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The cybermatrix protocol: a link between classical aircraft design and formal multidisciplinary optimization

Caslav Ilic, Andrei Merle, Mohammad Abu-Zurayk,
Martin Leitner, Matthias Schulze, Andreas Schuster,
Michael Petsch, Sebastian Gottfried

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A merger of two approaches

- **Classic aircraft design**
  - Focus on process automation, many disciplines, data modeling
  - No specific focus on high-performance computing (HPC)
  - No formal optimality criteria, suboptimal designs by construction
- **Formal multidisciplinary optimization**
  - Focus on analysis fidelity, modeling constraints, and adding disciplines
  - Explicit consideration of optimality criteria and often high HPC use
  - Simplifed tools, poorly scalable in number of disciplines/experts
- **The proposed solution establishes a link between the two approaches**
  - Developed within the **DLR project VicToria**
  - Optimality criteria explicit, but applied in a heuristic manner
  - Parallelism from ground up, both in expert participation and in use of HPC
  - Implementation (human) and execution (computer) phases with analogous communication and control in a matrix-like structure → **cybermatrix**

The design equation

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

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

  where ***f*** goal ($\mathbb{R}^1$), ***c*** constraints ($\mathbb{R}^m$), ***p*** design parameters ($\mathbb{R}^n$),
  q goal-to-constraint sensitivities (Lagrange multipliers, $\mathbb{R}^m$)
  → approximate first KKT optimality condition

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

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

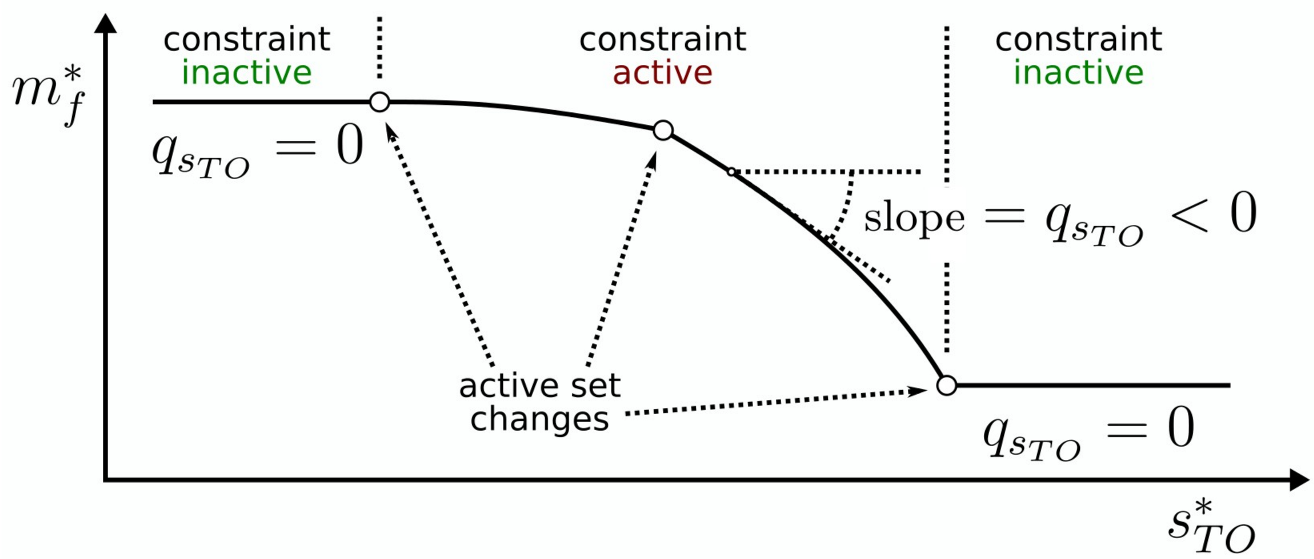
$$\widehat{\frac{\partial F}{\partial f_A}} \widehat{\frac{df_A}{dp_B}} + \widehat{\frac{\partial F}{\partial f_B}} \underline{\widehat{\frac{df_B}{dp_B}}} + \widehat{\frac{\partial F}{\partial f_C}} \widehat{\frac{df_C}{dp_B}} - \widehat{\frac{dc_A}{dp_B}}^T q_A - \underline{\widehat{\frac{dc_B}{dp_B}}^T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

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

Sidenote: An interpretation of Lagrange multiplier

- *Example*: Find *p*, *q* for an aircraft that minimize mission fuel expenditure (m_f) under max. take-off field length (s_{TO}) and other constraints

$$m_f^* = \min_{p,q} m_f$$
$$s_{TO} \leq s_{TO}^* \;(\rightarrow q_{s_{TO}})$$
$$etc.$$



- The measure of how much the goal would change per unit constraint change
  - An information highly sought for by designers

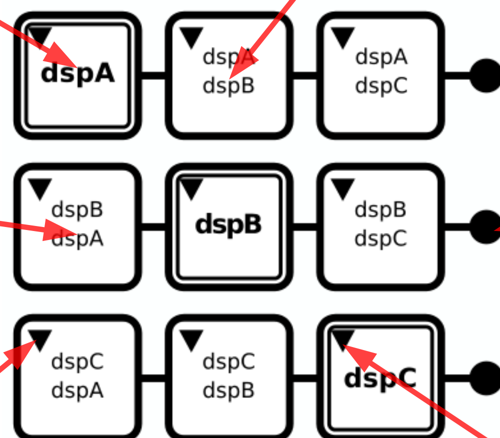
Why are we never reporting it?

The representation protocol

- Since the design equation is usually implied, use a schematic representation
- Let each row belong to one discipline (all related to its design parameters)

data dependencies
discipline A takes
from discipline B

disciplinary design
process



backbone-line indicating
that the row *belongs*
to one discipline
to converge it to zero

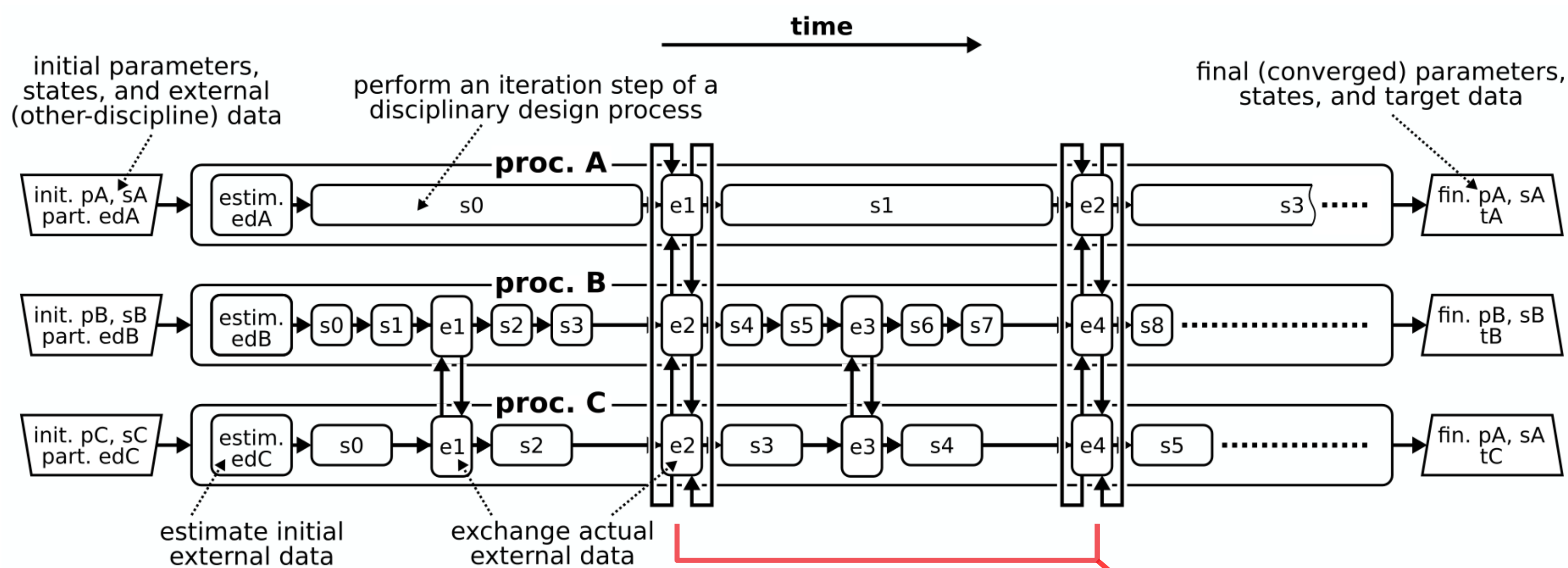
data dependencies
discipline B takes
from discipline A

indicator that also
design dependencies (Jacobian-like data)
is exchanded, and not only
consistency dependencies (state-like data)

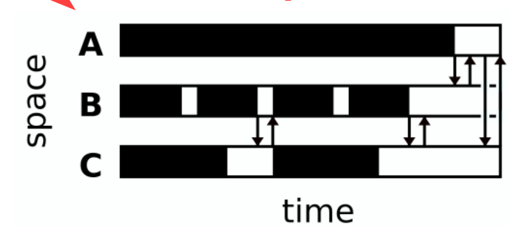
indicator that
the disciplinary design
also takes into account global goal

The communication protocol

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



practical visualisation:
the base period



- Different disciplines may have different exchange periods
- Selection of rows, steps and exchange periods recover any possible “MDO architecture”
  - **In practice always a hybrid architecture**

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Sidenote: *An* iteration with gradient based processes

- Assume all disciplinary processes A, B, C are gradient-based processes, using (different) off-the-shelf gradient-based optimization algorithms
- Step *k* of A (analogous for B, C) *could be* a single gradient computation plus the associated line/trust-region search

$$\frac{\widehat{\partial F}}{\partial f_A}\underline{\frac{\widehat{df_A}}{dp_A}}\Bigg|_{p_A^{k+1},p_{B,C}^k} + \left(\frac{\widehat{\partial F}}{\partial f_B}\frac{\widehat{df_B}}{dp_A} + \frac{\widehat{\partial F}}{\partial f_C}\frac{\widehat{df_C}}{dp_A} - \frac{\widehat{dc_B}}{dp_A}^T q_B - \frac{\widehat{dc_C}}{dp_A}^T q_C\right)_{p_{A,B,C}^k} - \underline{\frac{\widehat{dc_A}}{dp_A}^T q_A}\Bigg|_{p_A^{k+1},p_{B,C}^k} = 0$$

which an off-the-shelf optimizer can be tricked to perform by modifying the original disciplinary goal function in the step *k* as

$$\widetilde{f_A}\Big|_{p_A^{k+1},p_{B,C}^k} = \frac{\widehat{\partial F}}{\partial f_A}\Bigg|_{f_A^k}\underline{f_A}\Big|_{p_A^{k+1},p_{B,C}^k} + \left(\frac{\widehat{\partial F}}{\partial f_B}\frac{\widehat{df_B}}{dp_A} + \frac{\widehat{\partial F}}{\partial f_C}\frac{\widehat{df_C}}{dp_A} - \frac{\widehat{dc_B}}{dp_A}^T q_B - \frac{\widehat{dc_C}}{dp_A}^T q_C\right)_{p_{A,B,C}^k}(p_A^{k+1} - p_A^k)$$

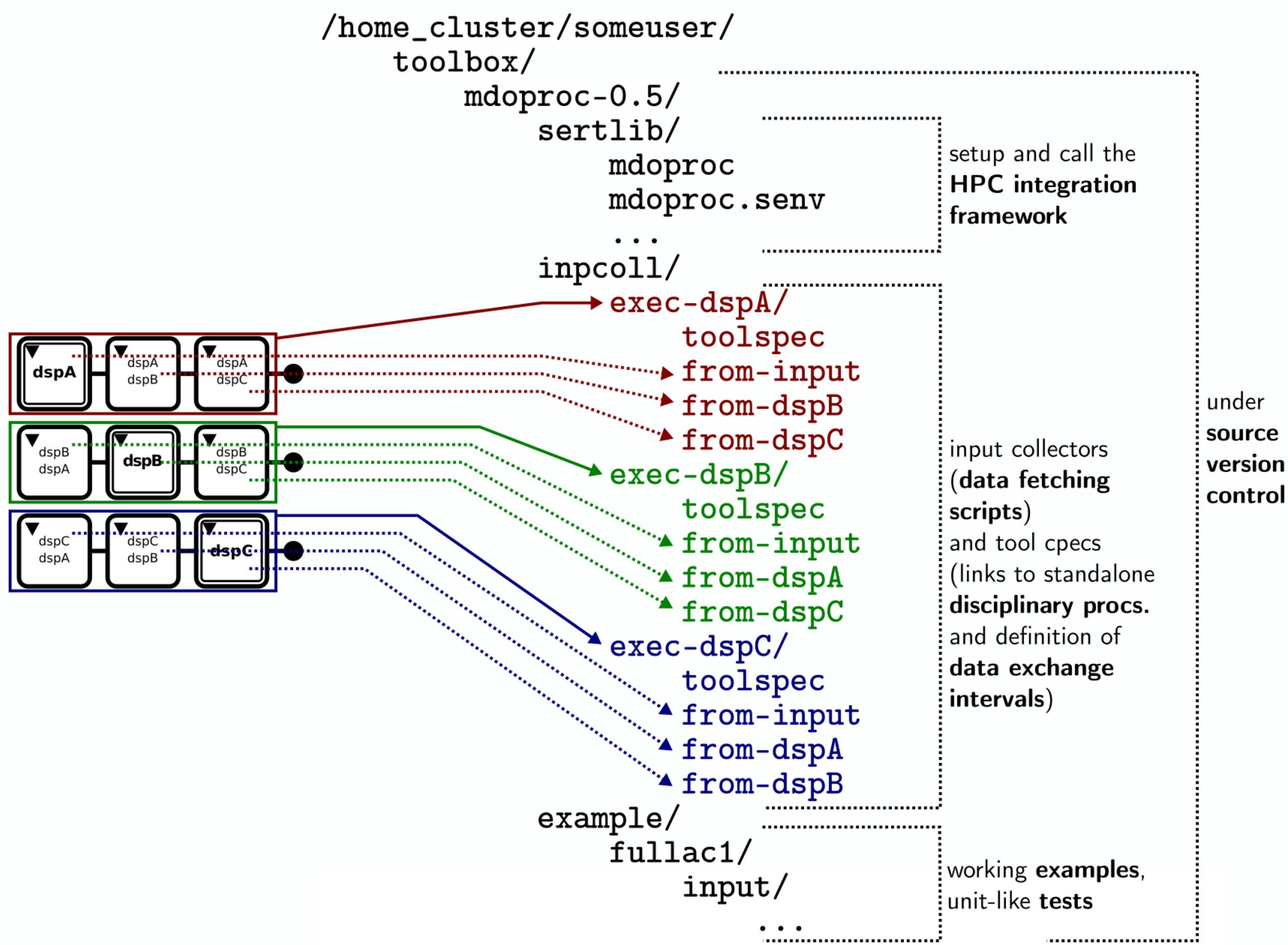
linearized “penalty” – how much to “give up” for other disciplines

- The same idea and rationale as e.g. for coupled-adjoint gradient evaluation
  - Jacobi/Gauss-Seidel fixed-point block-iteration to couple processes, each using the best method for its internal iteration, with “rhs modification”

A realization on HPC clusters

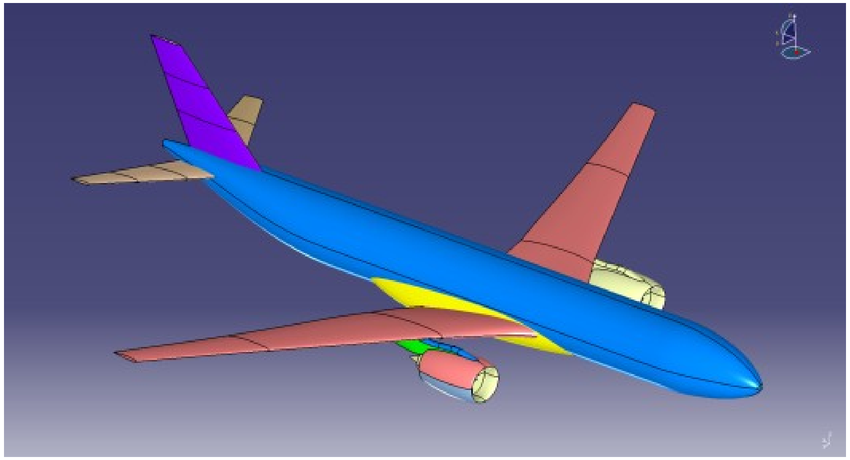
- A cybermatrix HPC process integration framework in development
  - Starts disciplinary processes, assigns resources, monitors progress
  - Triggers data exchanges and determines global convergence
- Disciplinary experts do not work with the framework directly
  - No need to learn yet another integration framework
  - Only provide **input collector** scripts to copy data from other disciplines
  - The whole MDO process implementation: a directory of input collectors
- Maintainable by standard software engineering tools and practices
  - Set of input collectors under source version control
  - Integration framework is an **interpreter** of the set of collectors and some meta-data (data exchange periods, etc)
- Currently data exchange performed over parallel on-disk file system
  - Parallel in-memory or area-network file system possible in principle
  - No changes to disciplinary processes in any case

On-machine appearance

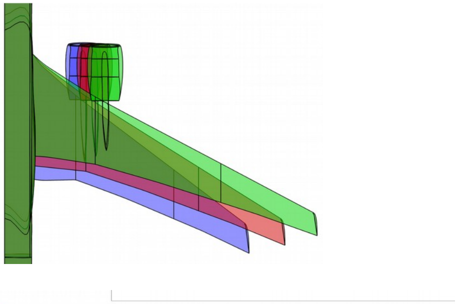


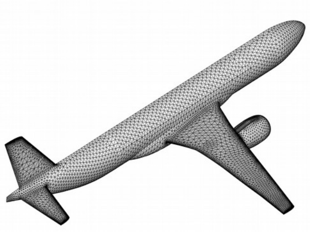
Example: MDO of a long-range transport aircraft

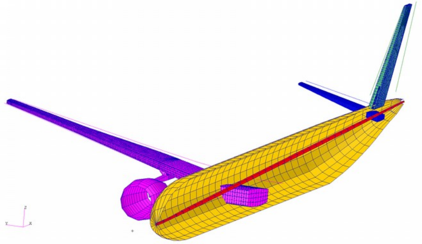
- Large twin-engine wide-body long-range transport aircraft
  - Wing-body-tail-pylon-flow through nacelle
  - 250 t max. take-off mass class
- Global goal function: **minimize fuel consumption**

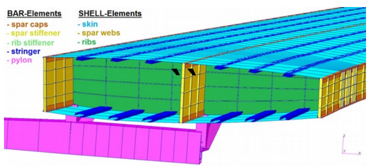


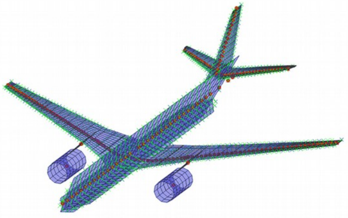
- Involved disciplinary processes:
  - Overall aircraft wing planform design (**oad**)
  - Aerodynamic design of wing airfoils (**aero**)
  - Structural member sizing of wing and tail (**struct**)
  - Determination and evaluation of design loads (**loads**)

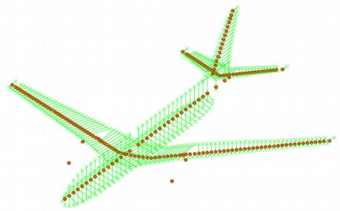












Example: Problem setup

oad
Rolling trade study
(tuned trust reg. SQP)
CAD+ROM wing shape,
< 10 design parameters
Minimize mission fuel
Step: one QP approx.
and trust reg. step

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

total mass

total drag

wing planform

global FEM, CoG

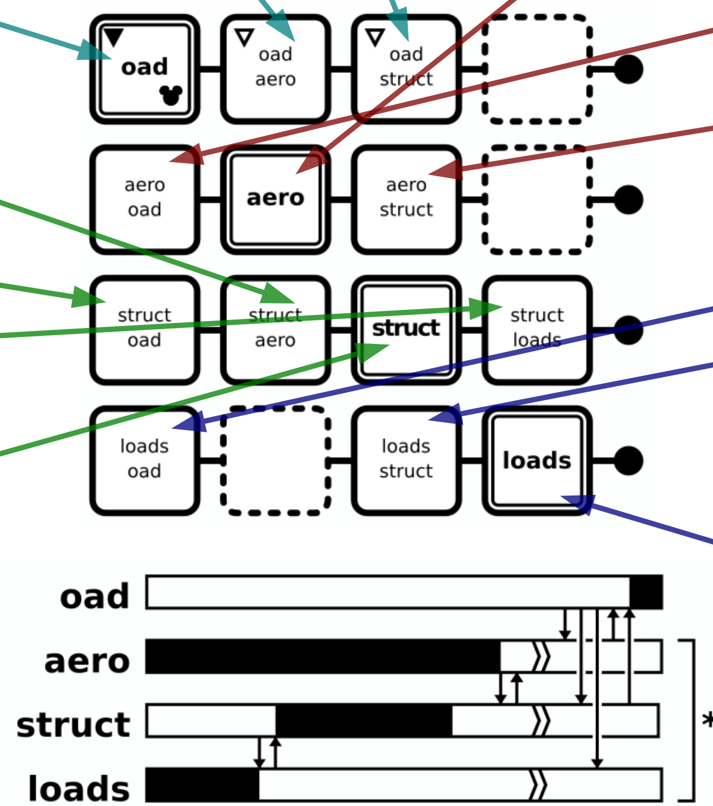
airfoil shapes

wing planform

design loads

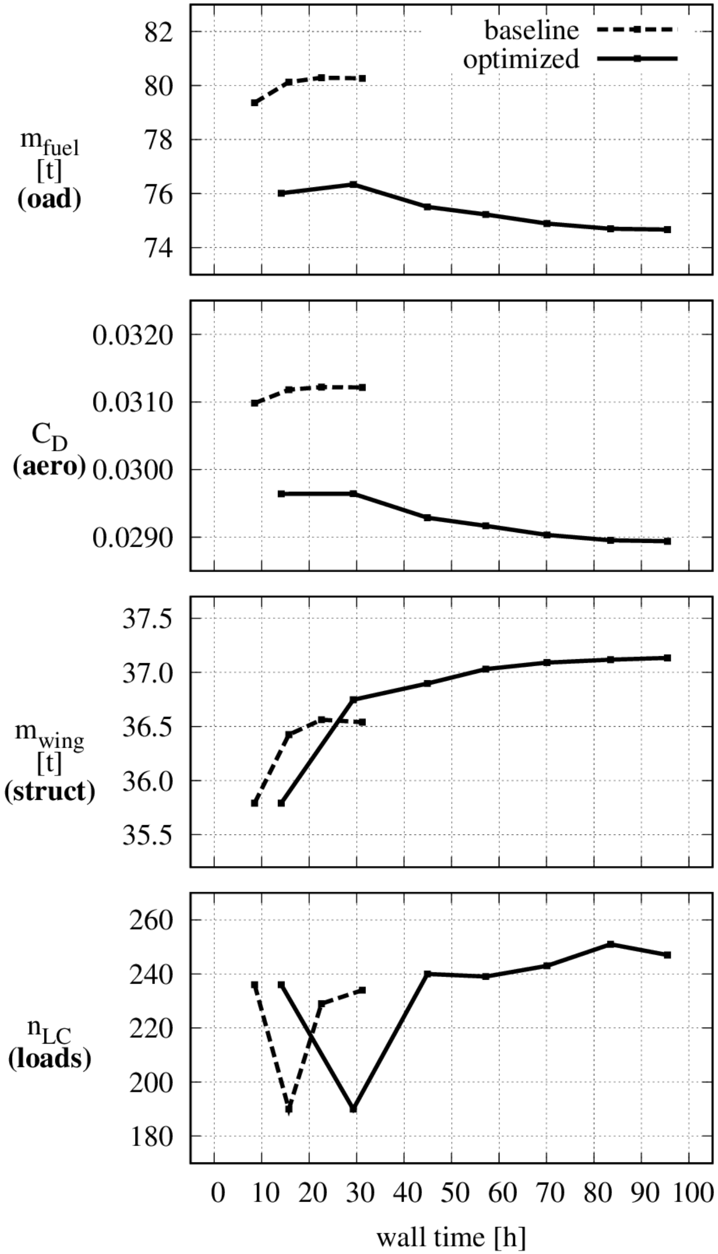
wing planform

dynamic FEM, MCs



struct
Fully-stressed design
Global FEM, 42,000 els
Model region thicknesses,
364 design parameters
Minimize mass for limit
strength, buckling per LC
Step: one full sizing

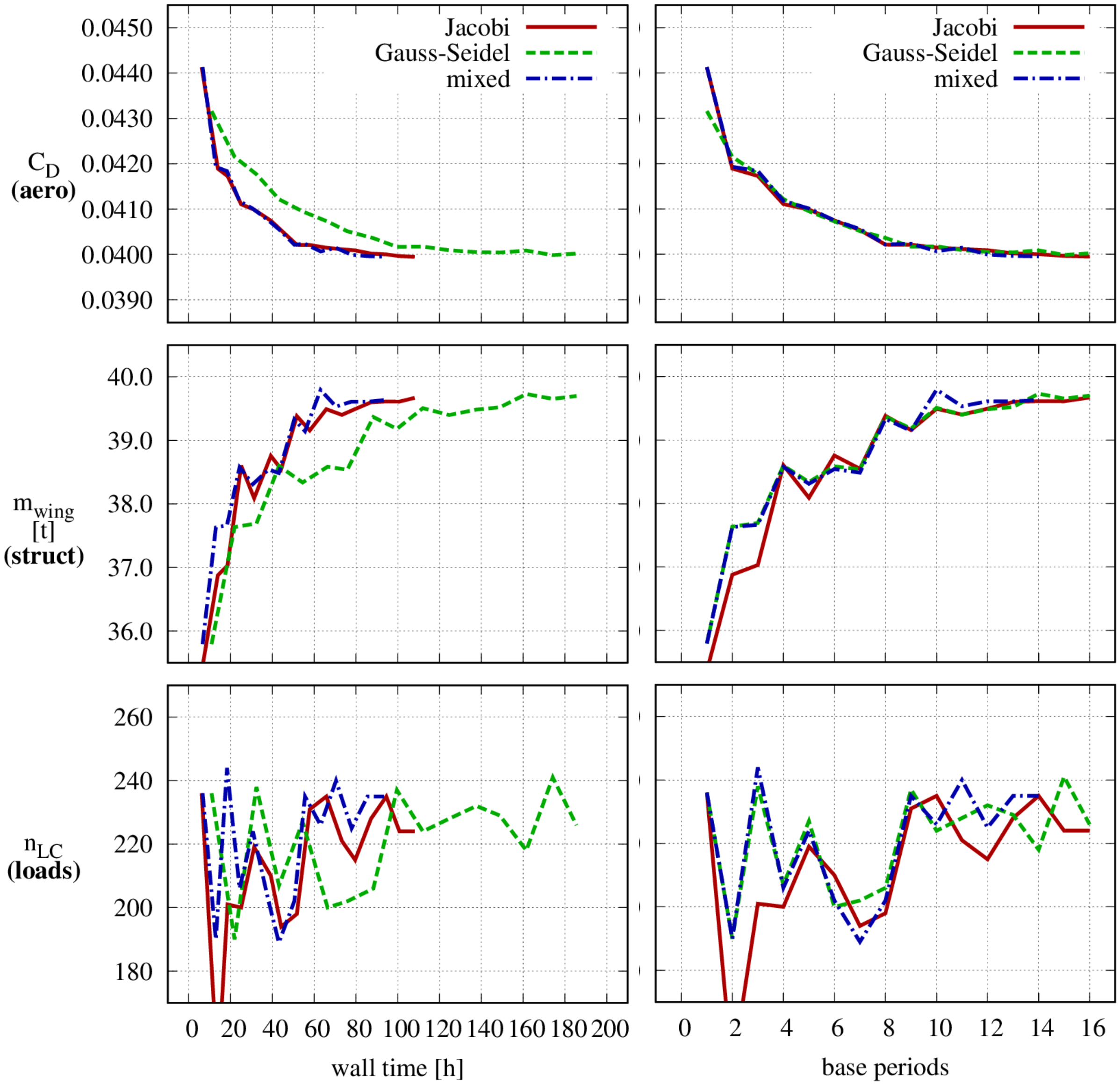
loads
Dynamic gust, turbulence
Dynamic FEM, 1,060 DoF
Panel aero, 1,160 boxes
1,200 LCs / 2 MCs
No goal/cons./design par.
Step: one full evaluation



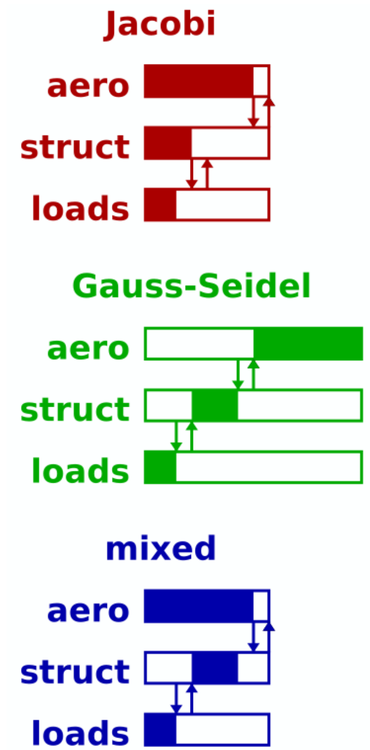
Example: Optimization results

- Still robustness problems on planform variations, so planform fixed → **oad** only for evaluation
- Total run time:**98 hours** on **192 cores**
  - Base period duration: 13.9 h avg
- Drag reduction (**-7.2%**) more significant than mass increase (**1.6%** wing, **0.16%** total), resulting in mission fuel reduction **(-6.9%**)
  - Wing sections slightly retwisted and reshaped to reduce shock waves
  - Somewhat less favorable spanwise load distribution results in higher design loads
  - Variation in number of design load cases not large, but not negligible
- What is the baseline for comparison?
  - Time 0 on wall-time axis has no meaning
  - Intention-dependent: here result of an optimization with fixed **aero** design param.

Sidenote: Jacobi, Gauss-Seidel, mixed iteration

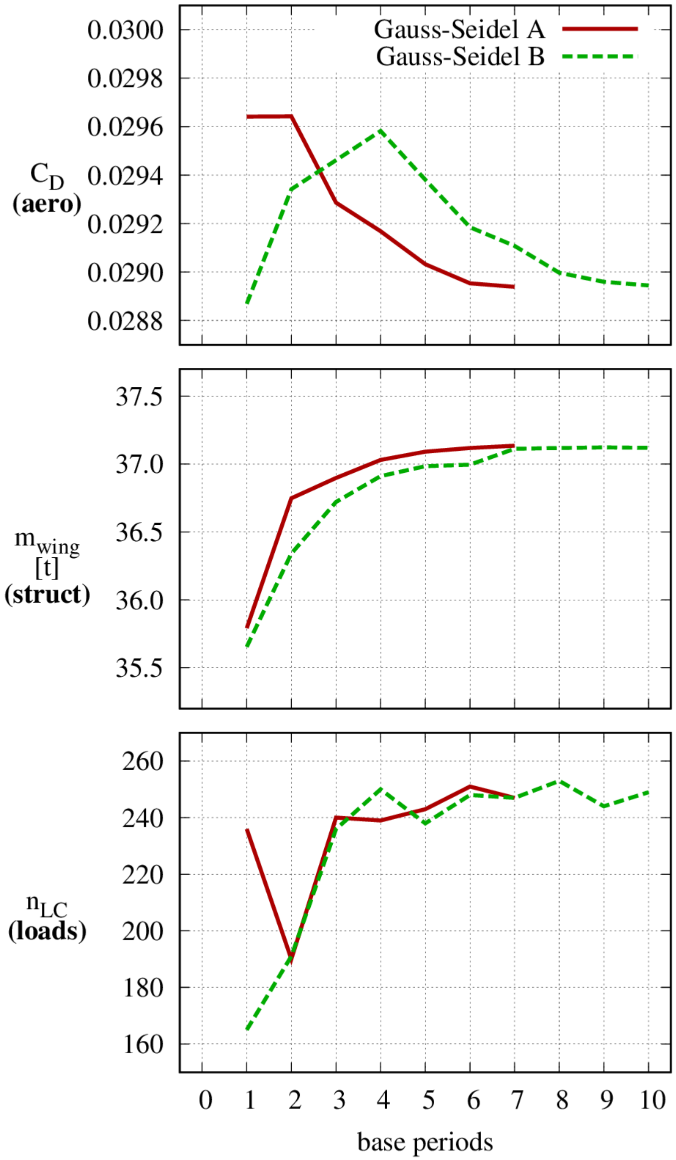


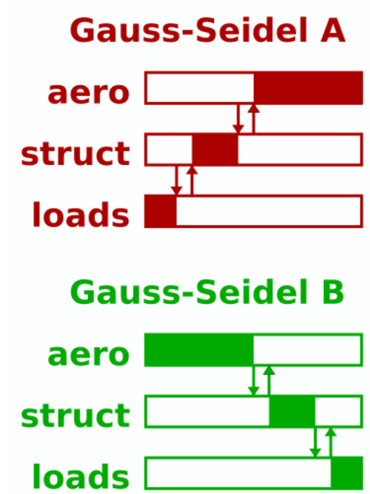
- Performed with a coarser CFD mesh



- What does this reveal about the problem?

Sidenote: Which process "must" run before which?



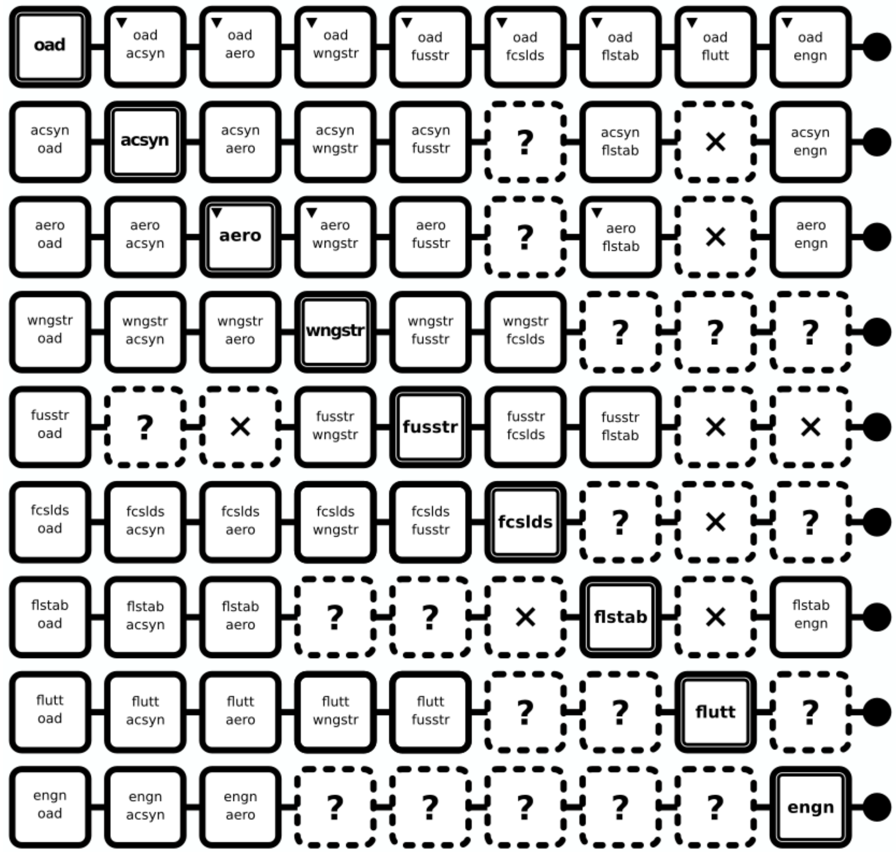


- Just a difference in time to convergence
- Though if multiple optima, could fall into a different one

Conclusions and outlook

- A core of a cybermatrix-based MDO process demonstrated
  - Aero-structural approximate overall aircraft optimization with configuration-dependent variable number of design load cases
  - Maneuver and gust loads process following certification regulations
  - CAD-based shape parametrization through reduced order modeling
- Improvement to the core process
  - More robustness in local design on planform variations
  - More flight points and powered engine for aerodynamic design
  - Control laws and high-fidelity corrections for loads
  - More design dependencies (Jacobian-like information)
- Beyond the core process
  - Higher fidelity structural modeling (separate wing/fuselage disciplines)
  - Tighter geometry and mass synthesis (aircraft synthesis discipline)
  - Configuration-dependent engine conceptual design (engine discipline)
  - Flutter analysis (to eliminate planforms exhibiting inherent flutter)

Thank you for your attention!



...plans of penguins and people...