VicToria

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The Cybermatrix Protocol For Multidisciplinary Optimization of Commercial Transport Aircraft

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Goal of The Work

- Kinds of disciplines in MDO
  - *Domain-like*: coupling of physical domains across interface boundaries (e.g. RANS fluid flow around wing, linear-elastic structure inside wing)
  - *Subsystem-like*: same physical domains, different vehicle components (e.g. wing, fuselage, and tail structure; fan, compressor, turbine)
  - *Phase-like*: e.g. conceptual, preliminary, detailed design

- Goal: A methodology for constructing MDO processes taking **TLARs and vehicle concept as input**, producing full **preliminary design as output**
  - Include all kinds of disciplines (domain-, subsystem-, phase-like)
  - Establish effective parallel collaboration of many expert teams
  - Employ multiple fidelities of physical modeling (up to hi-fi PDE solvers)
  - Include from ground-up use of HPC and parallel execution
  - Allow for use of “clever” design methods

- Work in DLR projects **Digital-X** (2012-2016) and **VicToria** (2016-2020)

Design Equation

- Any design process can be seen as an **approximate** optimization process:

$$\frac{\widehat{\partial f(p)}}{dp} - {\frac{\widehat{\partial c(p)}}{dp}}^T q = 0, \quad c(p) = 0$$

  where ***f*** objective ($\mathbb{R}^1$), ***c*** constraints ($\mathbb{R}^m$), ***p*** design parameters (DPs, $\mathbb{R}^n$),
  q design influences (DIs, Lagrange multipliers, $\mathbb{R}^m$)
  → approximate KKT optimality condition

- Expanded for three disciplines **A**, **B**, **C** and global objective function ***F*** ($\mathbb{R}^1$):

$$\frac{\widehat{\partial F}}{\partial f_A}\underline{\frac{\widehat{df_A}}{dp_A}} + \frac{\widehat{\partial F}}{\partial f_B}\frac{\widehat{df_B}}{dp_A} + \frac{\widehat{\partial F}}{\partial f_C}\frac{\widehat{df_C}}{dp_A} - \underline{{\frac{\widehat{dc_A}}{dp_A}}^T q_A} - {\frac{\widehat{dc_B}}{dp_A}}^T q_B - {\frac{\widehat{dc_C}}{dp_A}}^T q_C = 0, \quad \underline{c_A} = 0$$

$$\frac{\widehat{\partial F}}{\partial f_A}\frac{\widehat{df_A}}{dp_B} + \frac{\widehat{\partial F}}{\partial f_B}\underline{\frac{\widehat{df_B}}{dp_B}} + \frac{\widehat{\partial F}}{\partial f_C}\frac{\widehat{df_C}}{dp_B} - {\frac{\widehat{dc_A}}{dp_B}}^T q_A - \underline{{\frac{\widehat{dc_B}}{dp_B}}^T q_B} - {\frac{\widehat{dc_C}}{dp_B}}^T q_C = 0, \quad \underline{c_B} = 0$$

$$\frac{\widehat{\partial F}}{\partial f_A}\frac{\widehat{df_A}}{dp_C} + \frac{\widehat{\partial F}}{\partial f_B}\frac{\widehat{df_B}}{dp_C} + \frac{\widehat{\partial F}}{\partial f_C}\underline{\frac{\widehat{df_C}}{dp_C}} - {\frac{\widehat{dc_A}}{dp_C}}^T q_A - {\frac{\widehat{dc_B}}{dp_C}}^T q_B - \underline{{\frac{\widehat{dc_C}}{dp_C}}^T q_C} = 0, \quad \underline{c_C} = 0$$

Analogy with Coupled-Adjoint

- Coupled-adjoint: compute **total** derivatives of objective/constraints cheaply, independent of number of DPs
- E.g. in "unconstrained" optimization with aerodynamic and structural disciplines:

$$\frac{\partial C_D}{\partial p_{a,s}} + \frac{\partial R_a}{\partial p_{a,s}}^T \lambda_a + \frac{\partial R_s}{\partial p_{a,s}}^T \lambda_s = 0$$

← total derivative to be set to zero by the optimizer

$$\frac{\partial C_D}{\partial u_a} + \frac{\partial R_a}{\partial u_a}^T \lambda_a + \frac{\partial R_s}{\partial u_a}^T \lambda_s = 0, \quad R_a = 0$$

← aerodynamic adjoint equation

$$\frac{\partial C_D}{\partial u_s} + \frac{\partial R_a}{\partial u_s}^T \lambda_a + \frac{\partial R_s}{\partial u_s}^T \lambda_s = 0, \quad R_s = 0$$

← structural adjoint equation

where $\boldsymbol{C_D}$ objective ($\mathbb{R}^1$), $\boldsymbol{R_{a's}}$ residual equations ($\mathbb{R}^m$), $\boldsymbol{p_{a,s}}$ DPs and $\boldsymbol{u_{a,s}}$ state variables ($\mathbb{R}^n$), $\boldsymbol{\lambda_{a,s}}$ adjoint state variables ($\mathbb{R}^m$)
→ **same structure as the design equation**, subsystem of the design equation

- For best robustness and convergence, each discipline solves its row in the coupled-adjoint system (block-Jacobi/Gauss-Seidel, "lagged update")
- **Extend the same principle to the whole design equation**

Cybermatrix Protocol

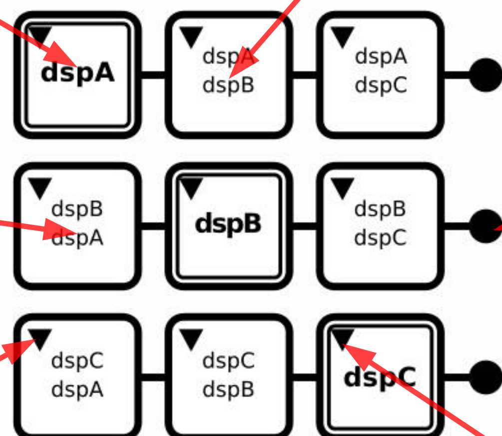
- Three principles:
  - **Reason** about the design problem directly through the design equation → **no** maze-like workflows, **no** loops-within-loops
  - **Distribute** modeling and solving of design equation between disciplines → **no** central MDO team, **no** "single source of truth"
  - **Parallelize** human collaboration and machine execution analogously → **no** parallel-as-afterthought, **no** single software framework
- Multidisciplinary design equation in the form of coupled-adjoint lagged update:

$$
\begin{aligned}
&\widehat{\frac{\partial F}{\partial f_A}}\,\widehat{\frac{\partial f_A}{\partial p_A}} - \widehat{\frac{\partial c_A}{\partial p_A}}^T q_A = \widehat{\frac{\partial F}{\partial f_B}}\,\widehat{\frac{\partial f_B}{\partial p_A}} - \widehat{\frac{\partial c_B}{\partial p_A}}^T q_B + \widehat{\frac{\partial F}{\partial f_C}}\,\widehat{\frac{\partial f_C}{\partial p_A}} - \widehat{\frac{\partial c_C}{\partial p_A}}^T q_C, \quad c_A = 0\\
&\widehat{\frac{\partial F}{\partial f_B}}\,\widehat{\frac{\partial f_B}{\partial p_B}} - \widehat{\frac{\partial c_B}{\partial p_B}}^T q_B = \widehat{\frac{\partial F}{\partial f_A}}\,\widehat{\frac{\partial f_A}{\partial p_B}} - \widehat{\frac{\partial c_A}{\partial p_B}}^T q_A + \widehat{\frac{\partial F}{\partial f_C}}\,\widehat{\frac{\partial f_C}{\partial p_B}} - \widehat{\frac{\partial c_C}{\partial p_B}}^T q_C, \quad c_B = 0\\
&\widehat{\frac{\partial F}{\partial f_C}}\,\widehat{\frac{\partial f_C}{\partial p_C}} - \widehat{\frac{\partial c_C}{\partial p_C}}^T q_C = \widehat{\frac{\partial F}{\partial f_A}}\,\widehat{\frac{\partial f_A}{\partial p_C}} - \widehat{\frac{\partial c_A}{\partial p_C}}^T q_A + \widehat{\frac{\partial F}{\partial f_B}}\,\widehat{\frac{\partial f_B}{\partial p_C}} - \widehat{\frac{\partial c_B}{\partial p_C}}^T q_B, \quad c_C = 0
\end{aligned}
$$

- **Solve in turn** for fixed right-hand side, **update periodically** right-hand sides

Reasoning Through Design Equation

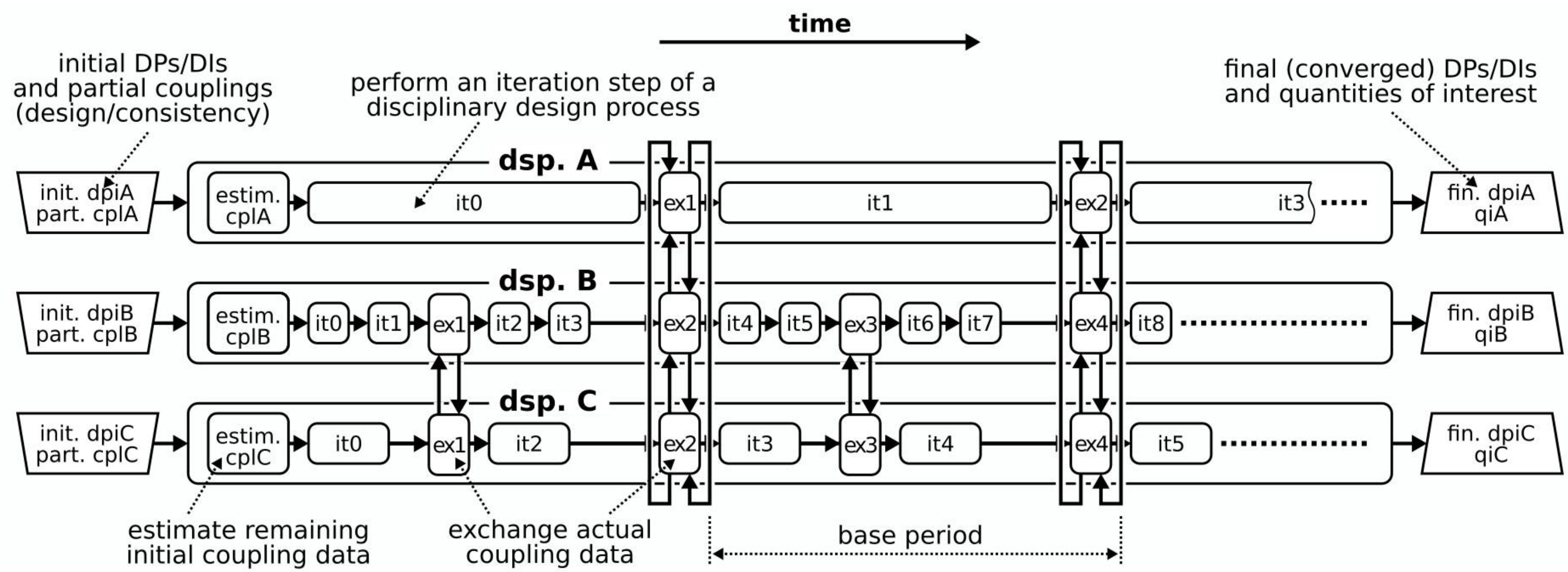
- Terms in multidisciplinary design equation often implied, use a schematic view
- Each row belongs to one discipline (everything related to its design parameters)



- All that is needed to reason about properties of the optimized design

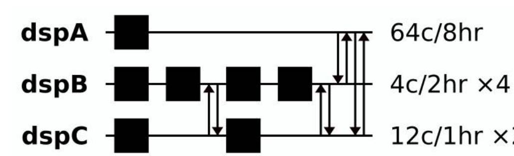
Distributed Modeling and Solving

- A disciplinary design process can have any form, only **iteration** assumed
- Add to it data exchange points and initial data estimators



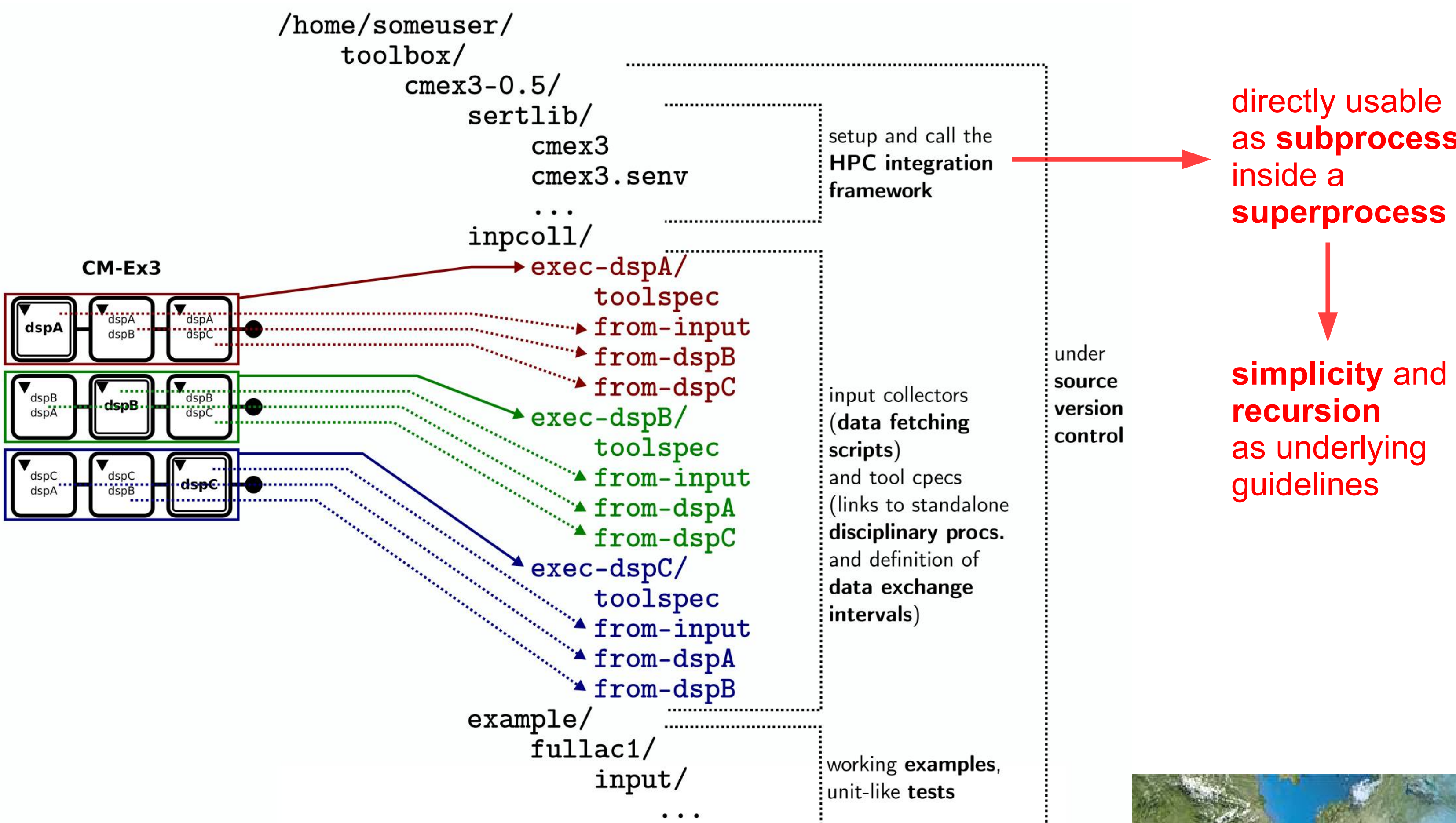
- Different disciplines may have different exchange periods
- Selection of rows, iterations and exchange periods produces an “MDO formulation”
  - In practice **always a hybrid formulation**

practical visualisation of the **base period**



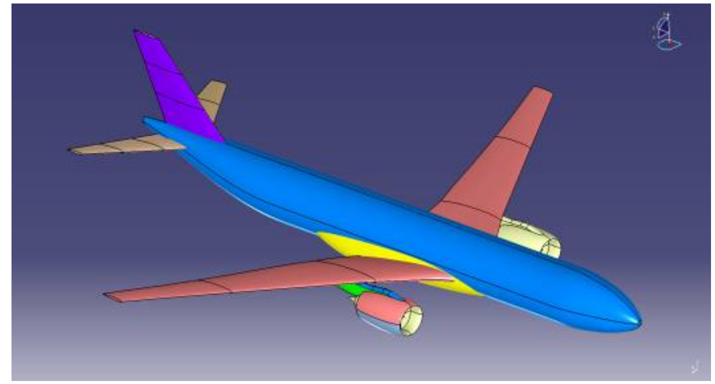
Parallel Collaboration and Execution

- An MDO process is a set of **input collectors** scripts, one per cybermatrix box
- Maintainable by **standard** software engineering **tools** and **practices**
- Execution framework is an **interpreter** of the set of collectors and some metadata
  - No need for disciplinary experts to learn yet another framework

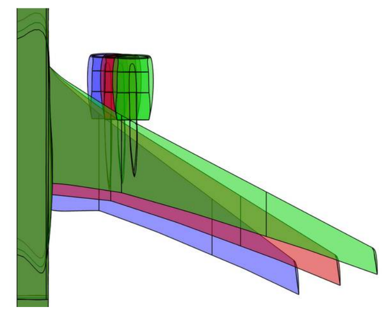


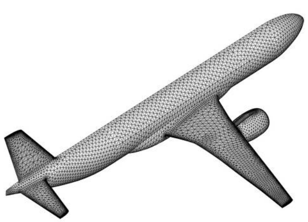
Demonstration: Overall Aircraft Design

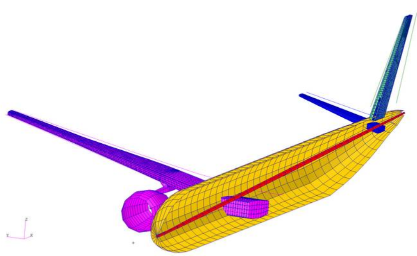
- Large twin-engine wide-body long-range transport aircraft
  - Wing-body-tail-pylon-flow through nacelle
  - Airbus XRF-1 baseline
- Global objective function: **minimize mission block fuel**

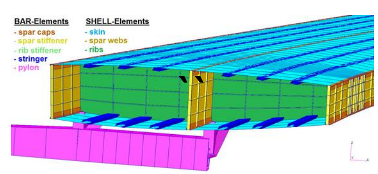


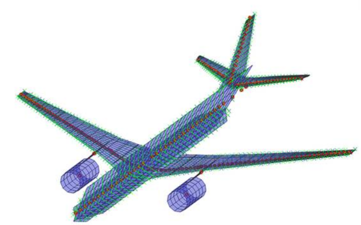
- Involved disciplinary processes:
  - Overall aircraft design (**oad**)
  - Aircraft synthesis (**acsyn**)
  - Aerodynamic airfoil design (**aero**)
  - Loads evaluation and structural design (**struct**)

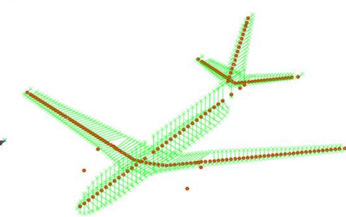












Demonstration: Cybermatrix and Base Period

oad
derivative-free SQP
tuned trust region
CAD-ROM wing planform,
2 DPs (AR, sweep)
Minimize block fuel
Iteration step:
one trust-reg. step
and Jacobian estimation

block fuel

wing AR

acsyn
Mission evaluation and
design masses accounting
Textbook methods, Breguet-eq.
Step: one mission evaluation
and mass accounting step

cruise lift and drag

mOEM, mMaxFuel

wing planform

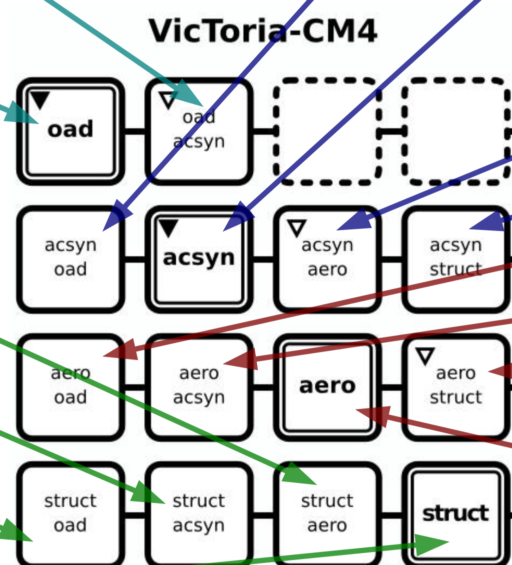
cruise conditions

global FEM, CoG pos.

airfoil shapes

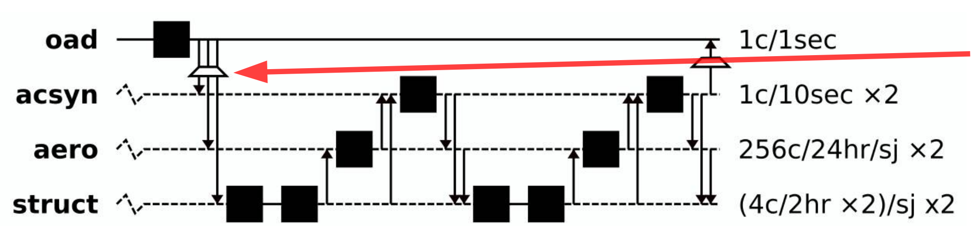
design masses

wing planform



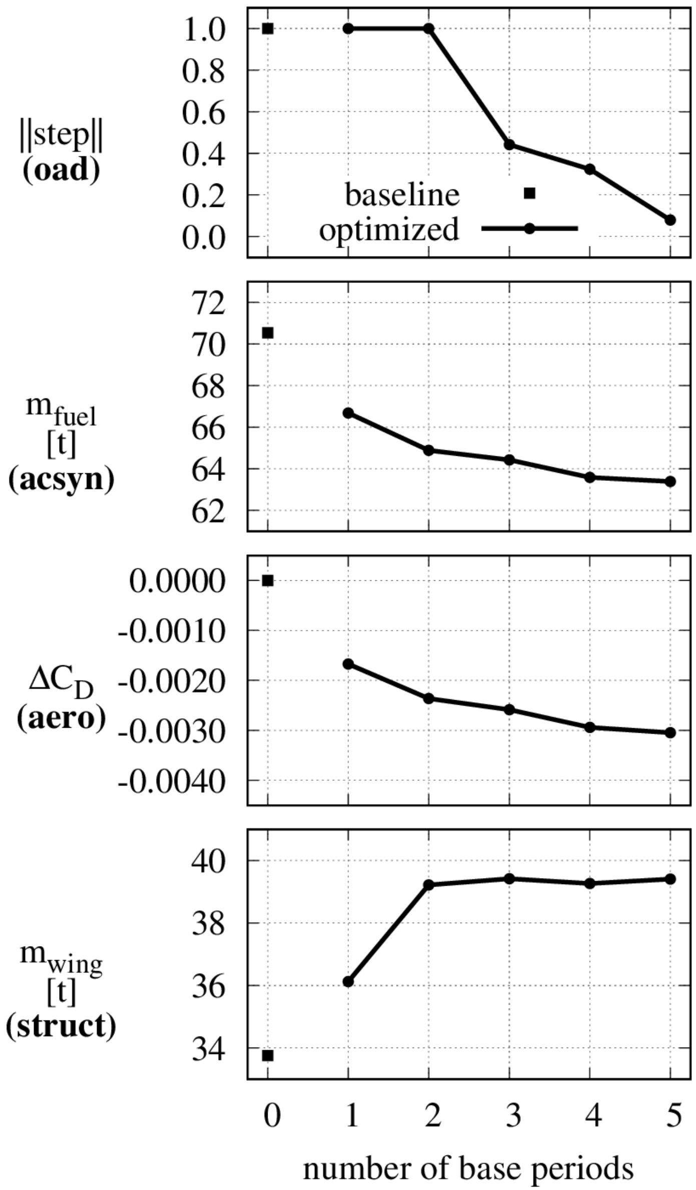
aero
Adjoint aeroelastic optimization
RANS flow, mesh 5,900,000 pts
CAD-ROM airfoil shapes, 126 DPs
Minimize drag at trimmed flight
Step: one gradient and line search

struct
DLM loads, 20 load cases
Grad.-based structural opt.
Global FEM, 42,000 els
Region thicknesses, 392 DPs
Minimize mass for limit
strength, buckling per LC
Iteration step:
one loads evaluation
and one full sizing



acsyn, **aero**, **struct**
tracks multiplexed
per planform (5x)
from **oad**

Demonstration: Optimization Convergence

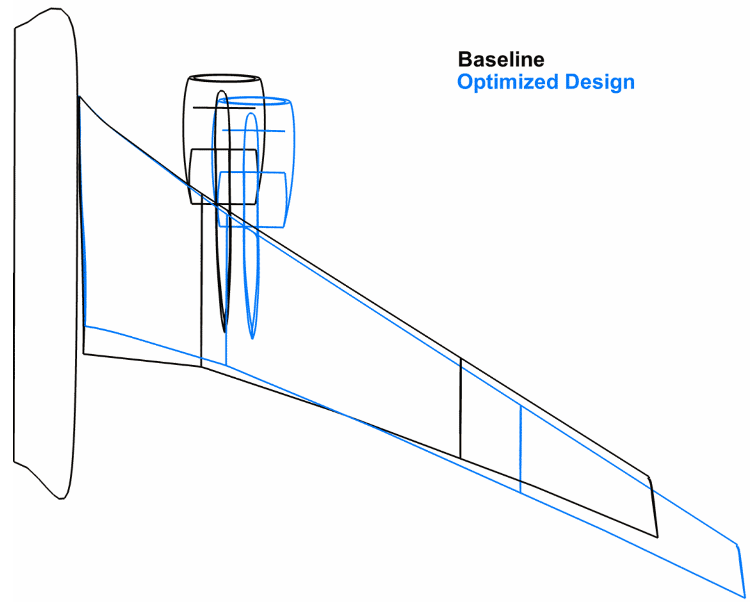


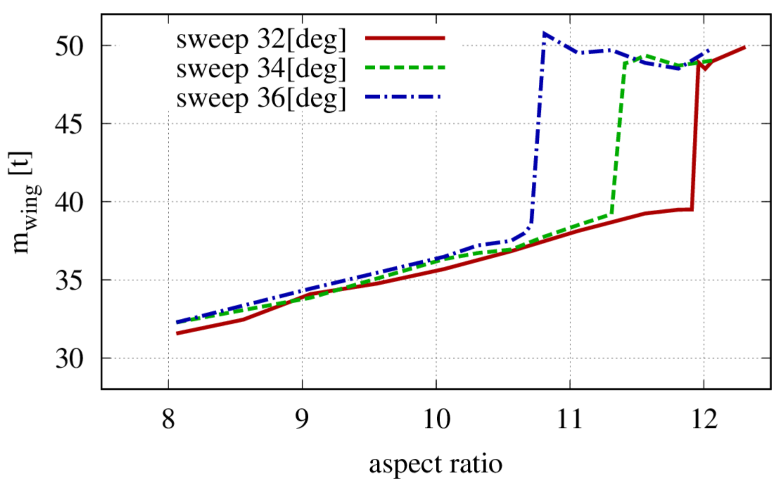
- Run time "clean" **12 days**, peak **1280 cores**
  - Base period duration: 56 hours avg.
  - Real time 16 days (cluster down, waiting for licenses, restart fixes)
- **Block fuel reduction** (**-10.2%**) coming from mass increase (**+15.7%** wing, **+8.6%** total) lift-to-drag increase (**+12.5%** mid-cruise)
- What is the baseline for comparison?
  - Index 0 on x-axis has no meaning; "abused" to show the optimized value when shape DPs (planform, airfoils) are kept fixed at initial values (XRF-1)

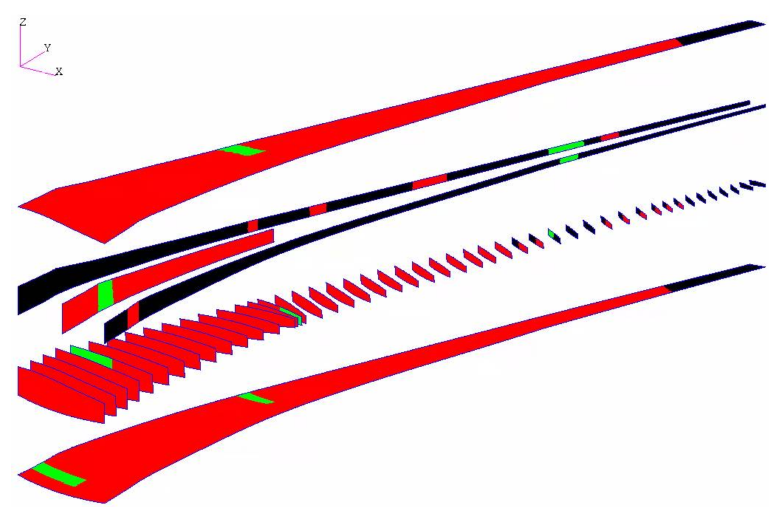
Some values shown as difference to baseline
due to XRF-1 data publications rules;
some visualizations omitted for the same reason

Demonstration: Optimized Design Analysis

- Expected design with higher AR and higher sweep wing reached
  - Many constraints not present...
- Wing structure shows substantial thickness increase (red-color areas)
- But not *quite as* high AR/sweep: a critical landing load case activates due to moving of main landing gear
  - wing mass discontinuity, handled without a problem

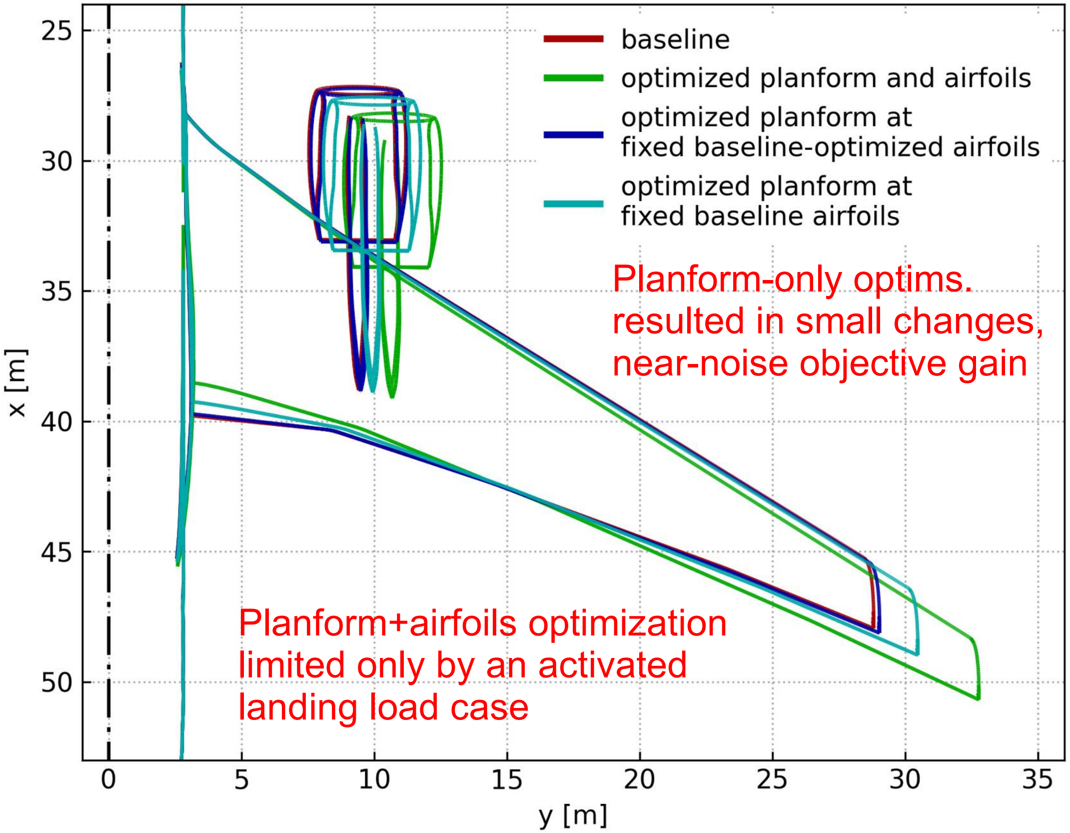


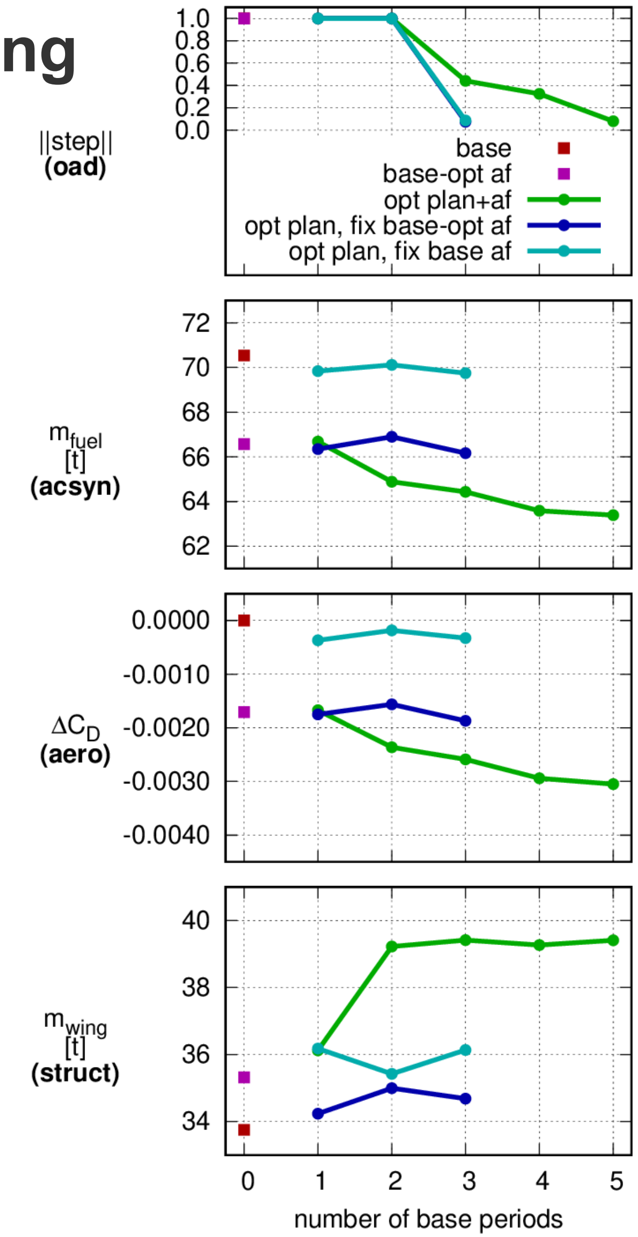




Sidenote: Planform-Airfoils Coupling

- Compare coupled planform-and-airfoils optimization with planform optimized while airfoils kept fixed...
  - ...at baseline airfoils
  - ...at optimized airfoils for baseline planform





Conclusions and Outlook

- The cybermatrix approach, aimed at constructing MDO processes that start from TLARs and concept and result in full preliminary design, demonstrated
  - Expected design with higher AR/sweep from previous studies reached
  - New interactions due to a more complex loads process seen
- Three directions of disciplinary improvements:
  - Increase of complexity within already employed disciplines (powered engine, hi-fi corrections to loads, landing gear integration...)
  - More disciplines, some already in various stages of readiness (specialized wing and fuselage design, engine conceptual design, flutter...)
  - Introducing more design couplings (mass sensitivity to airfoil thickness in aerodynamic airfoil design...)
- Further work on the protocol definition and process integration framework

Thank you for your attention!