipline highly-parallel approach (3)

- Disciplinary design subprocesses (cybermatrix rows) running **interleaved**



- Data exchange: exclusively **file I/O**, over file system **in general sense**
  - disk FS (workstation), memory FS (workstation), parallel-disk FS (cluster), parallel-memory FS (cluster), area network FS (multi-cluster/workstations)…
- Development of a new **HPC process integration framework**

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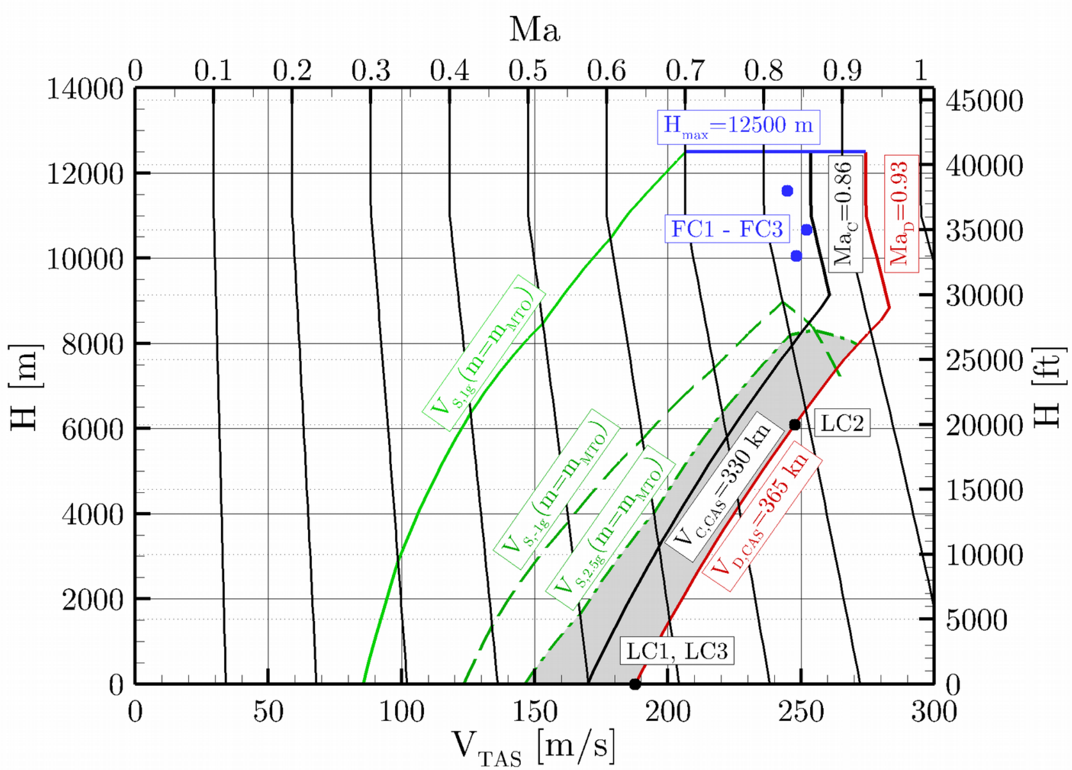
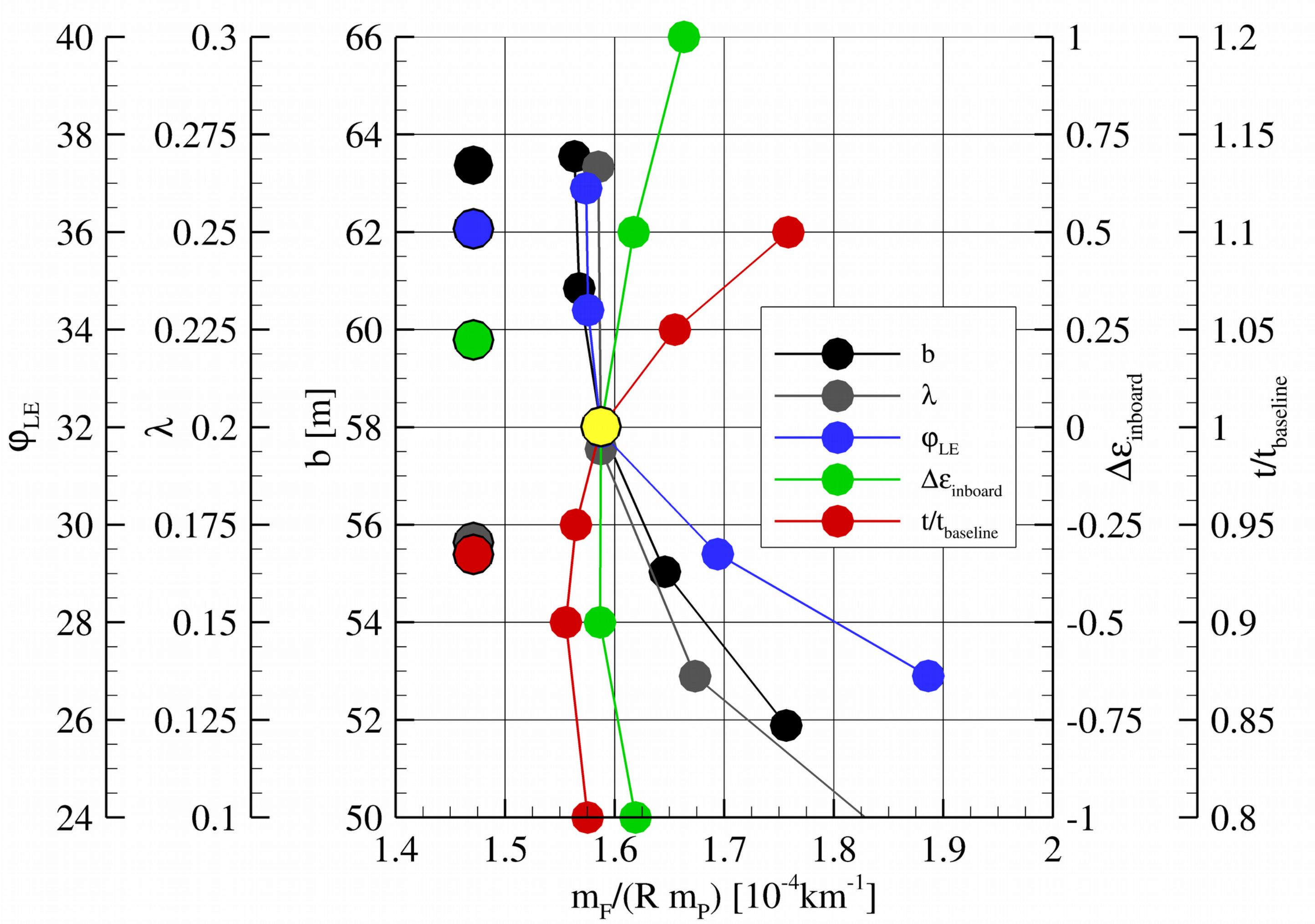
Integrated aerostructural wing optimization

Design task

- Minimize fuel consumption over multiple missions
- Design parameters (20 total):
  - Wing planform (aspect ratio, taper ratios, sweep angle)
  - Twist and thickness distribution
  - Orthotropy direction and percentage zero degree layers
- Constraints:
  - Const. max. takeoff mass
  - Const. wing area
  - Const. fuselage, engine and tailplane masses
  - Const. structure layout (spar position, rib spacing)
  - Const. specific masses of leading and trailing edges
  - Fixed design missions (3) and load cases (3)



Integrated aerostructural wing optimization
Trade study

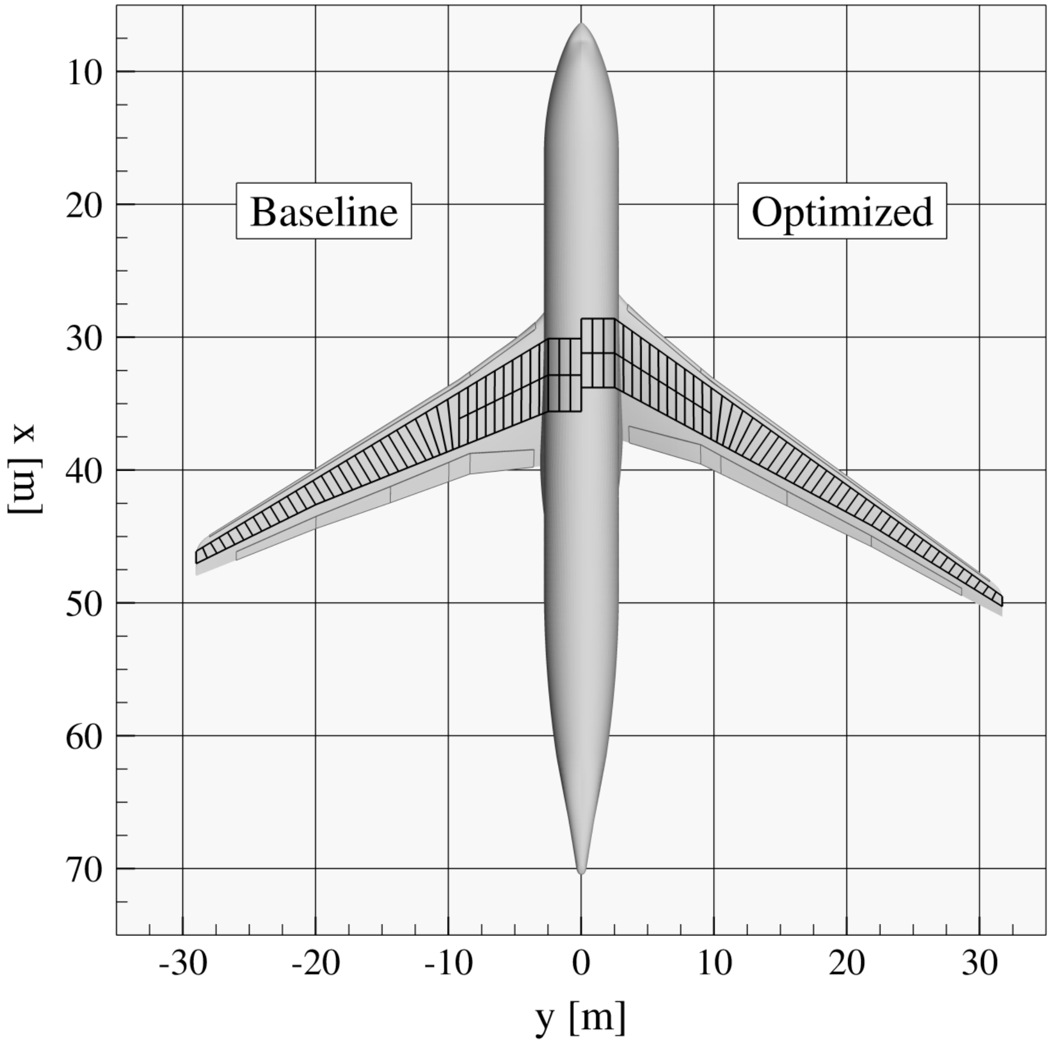


Integrated aerostructural wing optimization

Mid-optimization best design

- Increased span, sweep reduced taper ratio

mission	w	Δspec. fuel
FC1 design	0.6	−5.6%
FC2 high speed	0.1	−13.0%
FC3 long range	0.3	−8.8%
weighted sum		**−7.3%**



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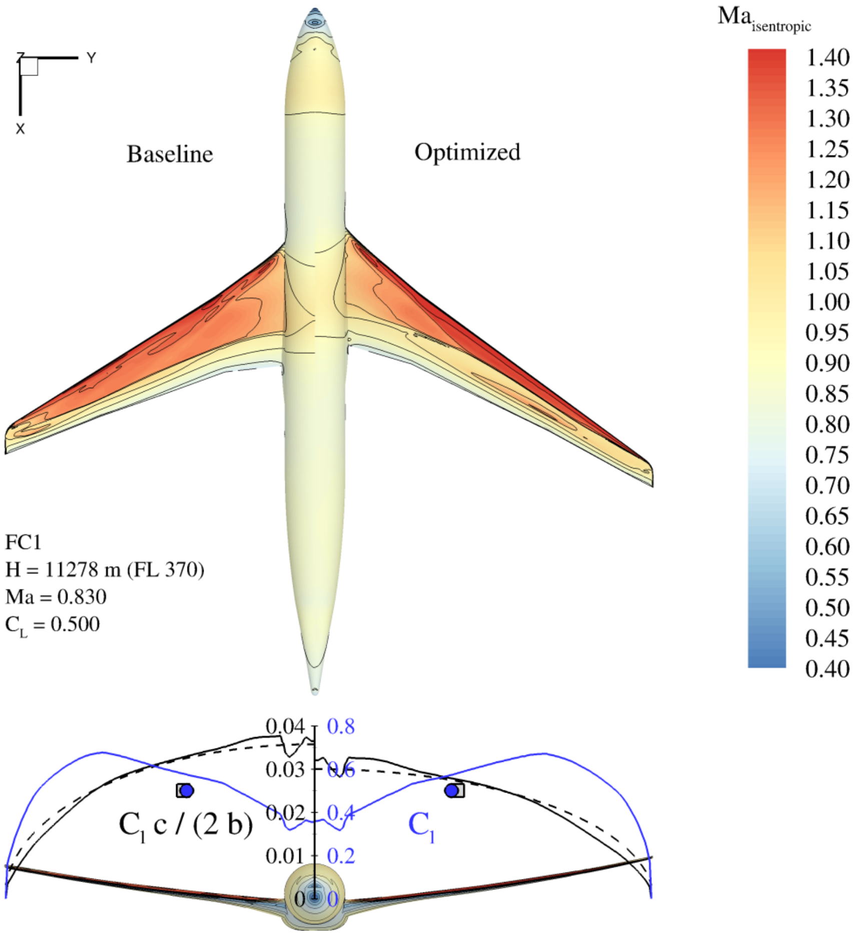
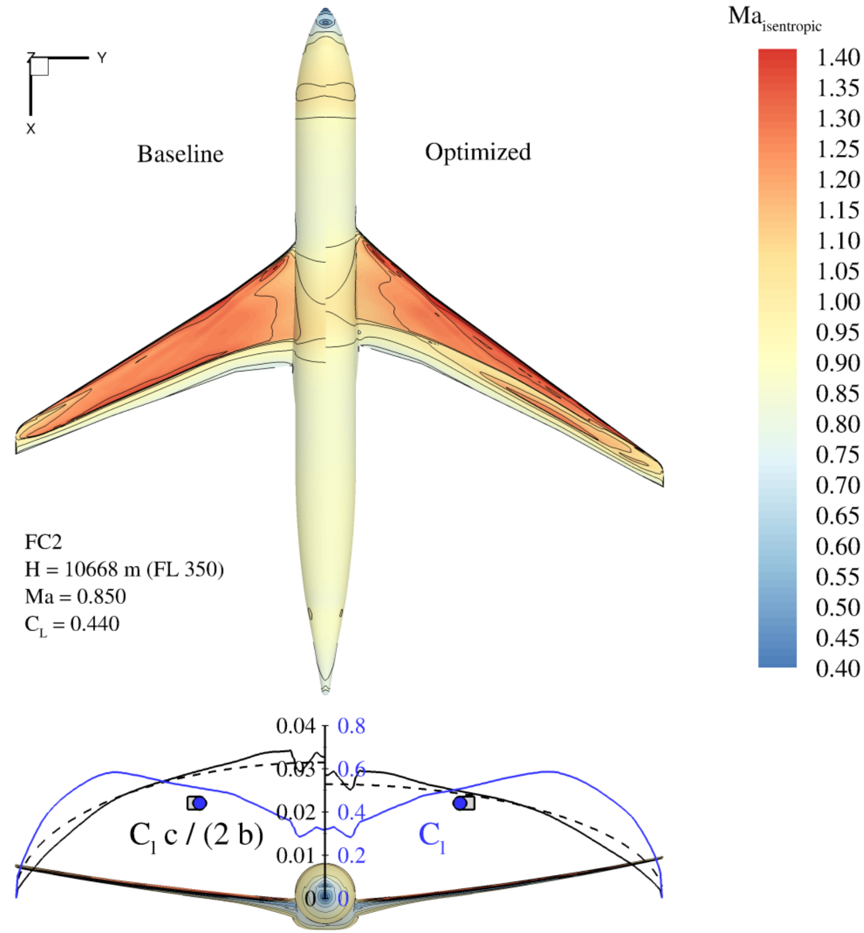
Integrated aerostructural wing optimization
Mid-optimization, flight cases





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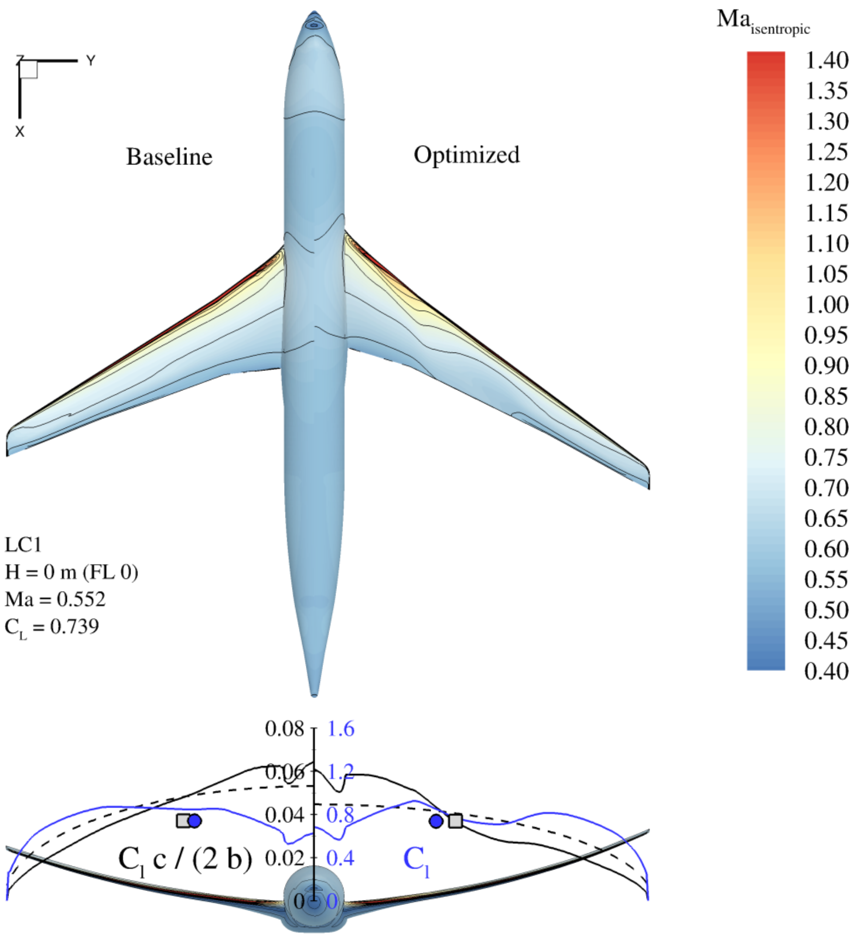
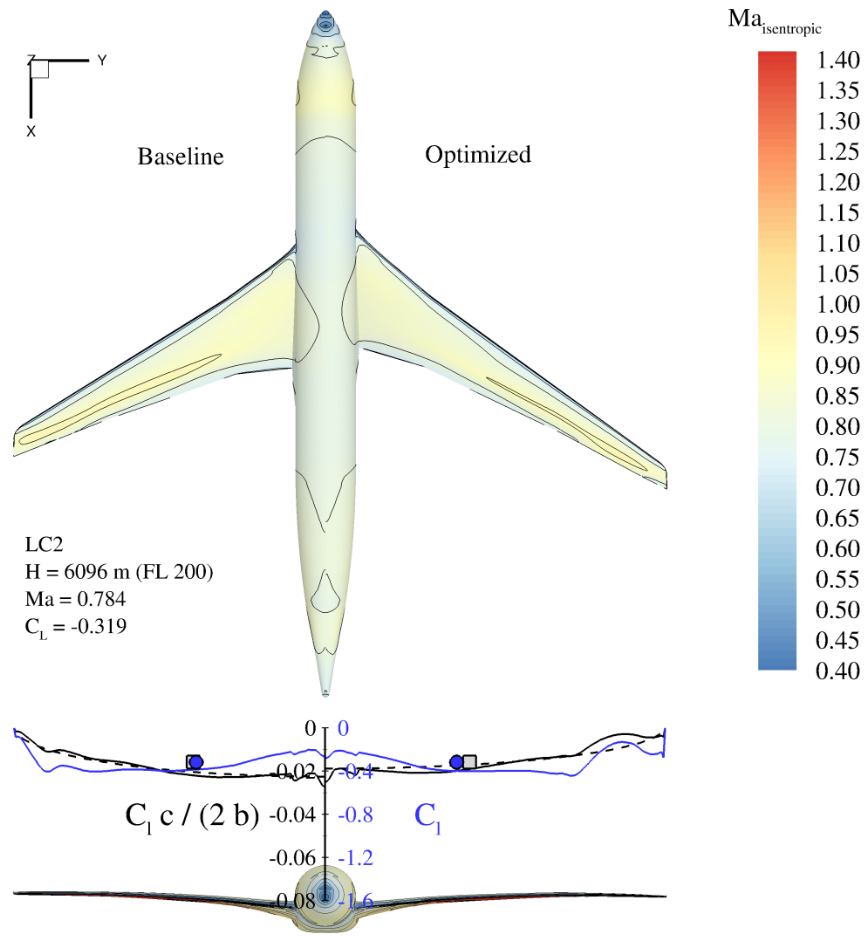
Integrated aerostructural wing optimization

Mid-optimization, load cases





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Conclusions

- Processes in various stages of development
- Integrated aerostructural wing optimization successfully implemented
  - Trades studies performed and improved designs already obtained from a full optimization run
- Multi-fidelity gradient-based approach near to first optimization run
  - Studies of cross-disciplinary gradients performed to determine their influences on the overall design
- Many-discipline highly-parallel approach running under reduced couplings
  - Incremental addition of missing couplings to improve physical consistency of the overall design

Outlook

- Further development until the end of the VicToria project: end of 2019
- Integrated aerostructural wing optimization to
  - provide for higher wing flexibility (advanced structural concepts)
  - introduce more control surface deflections (load alleviation)
  - add more configuration elements (engine and pylon)
- Multi-fidelity gradient-based approach to
  - examine multi-level MDO architectures for better optimality and run time
  - study how to introduce corrections to OAD from hi-fi process parts
- Many-discipline highly-parallel approach to
  - add both more consistency and more design couplings
  - examine further opportunities for parallel execution and assembly

Thank you for your attention!