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Bilevel MDO Process Applied To Strut Braced Wing Configuration

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Outline

1. Context
2. The Bilevel MDO Approach
3. Implementation
4. The Strut Braced Wing Use Case

The Initial Optimization Problem

$Min_{X\in\mathbb{R}^N}$ fuel_burnt(X) with $X = [\text{planform, structure variables, wing profiles}]$

s.t.

$\text{structure\_reserve\_factor}(X) \leq 0$

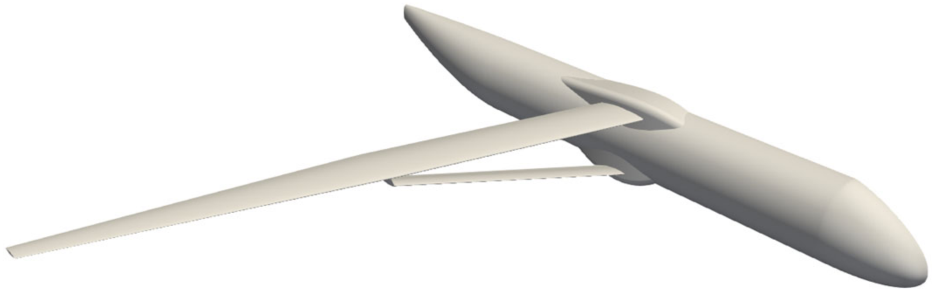
$\text{flutter\_ratio}(X) \leq 0$

$X_{lower} \leq X \leq X_{upper}$

Solver 1: **FEMWET** – static aero-structure model

Solver 2: SHARPy – dynamic aero-elastic model

Solver 3: **RAZOR** – High-fidelity correction based on data-driven reduced order model

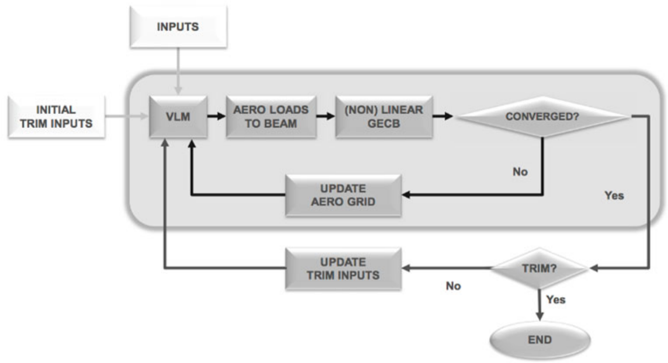


The Tools (solvers)

$$\begin{matrix}\text{Aero}\\ \text{Structure}\\ \text{Weight/Lift}\\ \text{VLM/MSES 2D}\end{matrix}\quad \begin{bmatrix} A(X,\, \Gamma,\, U,\, \alpha) \\ S(X,\, \Gamma,\, U) \\ W(X,\, \Gamma) \\ C(X,\, \Gamma,\, U,\, \alpha,\, \alpha_i) \end{bmatrix} = 0$$

FEMWET: static aero-structure optimization in MATLAB

- Quasi-three-dimensional aerodynamic solver;
- Equivalent finite beam element method for composite structure;
- Coupled-adjoint sensitivity analysis augmented by Automatic Differentiation.

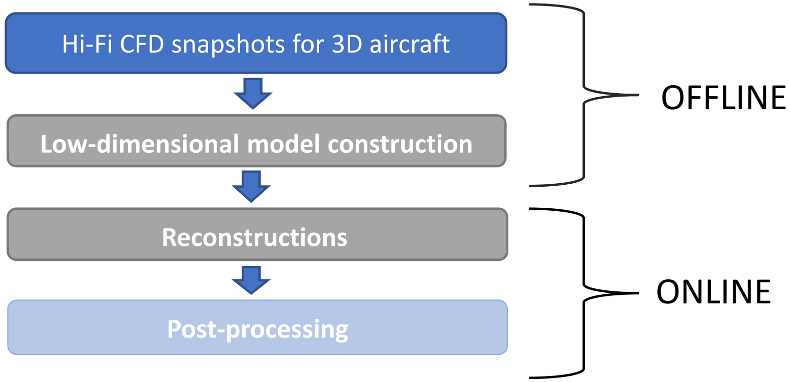


SHARPy: dynamic aero-elastic in Python

- Aerodynamic based on UVLM;
- Geometrically non-linear beam formulation;
- Flutter instabilities computed around the non-linear trimmed equilibrium;
- No gradient computation.

RAZOR: reduced order modeling for CFD in C++

- POD-based method;
- Provide HiFi-based corrections for FEMWET and SHARPy.



How To Solve The Problem?

$Min_{X \in \mathbb{R}^N}$ fuel_burnt(X) with X = [planform, structure variables, wing profiles]

s.t.

structure_reserve_factor$(X) \leq 0$

flutter_ratio$(X) \leq 0$

$X_{lower} \leq X \leq X_{upper}$

X large -> gradient-based optimization

Coupling schema: N2 diagram

RAZOR	Correction_1 (drag coeff)	Correction_2 (sectional polars)
FEM model	**FEMWET**	FEM, panels…
		SHARPy

No access to the full analytical coupled jacobian (RAZOR/FEMWET/SHARPy): the MDF (Multi-Disciplinary Feasible) is not affordable

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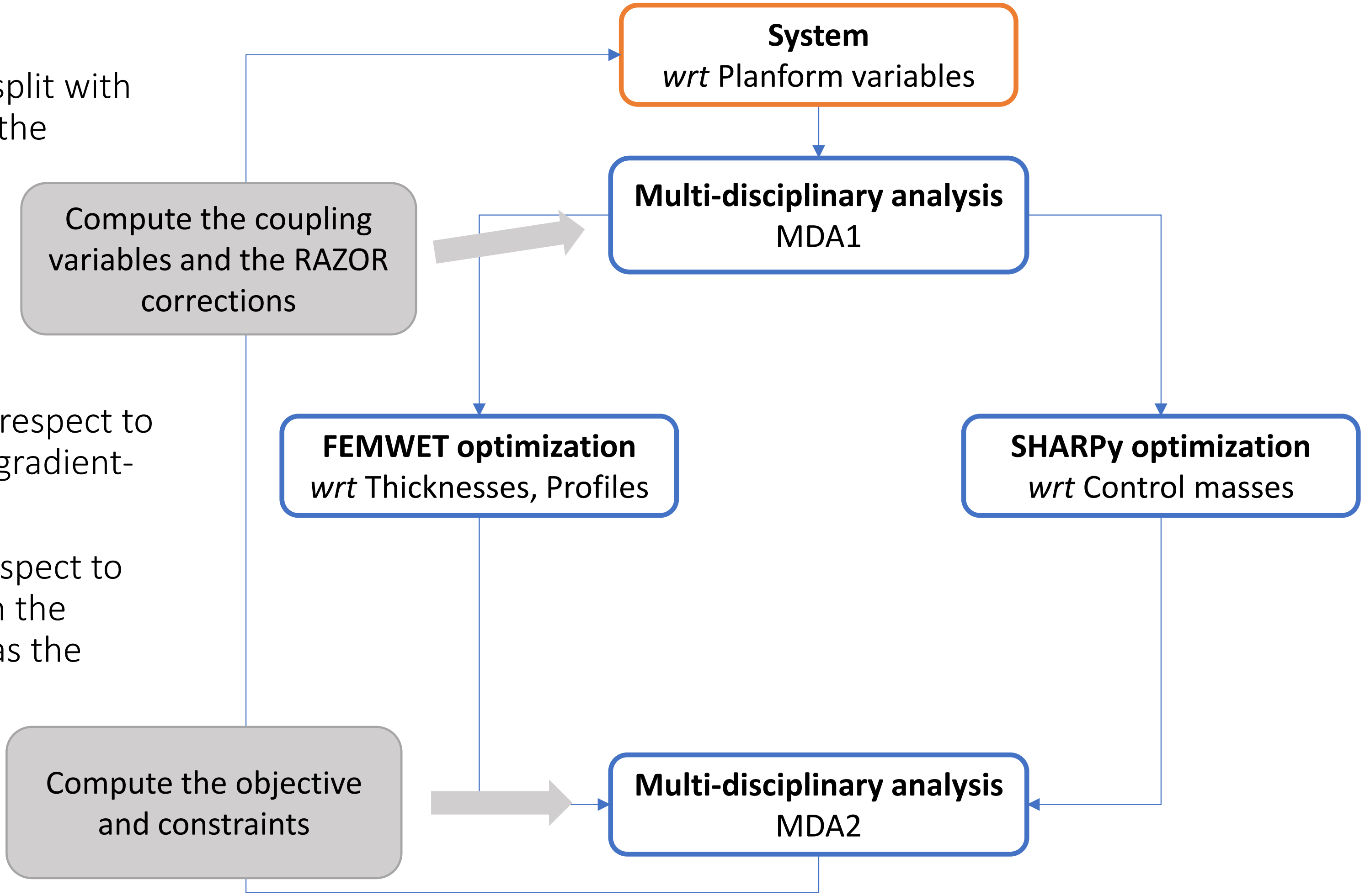
The Bilevel Approach

Divide and conquer: the problem is split with respect to the design variables and the capabilities of the tools

Formulation:

- The System Level optimizes with respect to the shared variables based on a gradient-free algorithm
- The Local Levels optimize with respect to the local variables, depending on the gradient access (e.g. FEMWET has the coupled adjoint)



The Bilevel Optimization Problem

$$Min_{x_0 \in \mathbb{R}^{N_0}} \text{fuel\_burnt}(x_0, x_f^*, x_s^*)$$

System level

s.t.

$$\text{femwet\_constraint} = \begin{cases} \text{structure\_reserve\_factor}(x_0, x_f^*, x_s^*) \leq 0 \\ \text{fuel\_volume}(x_0, x_f^*, x_s^*) \leq 0 \\ \text{takeoff\_requirement}(x_0, x_f^*, x_s^*) \leq 0 \\ \text{mission\_consistency}(x_0, x_f^*, x_s^*) = 0 \\ x_{f\,lower} \leq x_f \leq x_{f\,upper} \end{cases}$$

$$\text{sharpy\_constraint} = \begin{cases} \text{flutter\_ratio}(x_0, x_f^*, x_s^*) \leq 0 \\ x_{s\,lower} \leq x_s \leq x_{s\,upper} \end{cases}$$

System level constraints

$$x_f^* = argmin_{x_f \in \mathbb{R}^{N_f}} \text{fuel\_burnt}(x_0, x_f, x_s) \text{ s.t. femwet\_constraint}(x_0, x_f, x_s)$$

$$x_s^* = argmin_{x_s \in \mathbb{R}^{N_s}} \sum \text{control\_masses\_values s.t. sharpy\_constraint}(x_0, x_f, x_s)$$

The local optimizations

$$x_{0\,lower} \leq x_0 \leq x_{0\,upper}$$

- x_0 = planform
- x_f = femwet_variables = [structure_thicknesses, wing_profiles, mission_target]
- x_s = sharpy_variables = [control_masses_values, control_masses_location]
- $X = [x_0, x_f, x_s]$

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Process Implementation – The Framework

GEMSEO

created in 2015 at IRT Saint Exupéry / MDO Competence Center

Generic Engine
for Multidisciplinary Scenarios,
Exploration and Optimization

- Automation of MDO processes based on MDO formulations
- Features: coupling, optimization, design of experiments, visualization, surrogate modeling, machine learning, uncertainty quantification, ...
- Easy to embed in simulation platforms or to use as a standalone software
- Can use tools in Python, Matlab, Excel, Scilab, executables, ...

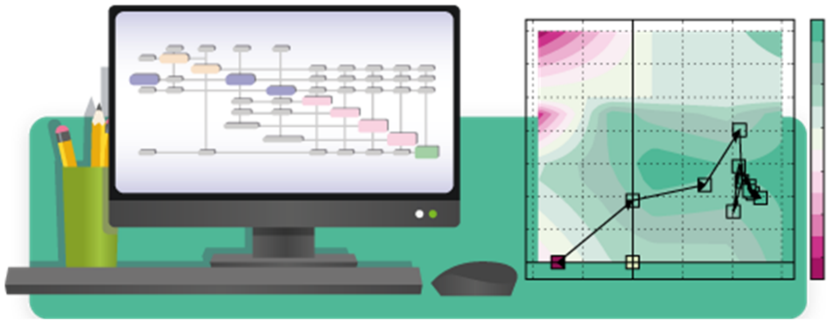
https://gemseo.readthedocs.io

User guide
Notebooks

open source
(May 2021)
GNU LGPL v3.0
+ Private plugIns

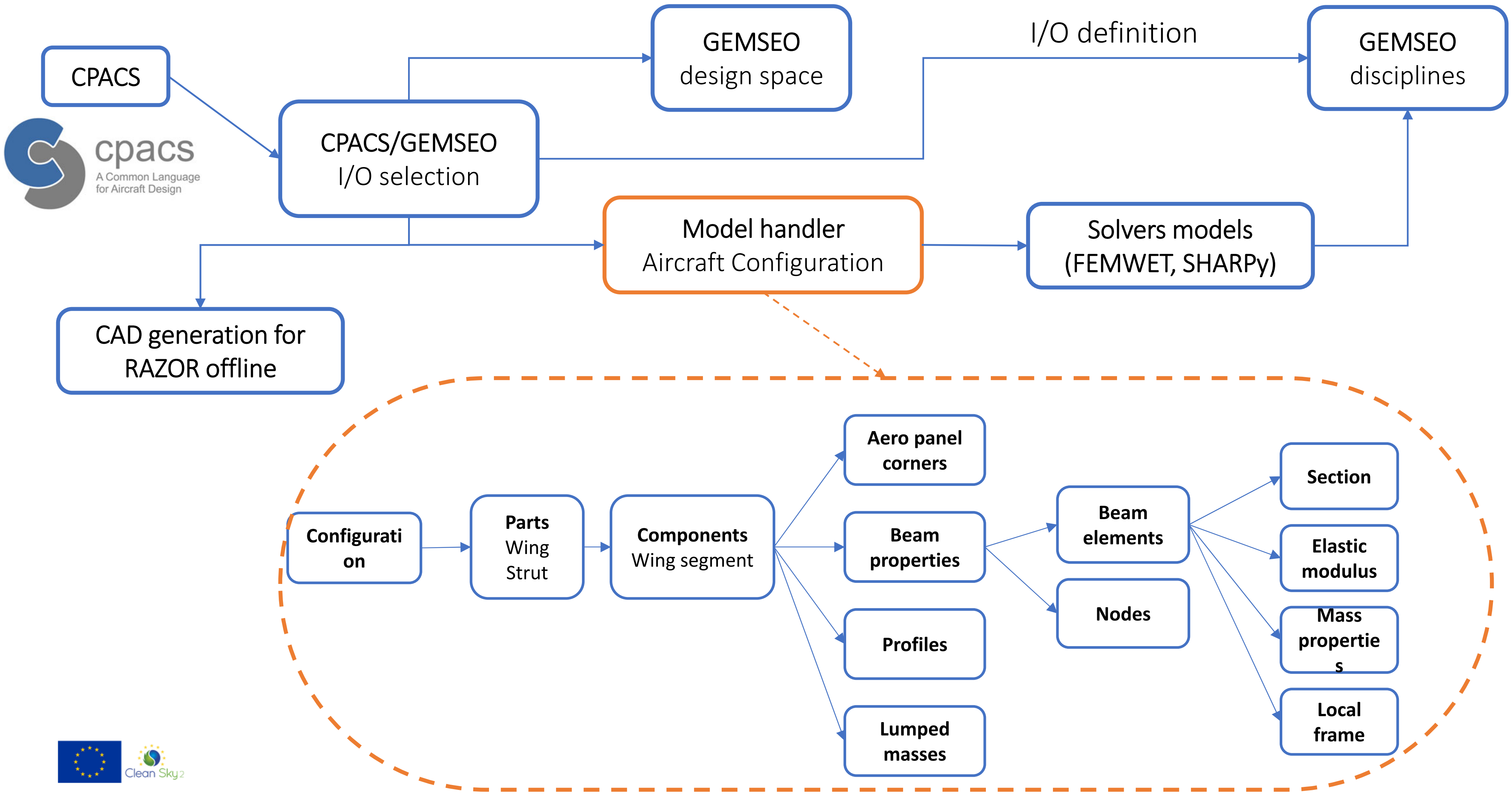
Python

Code quality
Testing
Documentation
Continuous
Integration

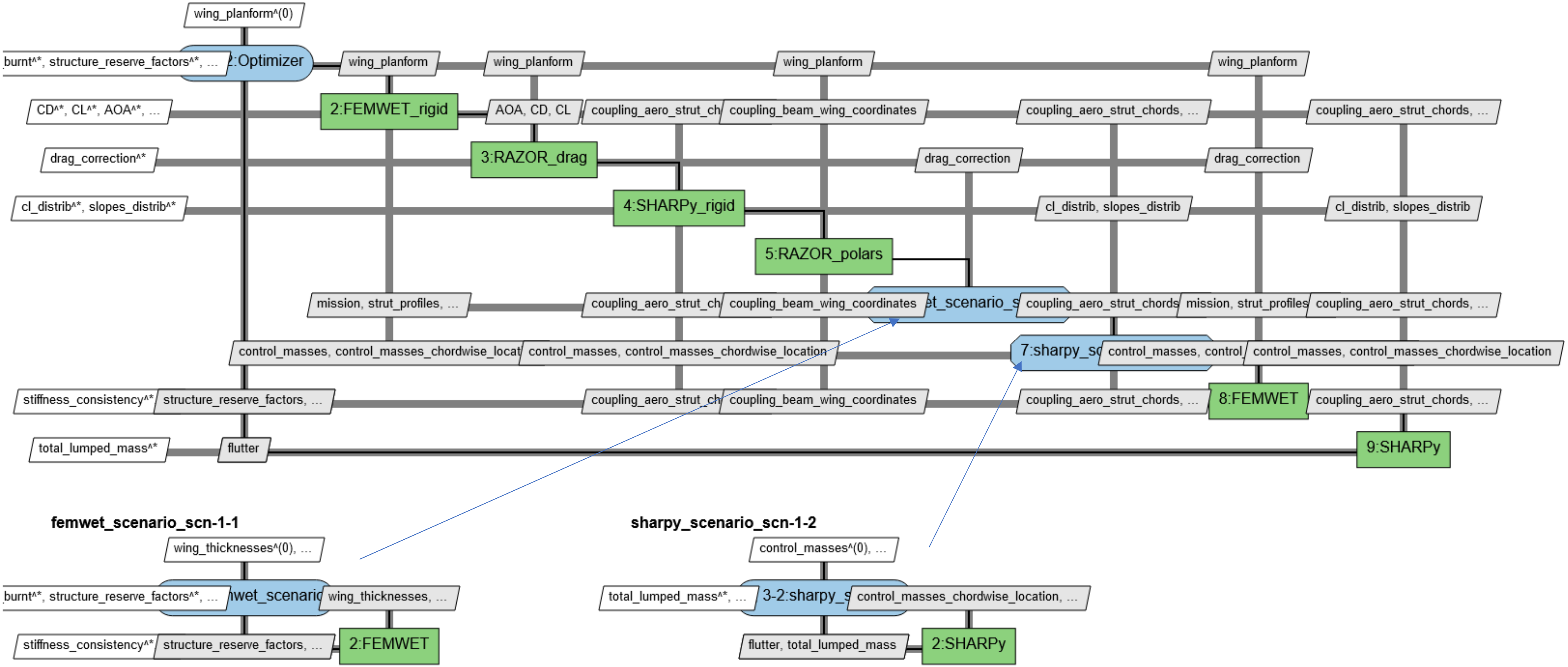


GEMSEO and its plug-ins are on GitLab
gitlab.com/gemseo/dev

Process Implementation – Need To Fill The Gap Between Tools



Bilevel Process: XDSM



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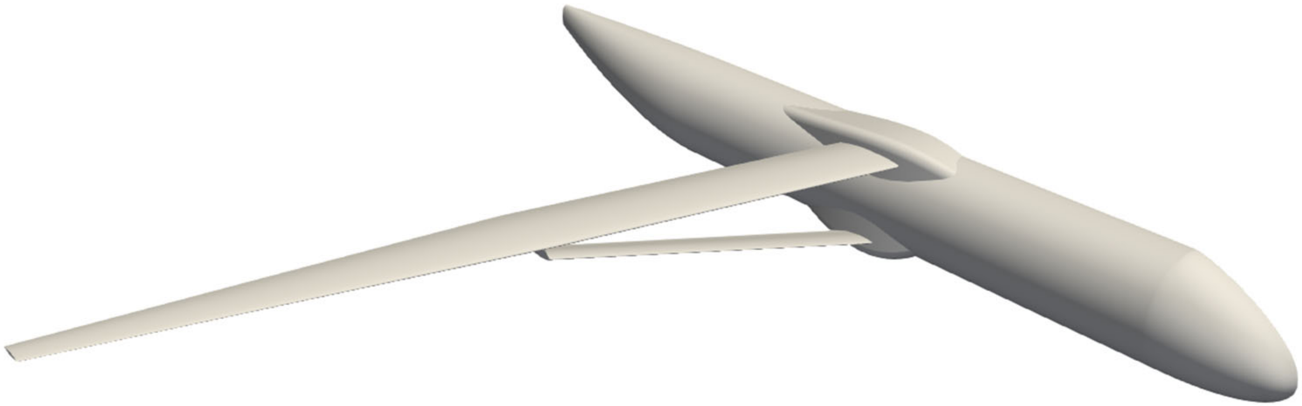
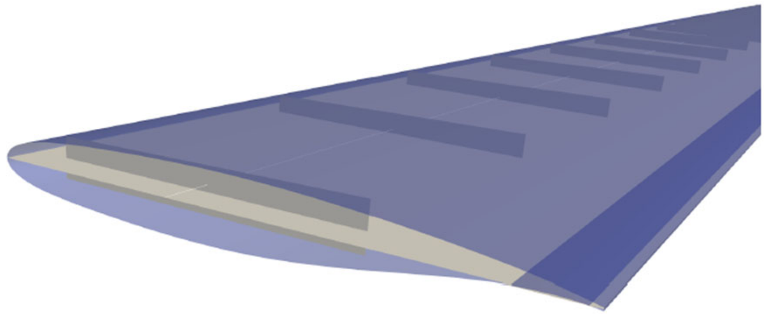
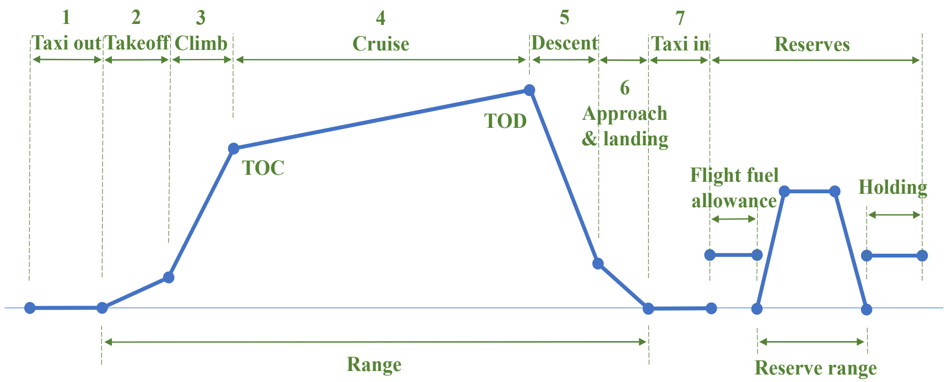
The Strut-Braced Wing For Middle Range (SBW-MR)





Variables	Optimization Level	Number
Planform	System	6
Wing box thicknesses	FEMWET	40
Strut box thicknesses	FEMWET	28
Wing profiles	FEMWET	50
Strut profiles	FEMWET	3
Mission	FEMWET	2
Control masses values	SHARPy	3
Control masses location	SHARPy	3

TOTAL = 135



Requirements referred to that of A320neo

4 Load cases:
- 2* Pull-up
- Push-down
- Cruise

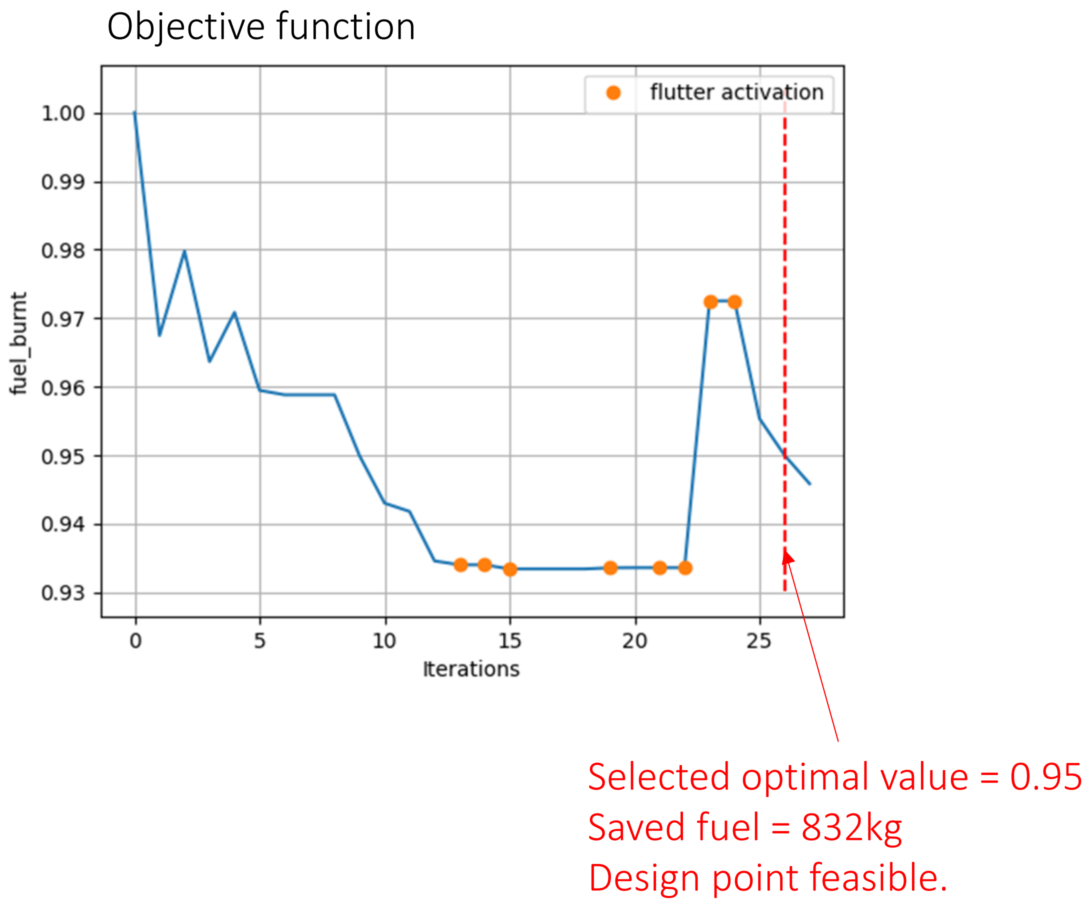
Optimization Results – Objective Function

Optimization algos:

- System level = COBYLA
- FEMWET level = SNOPT
- SHARPy level = COBYQA

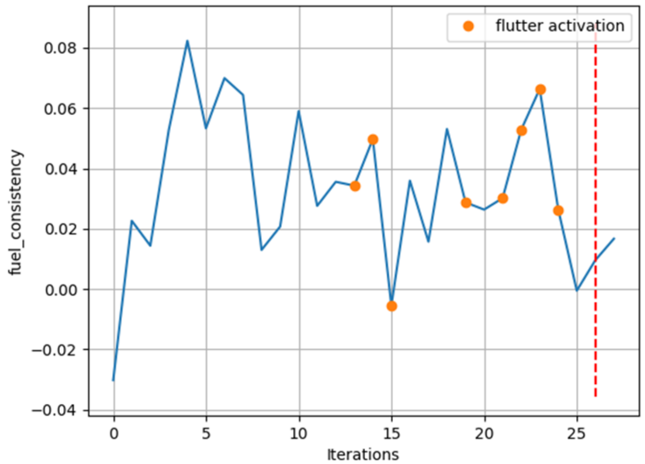
CPU time (approx) :

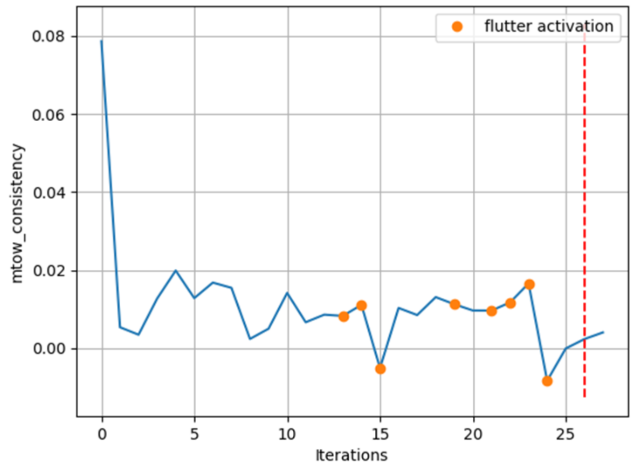
- FEMWET optim (all load cases) = 7-8h
- SHARPy optim = 1.5h
- MDA with correction (FEMWET rigid + RAZOR + FEMWET flexible) = 1.5h
- 25 system iterations = 10-11 days

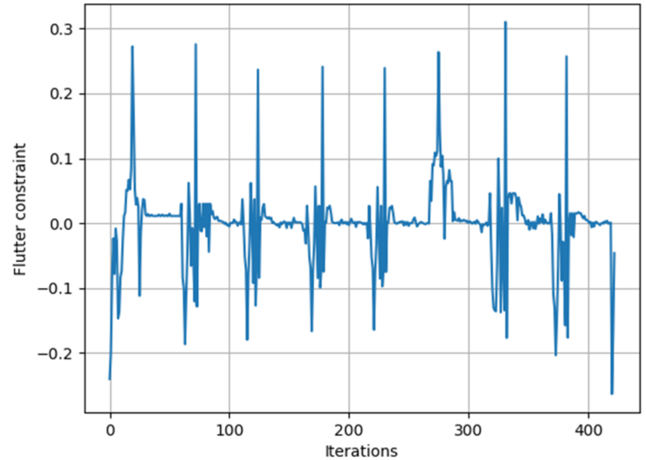


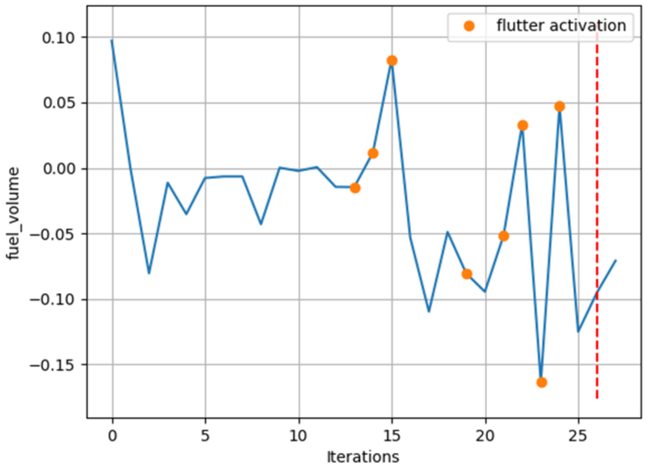
Optimization Results - Constraints

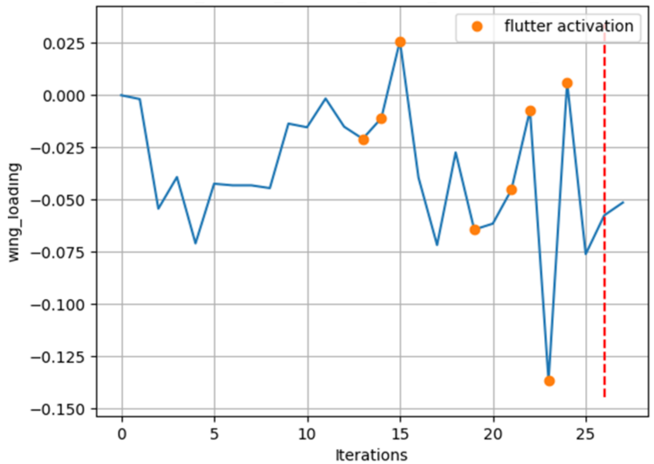
Flutter: concatenation of evaluations



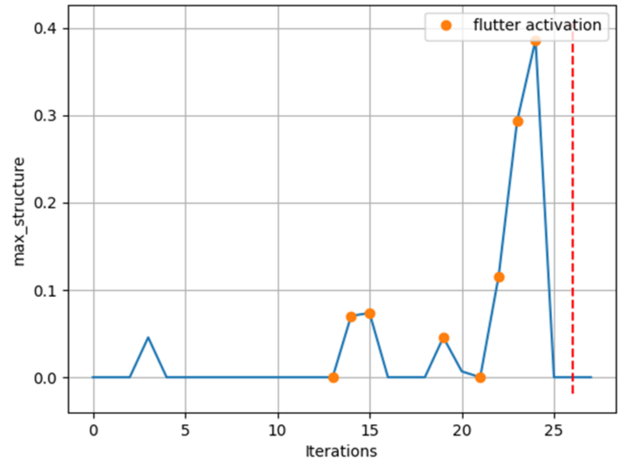




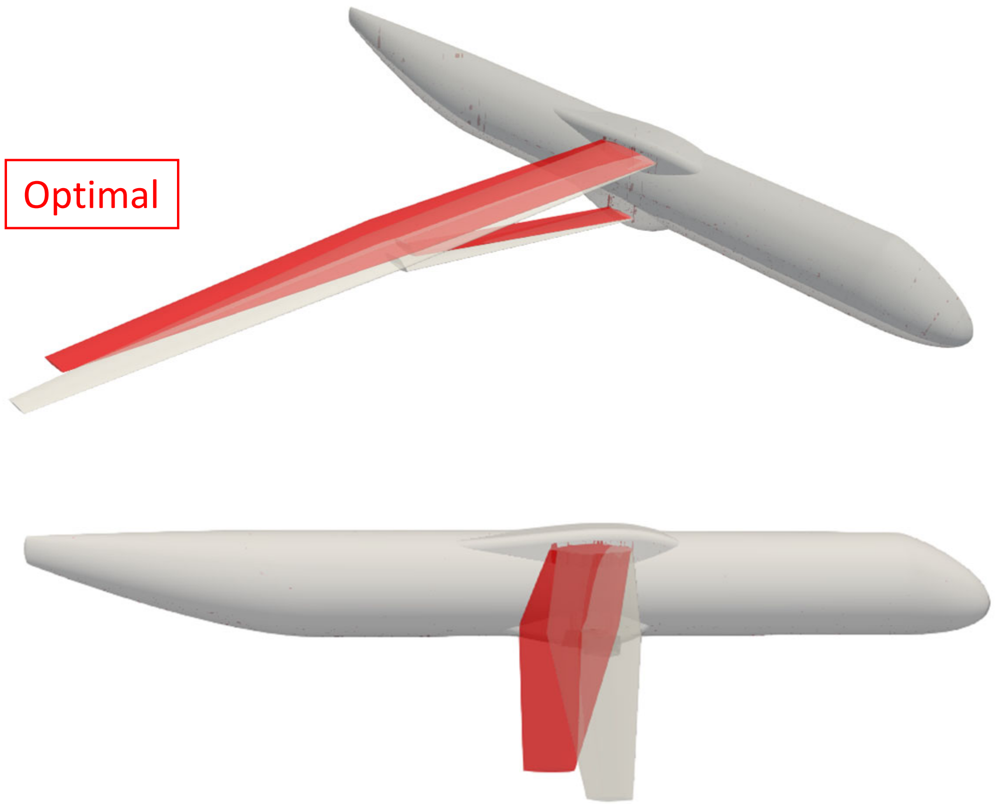


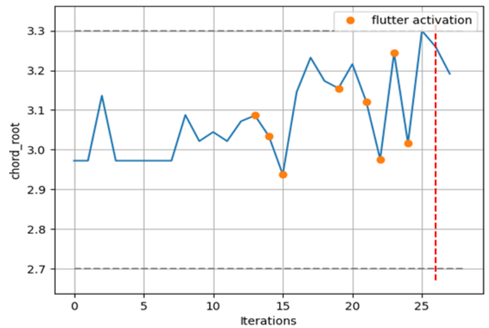


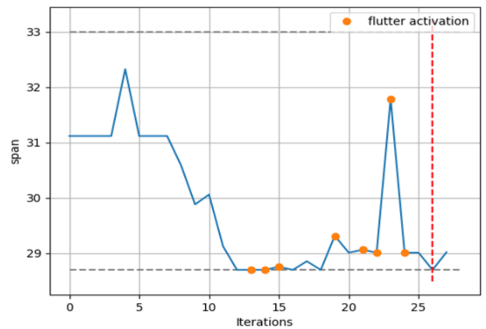
RF structure

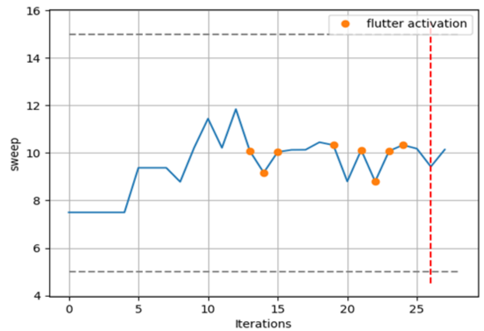


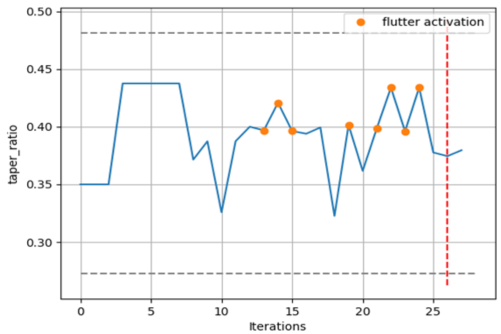
Optimization Results - Planform

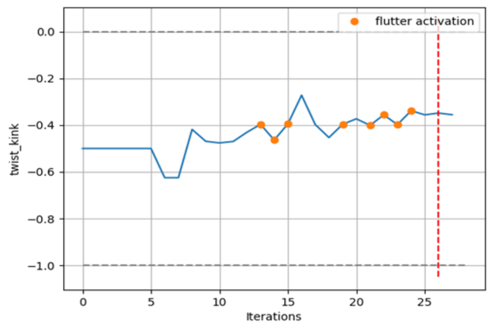


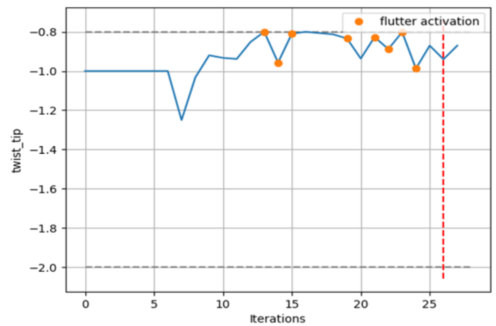




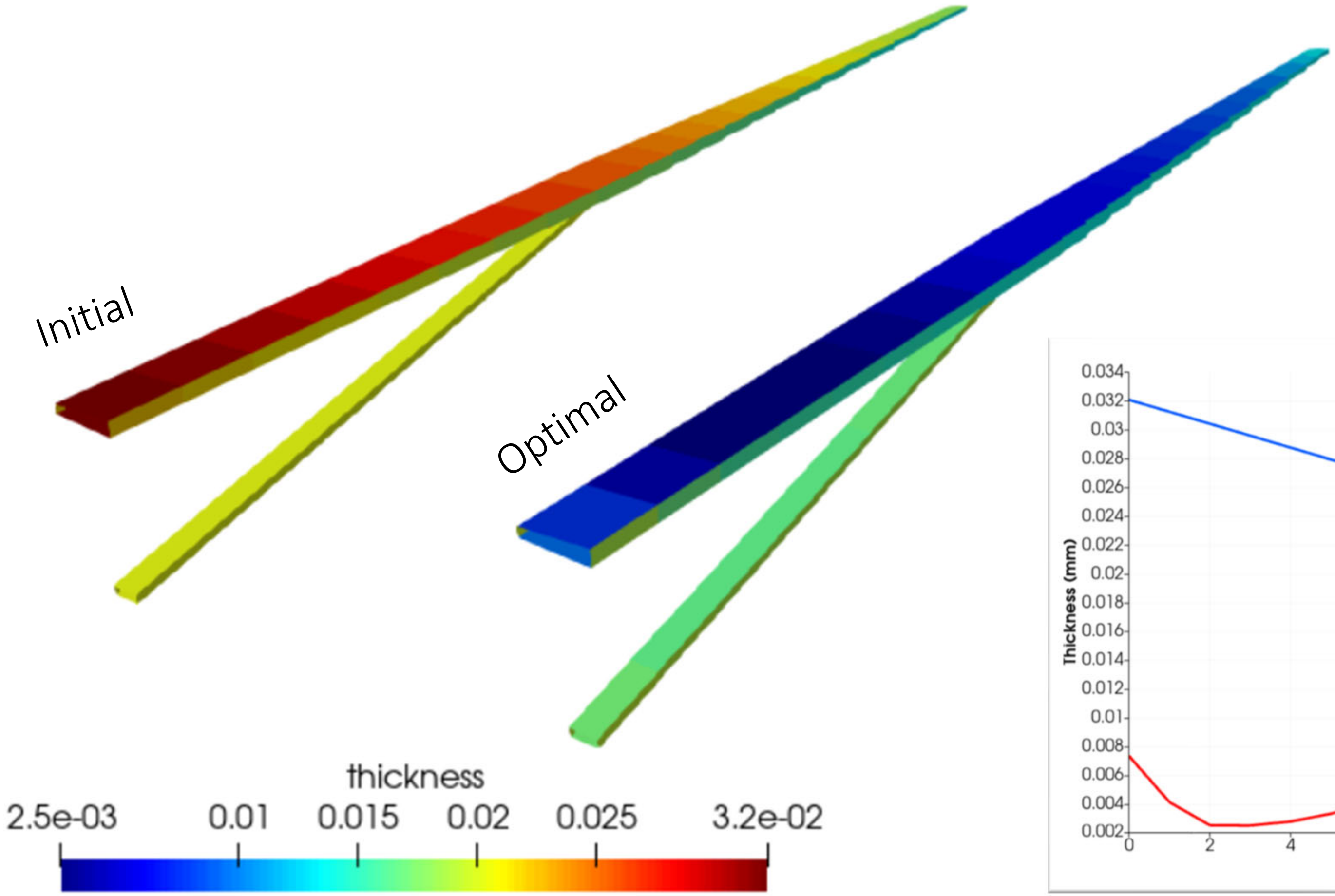


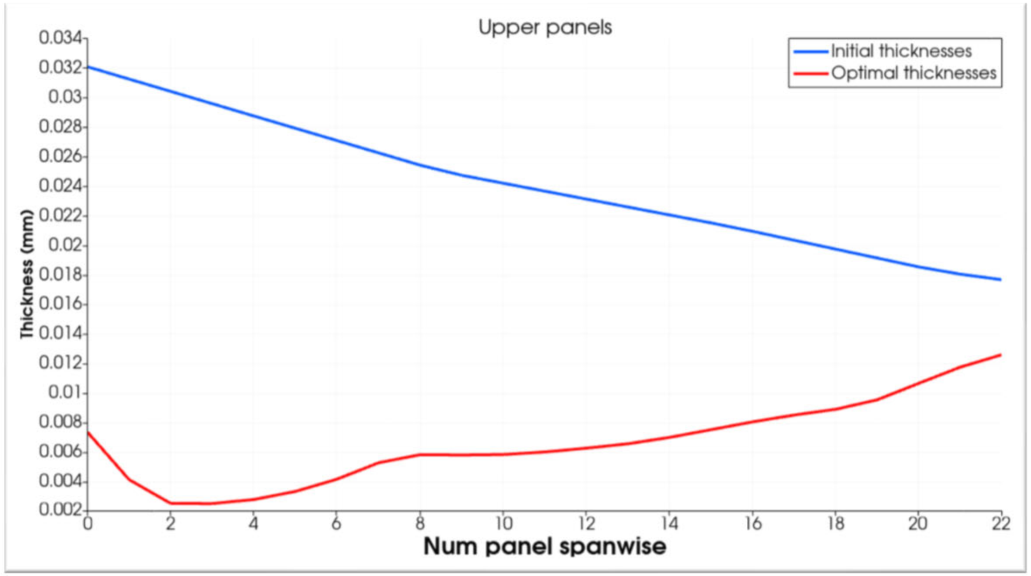






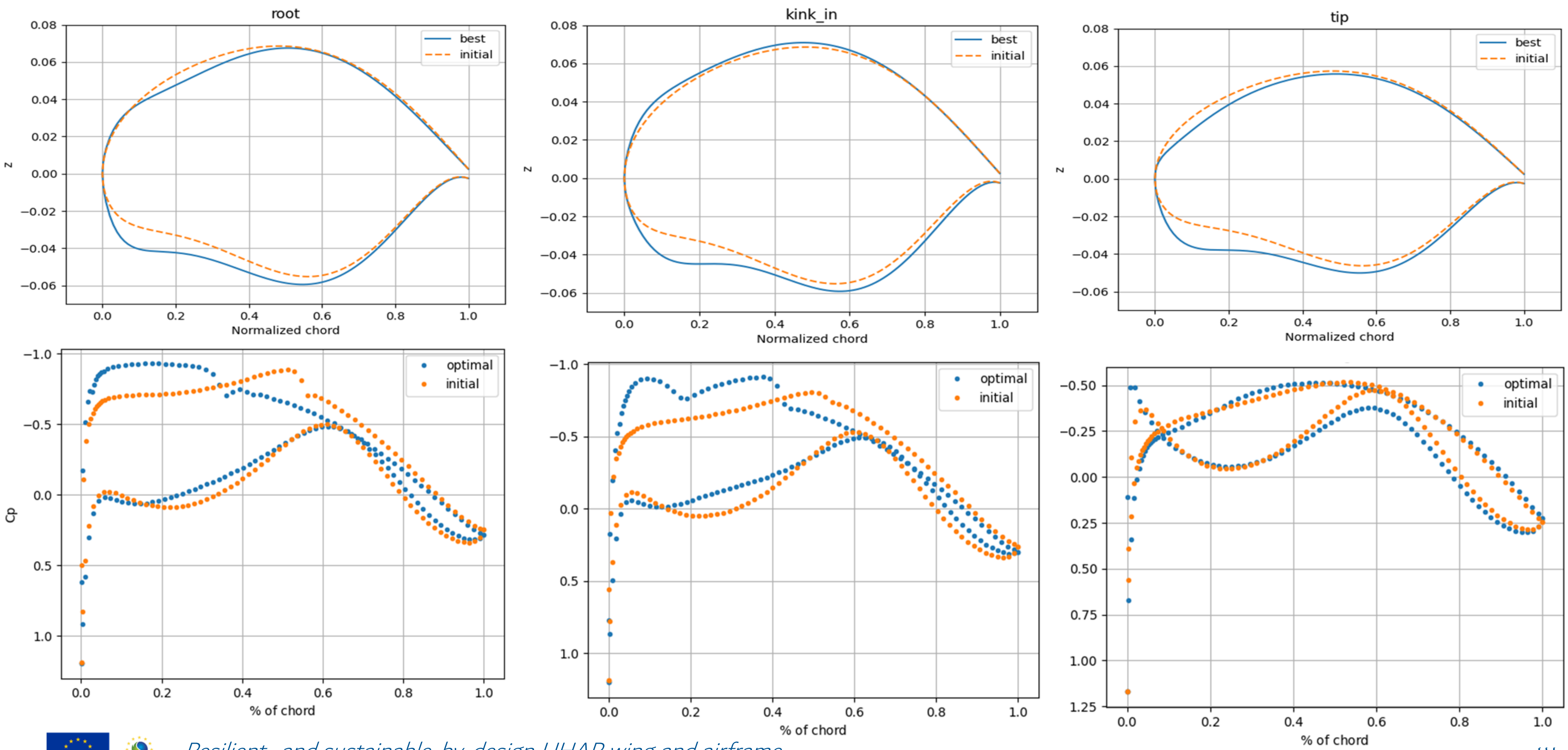
Optimization Results - Thicknesses





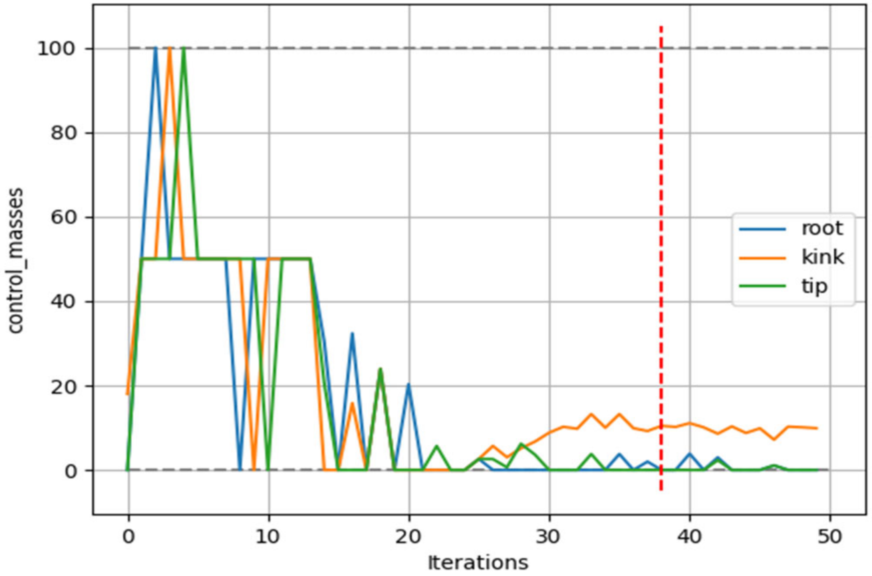
Optimization Results - Profiles

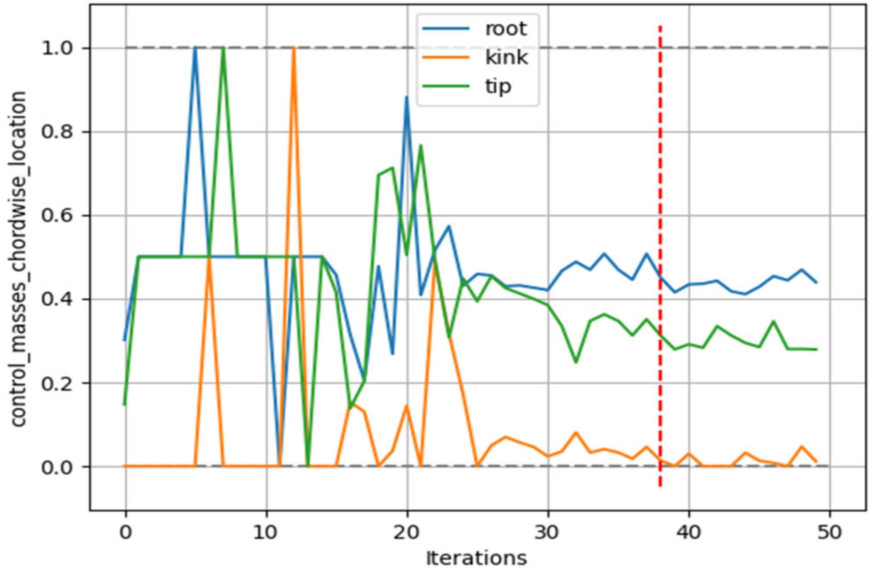
Turbulent flow with initial natural laminar airfoils...



Optimization Results – Control masses (flutter)

Example of the 8th (last) flutter optimization scenario





Conclusion

- The bilevel MDO process enabled to provide a solution to the optimization problem with the required tools.
- A full workflow has been built based on a CPACS parametrization with a model handler that managed the consistency between the solvers models.
- The non-linear flutter optimization has been integrated into the process through the activation of control masses that may vanish the instabilities.
- From the physical assumptions made, a feasible design has been proposed with a reduction of 5% on the fuel burnt (832kg)

Clean Sky 2

Imperial College London

DNW German-Dutch Wind Tunnels

IRT Saint Exupery