Adding more disciplines in the MDO of HAR Aeroelastic Wing Design

Prof. Joseph Morlier

AR20+: Workshop on High Aspect Ratio Wing Technologies

About Me? https://ica.cnrs.fr/en/author/jmorlier/

- Prof in Structural and Multidisciplinary Optimization
- **SA-I*** group leader

Sustainable Aerostructures Initiative

Cleaner Environmental Systems
Volume 9, June 2023, 100114

A fast method of material, design and process eco-selection via topology optimization, for additive manufactured structures

Edouard Duriez [a], Catherine Azzaro-Pantel [b], Joseph Morlier [a], Miguel Charlotte [a]

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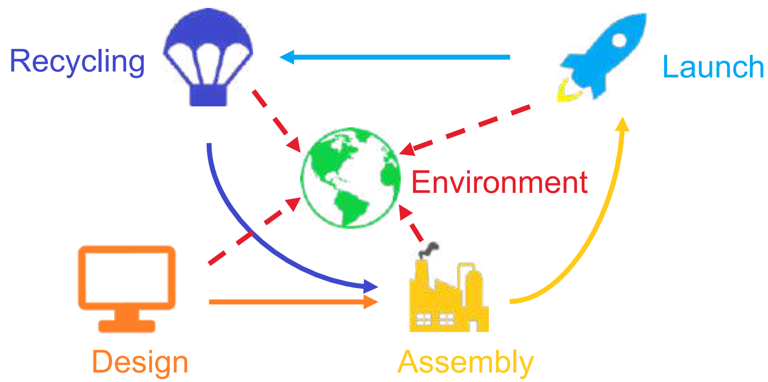
MDO for Aerospace systems Including LCA

: = EcoOptimization



Summary

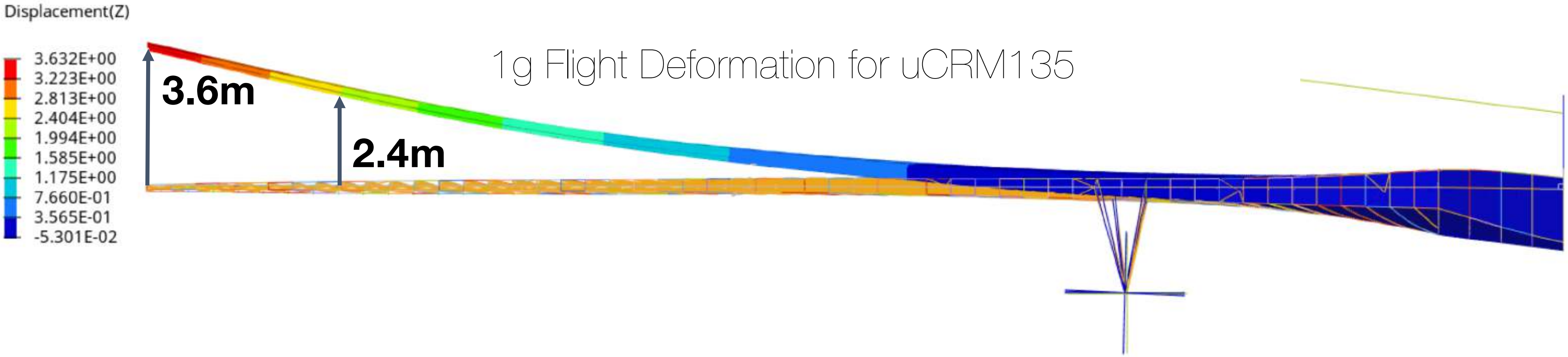
1. **Adding Control 4 Active Flutter Suppression**
2. Adding Longitudinal stability 4 Load Alleviation
3. Adding LCA 4 Hybridization of an aircraft
4. Conclusions

Summary

Feedback on Multifidelity

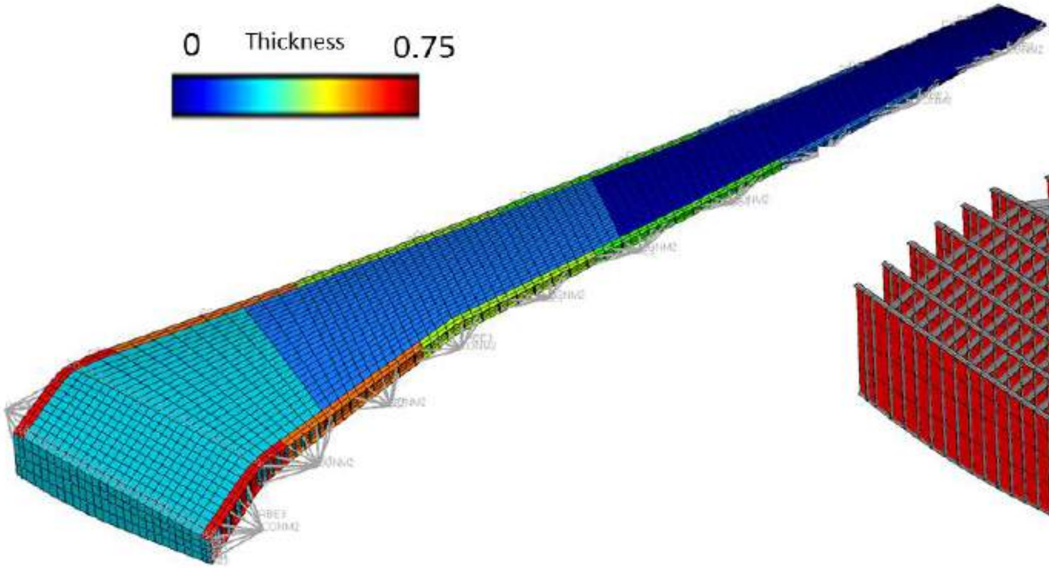
1. ~~**Adding Control 4 Active Flutter Suppression**~~
2. Adding Longitudinal stability 4 Load Alleviation
3. Adding LCA 4 Hybridization of an aircraft
4. Conclusions

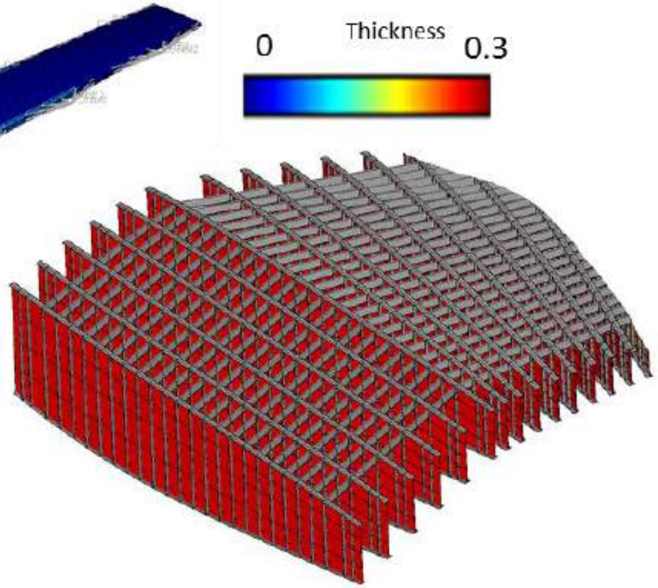
HAR: First effect?



Multifidelity ?

Le Lamer, Y., Quaglia, G., Bénard, E., & Morlier, J. (2021). Multifidelity aeroelastic optimization applied to har wing. In I ECCOMAS Thematic Conference on Multidisciplinary Design Optimization of Aerospace Systems (Aerobest 2021)

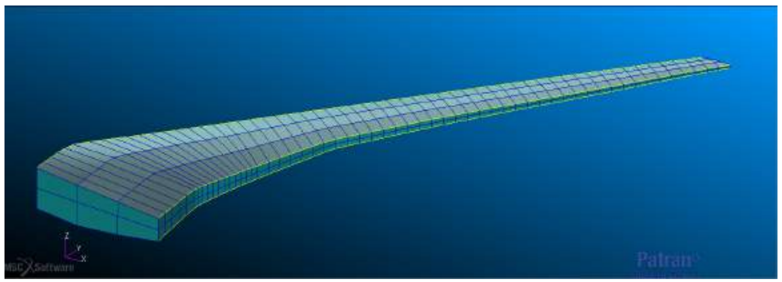




It is composed of ~10k nodes and ~26k elements.

HF

For static Aeroelasticity

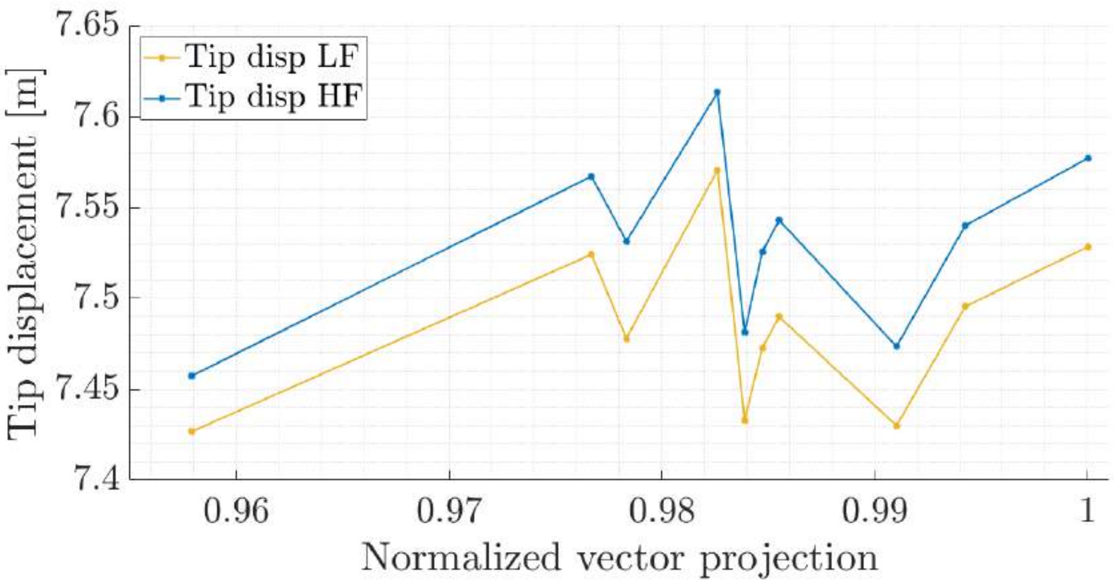


Coarsening mesh
Nodes: 690
Elements: 2168

LF

Correlation analysis

Case 1: Random variation of the panel thicknesses.

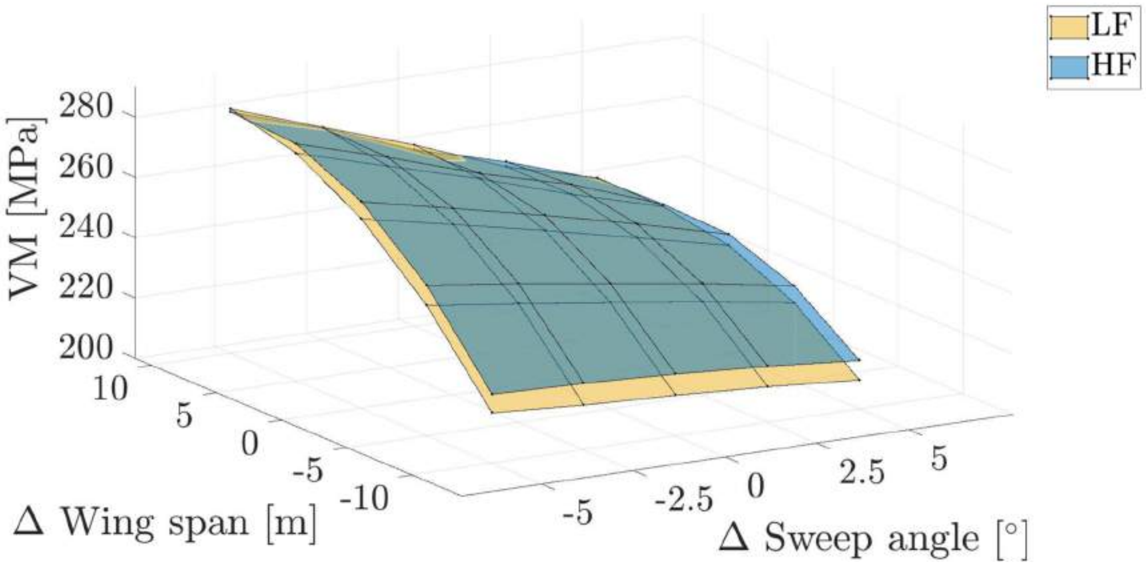


QoI comparison:

	CL	CDi	Tip disp.	Max VM
R2	**0.9995**	**0.9987**	**0.9903**	**0.9849**
Δmax.	**1.365%**	**1.693%**	**0.704%**	**3.477%**
Δmin.	**1.126%**	**0.790%**	**0.404%**	**0.219%**

Correlation analysis

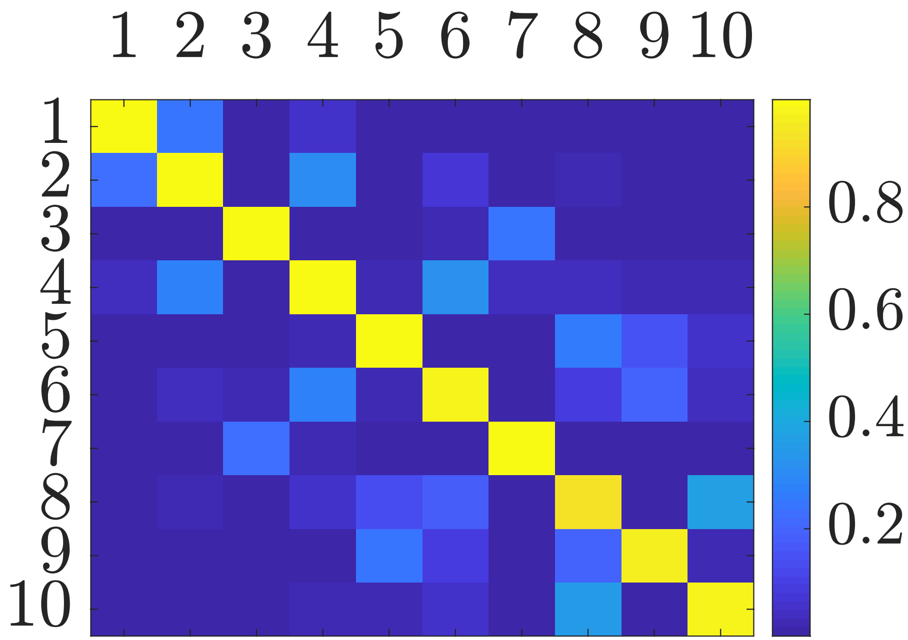
Case 2: Variation of wing span and sweep angle values by defined intervals.



QoI comparison:

	CL	CDi	Tip disp.	Max VM
R2	0.9998	0.9982	0.9997	0.9945
Δmax.	1.694%	1.547%	0.884%	2.841%
Δmin.	0.354%	0.119%	0.015%	0.118%

Now SD only. Check Normal modes !



MAC correlation matrix

$$MAC(i,j) = \frac{\left\|\Phi_{HF_i}^{T}\Phi_{LF_j}\right\|^2}{(\Phi_{HF_i}^{T}\Phi_{HF_i})(\Phi_{LF_j}^{T}\Phi_{LF_j})}$$

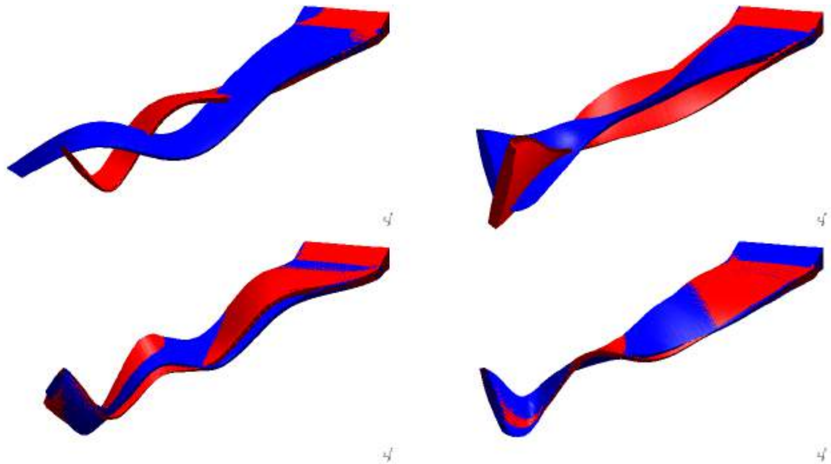
HF (Hz)	LF (Hz)	Relative error
1.9320	1.9398	-0.400
5.7476	5.7409	0.117
7.9694	7.9275	0.525
11.650	11.402	2.126
17.672	16.227	8.172
19.002	18.413	3.102
22.289	22.067	0.992
26.817	26.038	2.906
31.016	28.620	7.725
35.742	34.826	2.561

Comparison of HF and LF modal frequencies

Good correlation between HF and LF structural modes

Use of MAC in Aeroelastic similarity

- When your DV are changing a lot, the modal basis is changing a lot !
- Solution: Mode tracking



Objective Function (min):

$$f = \frac{N - tr\left(MAC([\Phi_r],[\Phi_m])\right)}{N}$$

Constraints:

$$\lambda_\omega \omega_{r,i} - \omega_{m,i} = 0 \quad i = 1, 2, \dots, N$$

$$\lambda_m M_r - M_m = 0$$

Mas Colomer, J., Bartoli, N., Lefebvre, T., Martins, J. R., & Morlier, J. (2021). An MDO-based methodology for static aeroelastic scaling of wings under non-similar flow. *Structural and Multidisciplinary Optimization*, *63*, 1045-1061.

Colomer, J. M., Bartoli, N., Lefebvre, T., Martins, J. R., & Morlier, J. (2021). Aeroelastic scaling of flying demonstrator: flutter matching. *Mechanics & Industry*, *22*, 42.

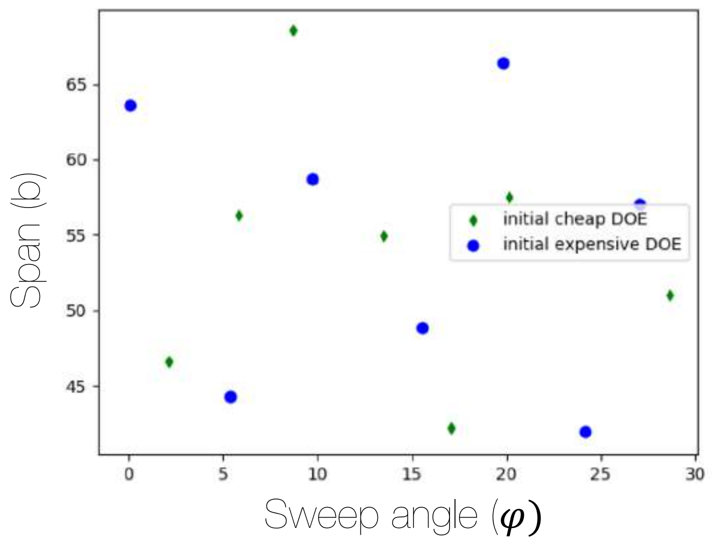
Colomer, J. M., Bartoli, N., Lefebvre, T., & Morlier, J. (2022). Aeroelastic scaling of flying demonstrators: mode tracking technique. *Mechanics & Industry*, *23*, 2.

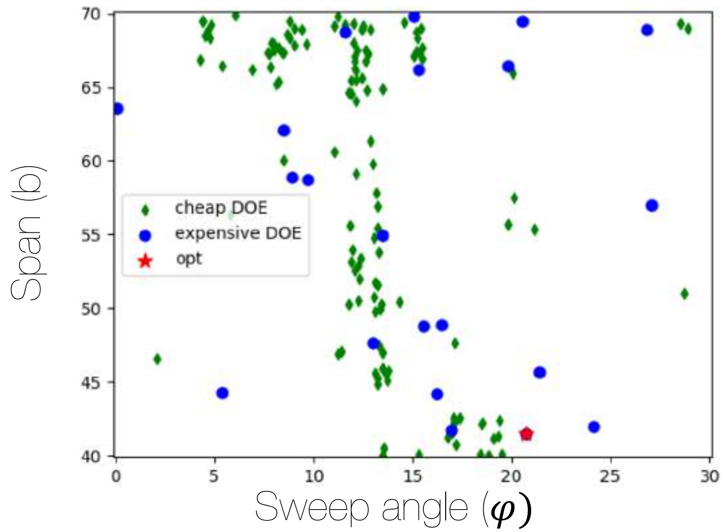
Multifidelity *optimization* in SD only*

Formulation of the optimization problem:

$$\min_{b,\varphi} \quad \frac{1}{f_2 - f_1}$$
$$\text{for} \quad b \in [40m, 70m]$$
$$\varphi \in [0°, 30°]$$

- Mixed Integer and Hierarchical Design Spaces (Variables, Sampling and Context)
- Mixed integer surrogate
- Mixture of experts (MOE)
- Variable-fidelity modeling (VFM)
- Multi-Fidelity Kriging (MFK)
- Multi-Fidelity Kriging KPLS (MFKPLS)
- Multi-Fidelity Kriging KPLSK (MFKPLSK)
- Efficient Global Optimization (EGO)





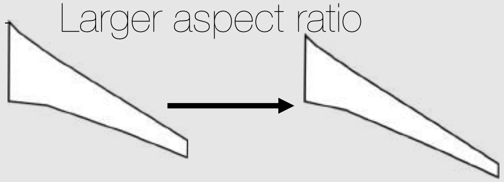
https://github.com/SMTorg/SMT

Methodology with a CFD application *Meliani, M., Bartoli, N., Lefebvre, T., Bouhlel, M. A., Martins, J. R., & Morlier, J. (2019). Multi-fidelity efficient global optimization: Methodology and application to airfoil shape design. In AIAA aviation 2019 forum (p. 3236).

MDO (PhD of Y. Le Lameur$, D. Muradas*)

AD rules:

Larger aspect ratio



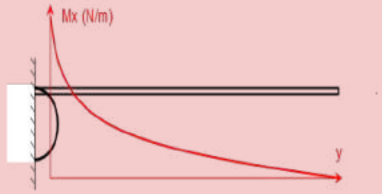
HARW permits better aerodynamic efficiency:

$$\frac{L}{D}_{max} = \frac{1}{2}\sqrt{\frac{e\,\pi\,AR}{CD_0}}$$

- I
- mproved aircraft design

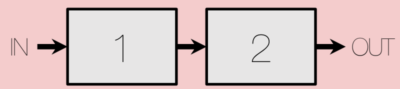
Problem encountered

- Higher wing weight



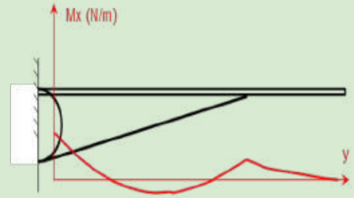
cantilever

- Sequential control design



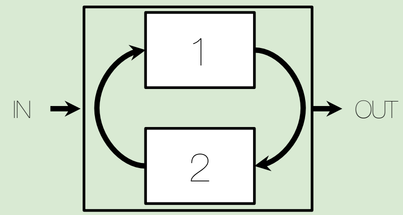
Proposed solutions

SBW can reduce bending moment and limits wing weight



SBW

MDO for Strut Braced Wing$ & Load Alleviation Function *

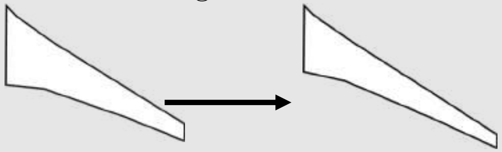


MDO (PhD of E. Duriez/T. Bellier)

AD rules:

Hybridization (fuel+electric)

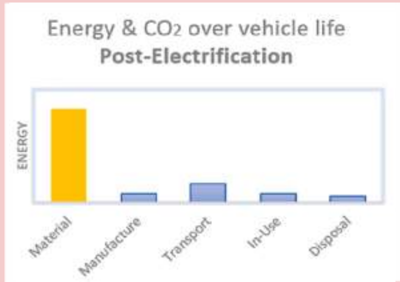
AR is not High here



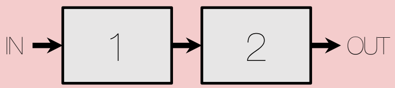
- Improved aircraft design

Problem encountered

- CO_2, manufacturing (**cf automotive**)



- Sequential control design



Proposed solution:

- Ecodesign and LCA

Water withdrawal

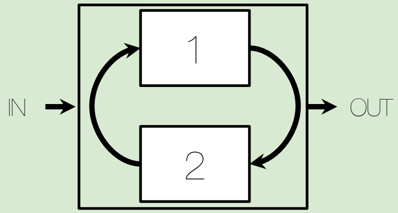
Generation of waste

Use recycled:
Fibers
Resin
Metals
Reuse & Repair

Carbon Footprint

Energy requirement

- MDO

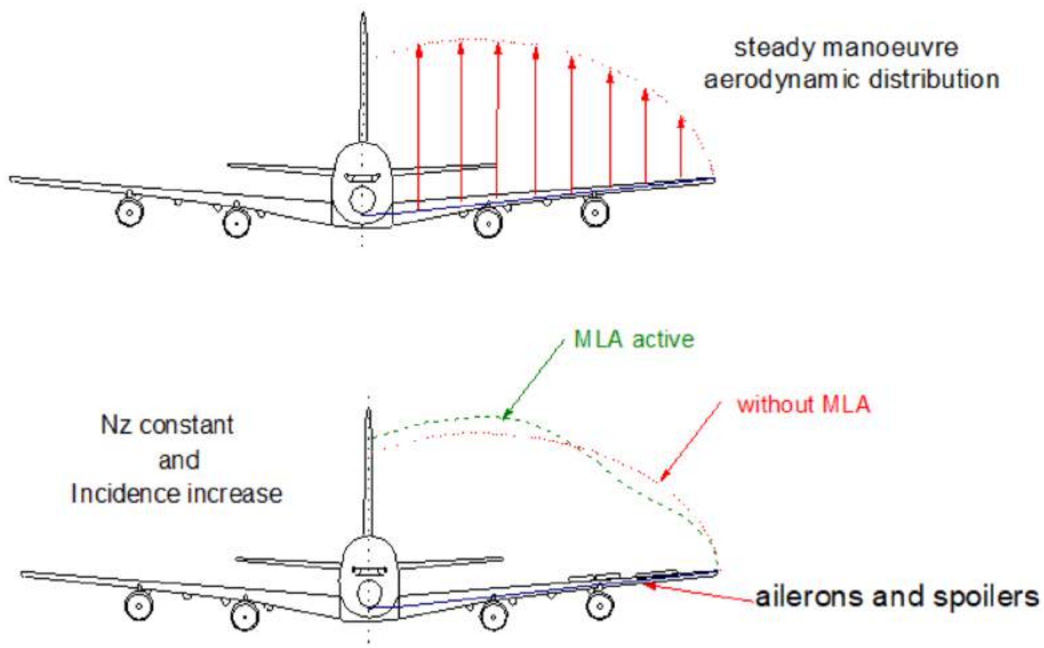


Summary

1. **Adding Longitudinal stability 4 Load Alleviation**
2. Adding LCA 4 Hybridization of an aircraft
3. Conclusions

What the Load Alleviation Function is about?

- **What is (LAF)?**
  Active system for aerodynamic redistribution using movables
- **HOW?**
  Control surfaces disrupting the flow, leading to a redistribution and also reducing the local lift.
- **Advantages**?
  Structural wing weight reduction thanks to internall loads reduction

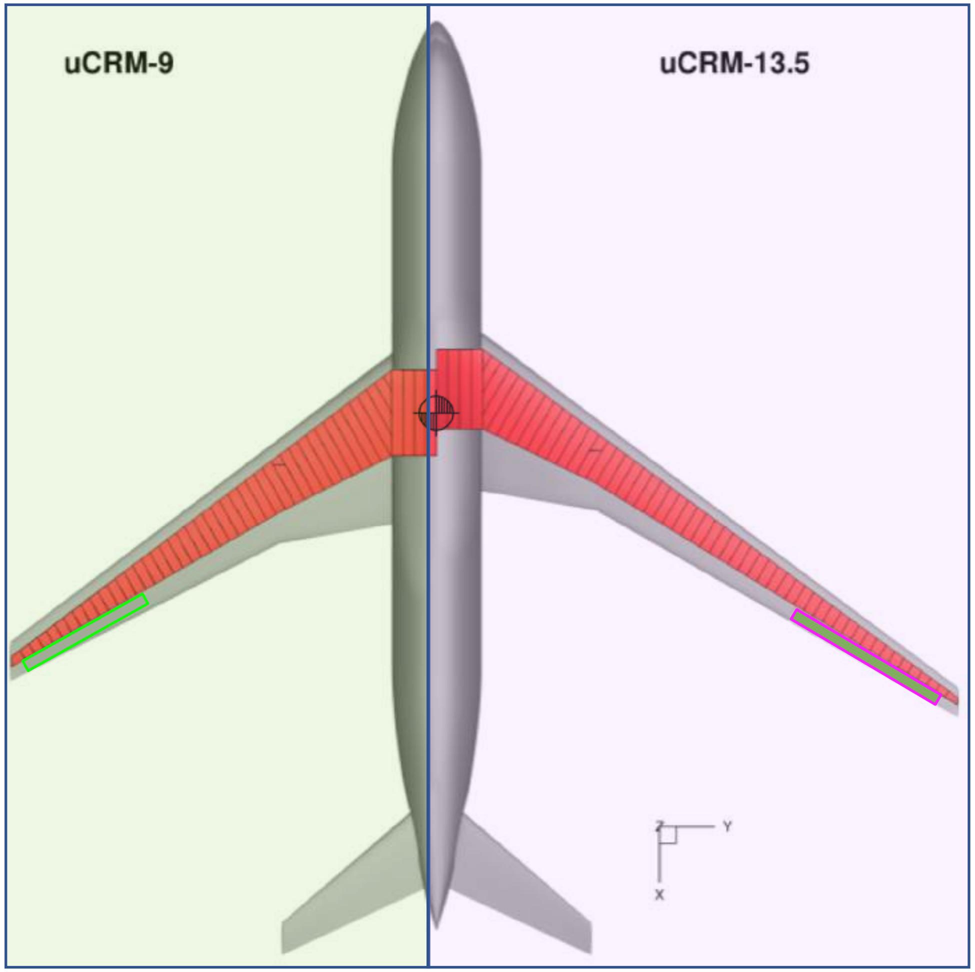


LAF/MLA (Maneuver Load Alleviation)

Aircraft Model description

- The NASA/Michigan models uCRM suits the ambition as it allows to compare High Aspect flexibility effects versus a classical configuration

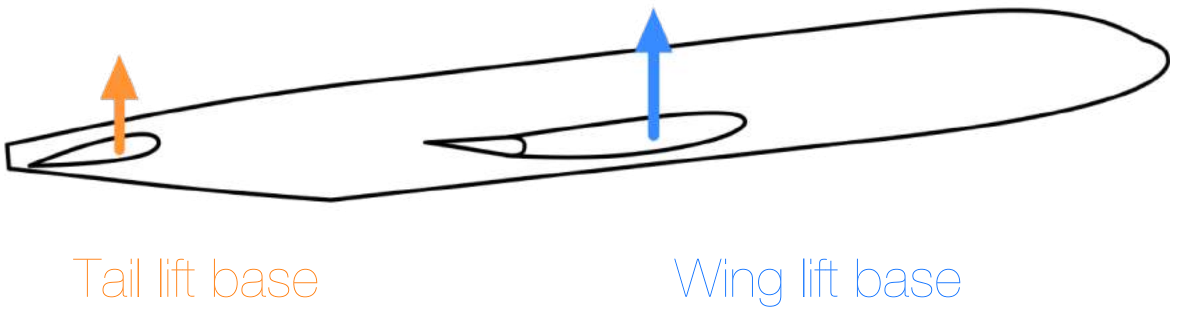
- uCRM-9 (AR 9)
  - Maximum TakeOff Weight: 297.5 Ton
  - Cruise flight: Mach 0.85 @ 37kft
  - 2 fuel conf.: 100% and 20%
  - **2 Ailerons (green)**
  - Center of Mass: (33.67786, 0.0, 4.51993)m
- uCRM-13.5 (AR 13.5)
  - Maximum TakeOff Weight: 284.256 Ton
  - Cruise flight: Mach 0.85 @ 37kft
  - 2 fuel conf.: 100% and 20%
  - **2 Ailerons (purple)**
  - Center of Mass: (33.67786, 0.0, 4.51993)m



Model comparison

Load Alleviation Function (LAF)

- LAF is achieved by deploying the movable (ailerons) conteracting the bending of the wing.
- center of pressure of the wing is changed and iAoA increases → the tail must compensate to preserve the longitudinal equilibrium.



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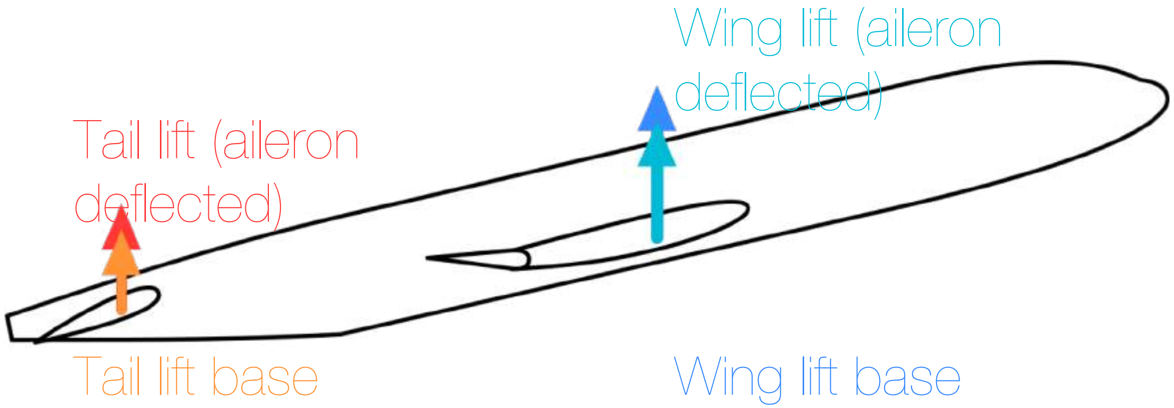
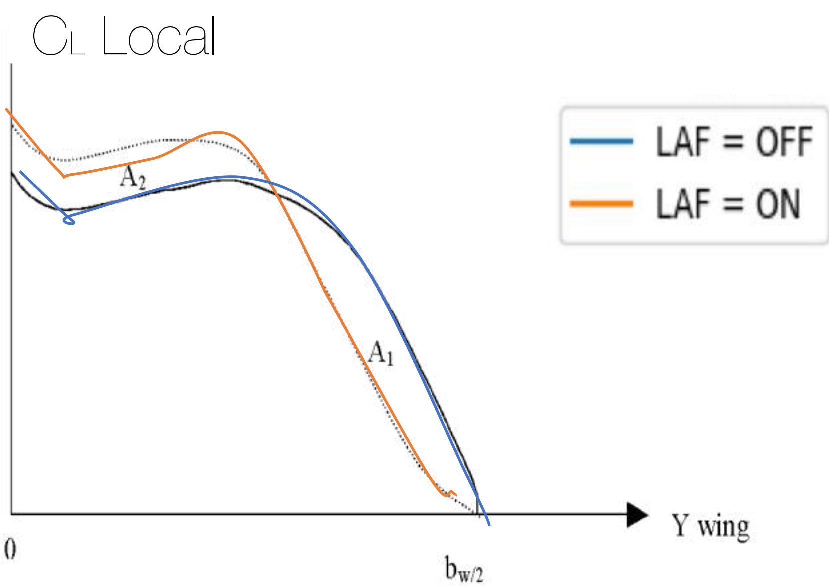
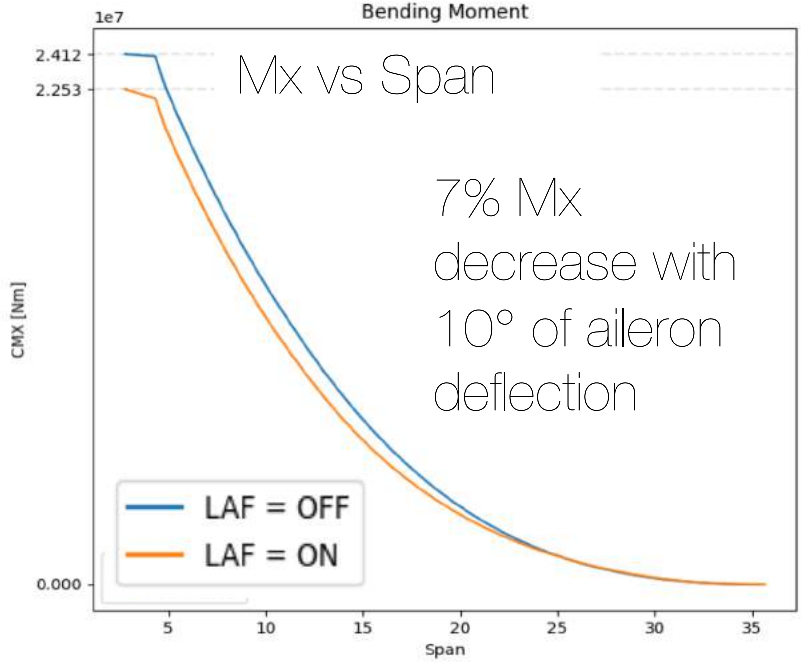
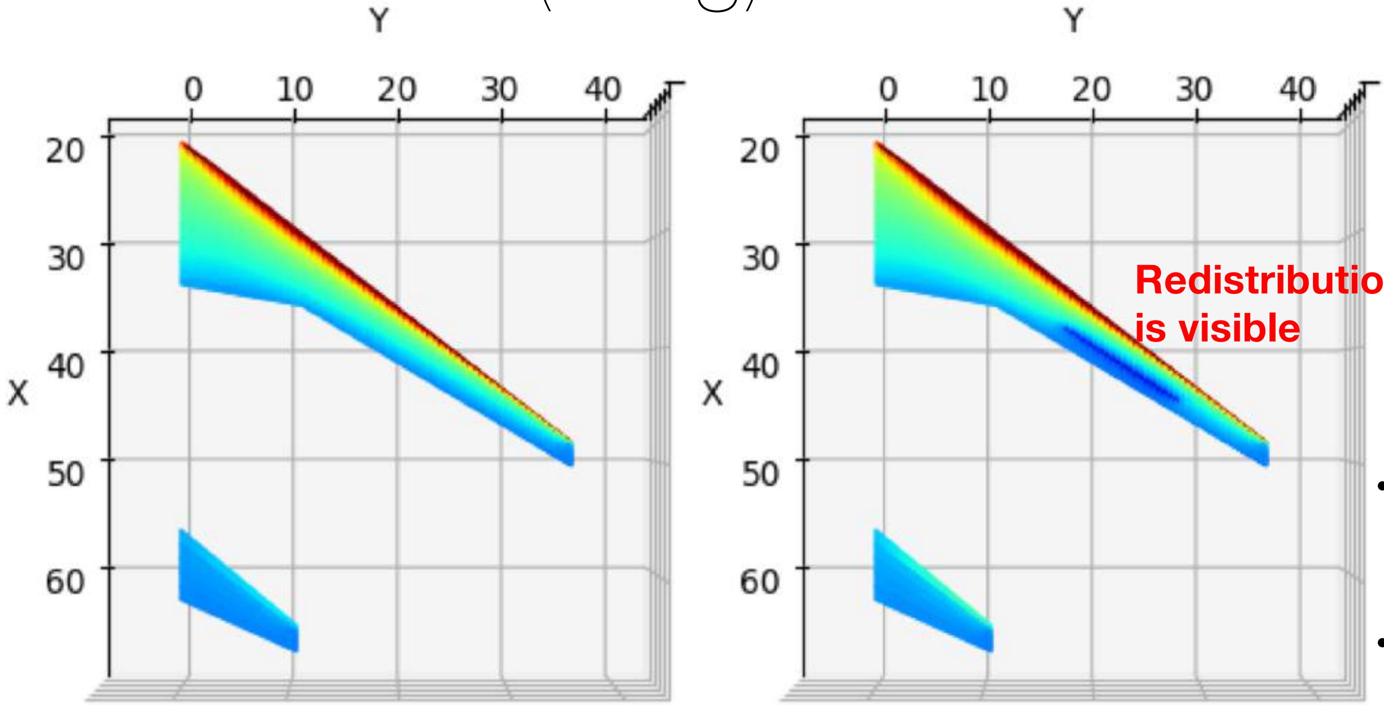






Aerostruct convergence loop for maneuver (2.5g)



Clean conf. LAF 10°

2.5g flight case

Redistribution due to aileron deflection is visible

- NASTRAN sol 144 was chosen as it would perform both the FSI and equilibrium quickly.
- **Opensource tool is in progress**

MDO Problem

Problem:

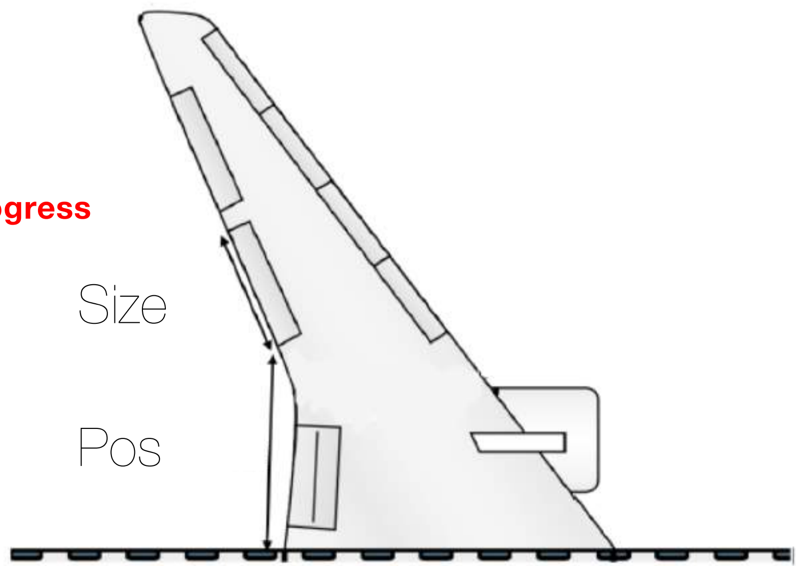
- Optimization of the **position & size of the control surfaces**, for improving the load alleviation **while preserving maneuverability of the aircraft*:**

*Work in progress

Objective:

- **wing root bending moment** (Mx), as the **main driver of the wing weight**

  - **Design variables**:
    Position and size of two ailerons
  - **Constraints**:
    Aileron max and min size & position



Aileron parametrization

$$
\begin{aligned}
\text{Minimize} \quad & M_x(\text{pos}, \text{size})_i \\
\text{w.r.t.} \quad & pos, size \\
\text{subject to} \quad & F_z(\text{pos, size}) < \text{Limit Loads}
\end{aligned}
$$

Results

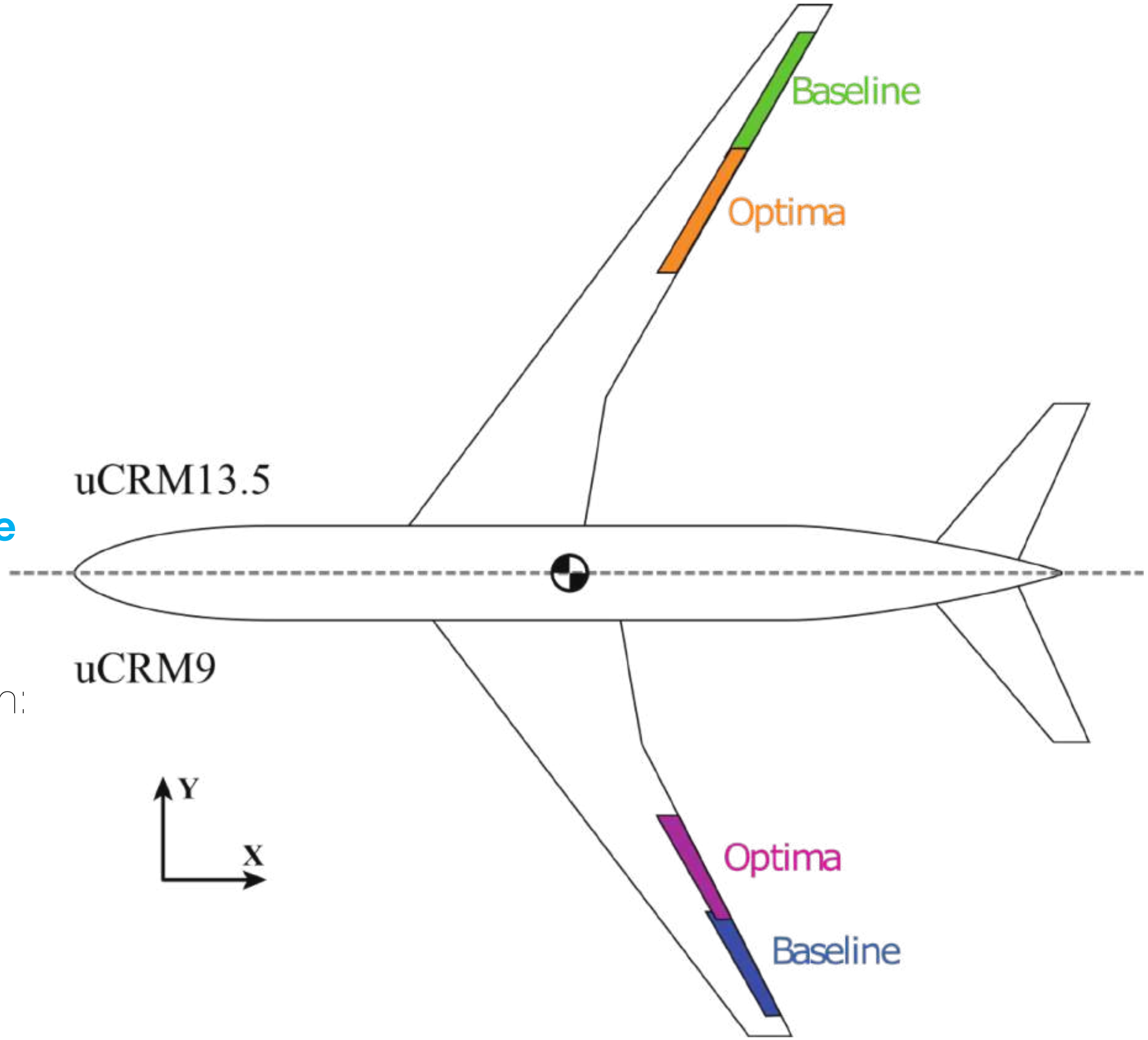
The optimal position found is:

- uCRM9: allows to reduce by **2%** the wing bending moment
- uCRM13.5: allows to reduce by **3%** the wing bending moment

The optimal position resides close to the root where flexible effects are less apparent

Loads Sizing case found at optimal configuration:

- M = 0.78 @ 38kft n=2.5

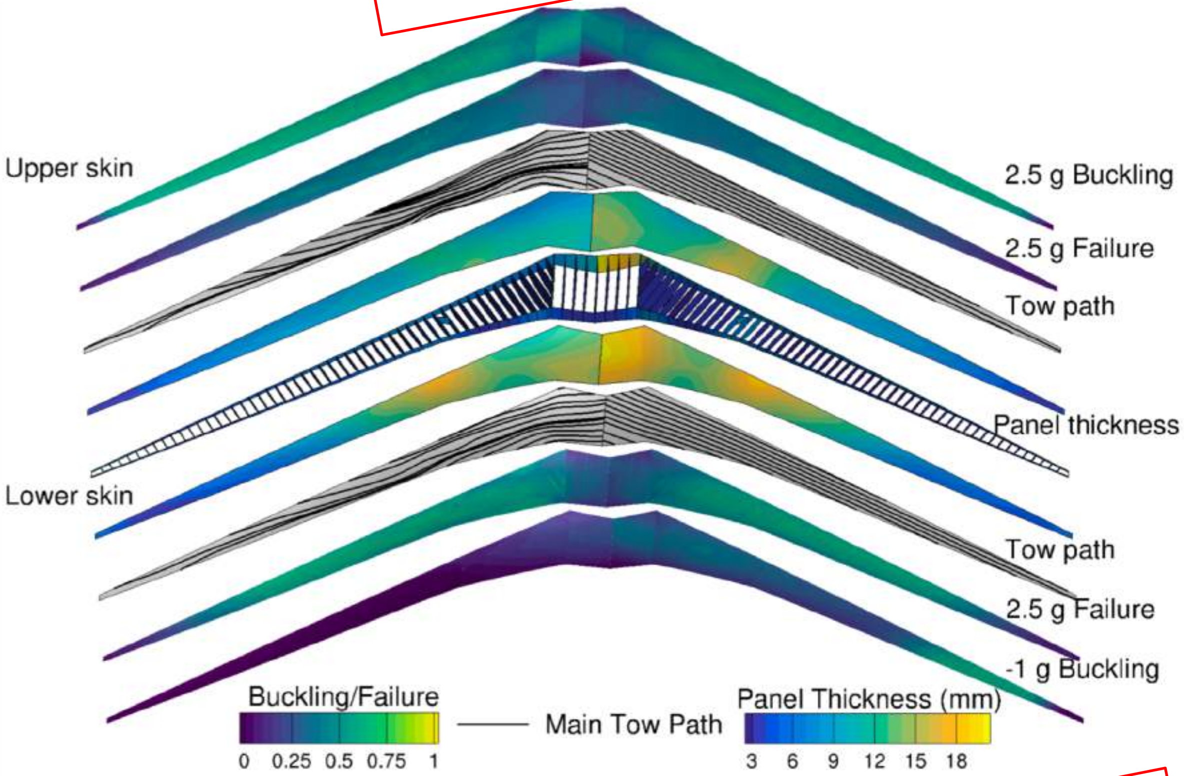


Summary

Material / Manufacturing as new DVs

https://www.compositesworld.com/articles/tow-steering-part-2-the-next-generation

X* is a UHAR Wing ;)



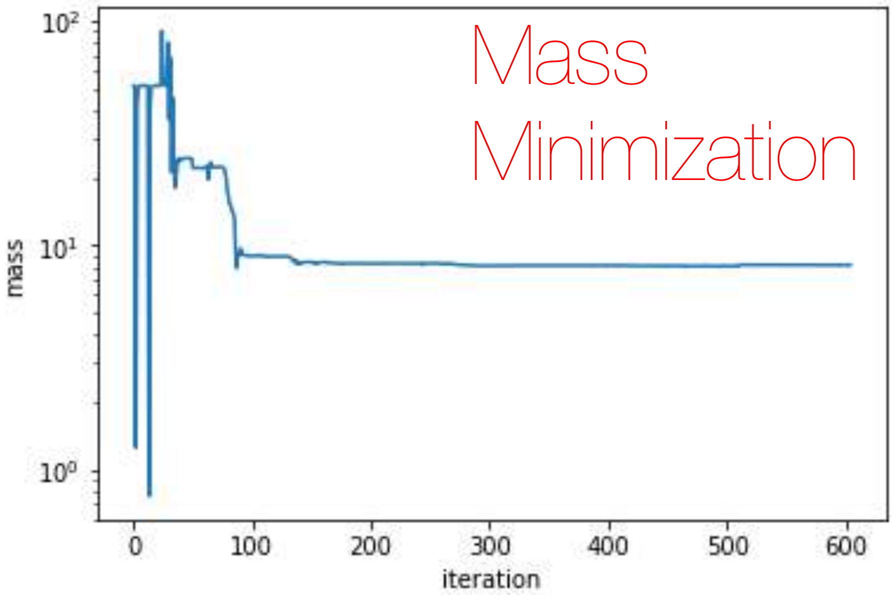
Brooks, T. R., Martins, J. R., & Kennedy, G. J. (2019). High-fidelity aerostructural optimization of tow-steered composite wings. Journal of Fluids and Structures, 88, 122-147.

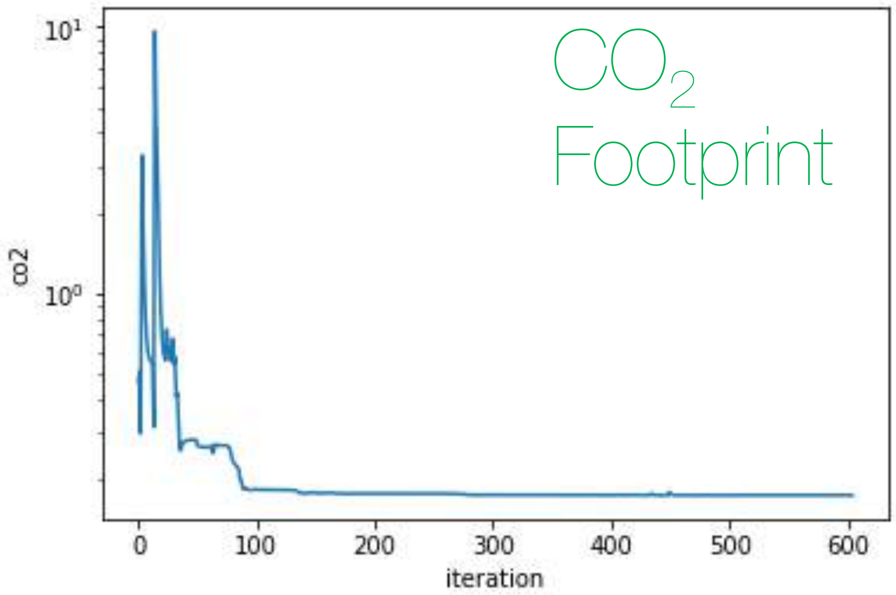
Brooks, T. R., Martins, J. R., & Kennedy, G. J. (2020). Aerostructural tradeoffs for tow-steered composite wings. Journal of Aircraft, 57(5), 787-799.

Lower wing mass, Less fuel burn

Change the Metric ?

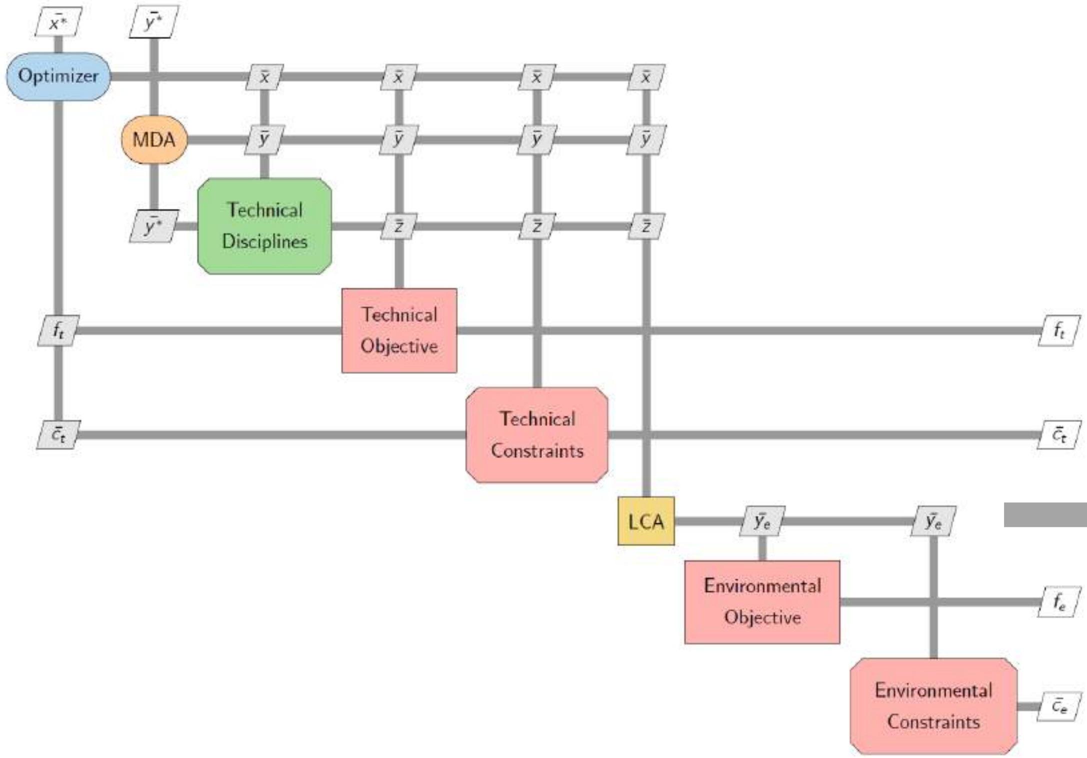
Duriez, E., Guadaño Martín, V. M., & Morlier, J. (2023). CO 2 footprint minimization of solar-powered HALE using MDO and eco-material selection. *Scientific Reports*, *13*(1), 11994

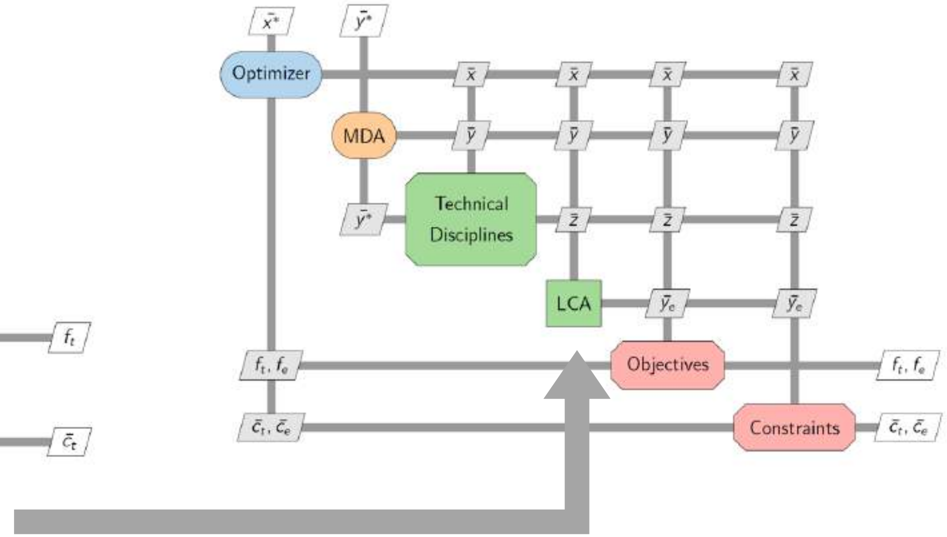




LCA With XDSM

ISO norm:
- Proper goal and scope definition, including functional unit
- Inventory analysis and the database problem
- Selection of impacts, and difference between raw flux, midpoint, and endpoint impacts





LCA integrated: environmental outputs available in all modules

HOW?

- LCA4MDAO (**needed LCA database ecoinvent)**
https://github.com/mid2SUPAERO/LCA4MDAO
- Brightway2
- OpenMDAO

Hybrid Aircraft Problem (MDOlab)

- Hybridised King Air C90GT from OpenConcept, built in *OpenMDAO* format
- Four disciplines:
  - Aero (wing geometry)
  - Propulsion (with hybrid system)
  - Structure
  - Trajectory simulation
- 6 variables converted into LCA database entries

Model parameter	Ecoinvent entry
Battery weight	battery cell production, Li-ion
Motor weight	electric motor production, vehicle
Engine weight	internal combustion engine production, passenger car
Empty weight	aluminium production, primary, ingot
Fuel used	market for kerosene
Electricity used	market group for electricity, low voltage

Benjamin J. Brelje and Joaquim R. R. A. Martins, "Development of a Conceptual Design Model for Aircraft Electric Propulsion with Efficient Gradients", 2018 AIAA/IEEE Electric Aircraft Technologies Symposium, AIAA Propulsion and Energy Forum, (AIAA 2018-4979) DOI: 10.2514/6.2018-4979

Eytan J. Adler and Joaquim R. R. A. Martins, "Efficient Aerostructural Wing Optimization Considering Mission Analysis", Journal of Aircraft, 2022. DOI: 10.2514/1.c037096

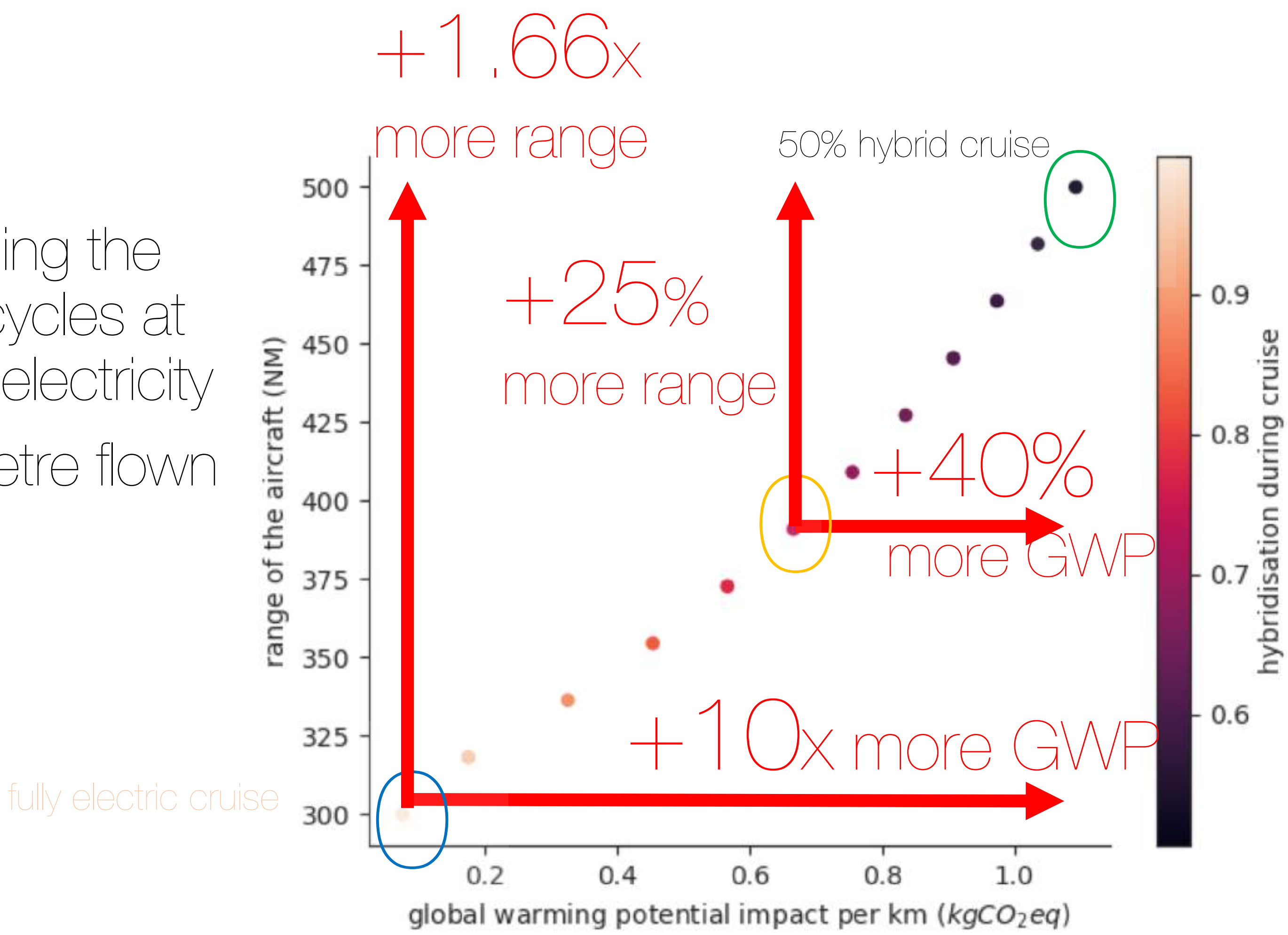
MOO

f1=Minimize (-range) and f2=minimise (GWP)

$$f = \alpha * f1 + (1 - \alpha) * f2$$

Results MOO

- LCA scope include building the aircraft and flying 1000 cycles at max range with fuel and electricity
- Functional unit is a kilometre flown

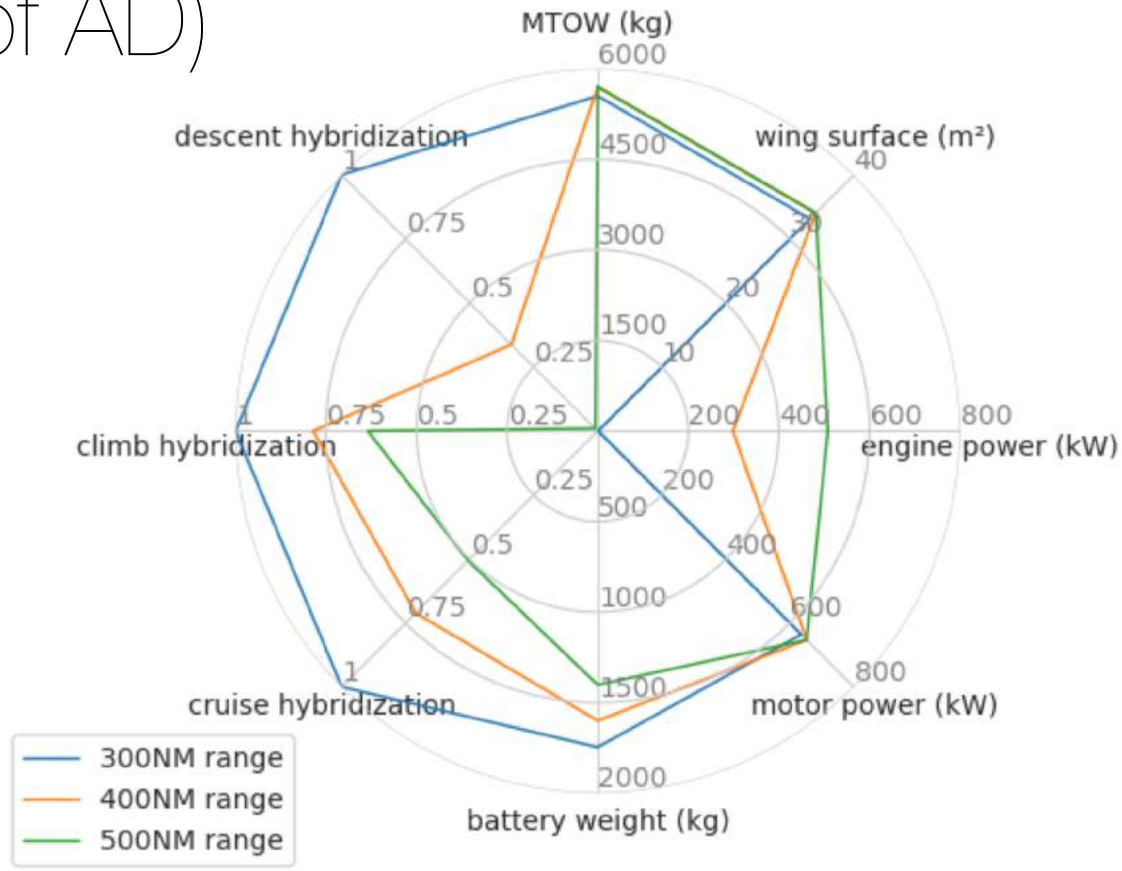


Results (link to physics of AD)

For the design variables, reducing the range:

- increases the hybridization
- reduces the engine size
- increases the battery weight

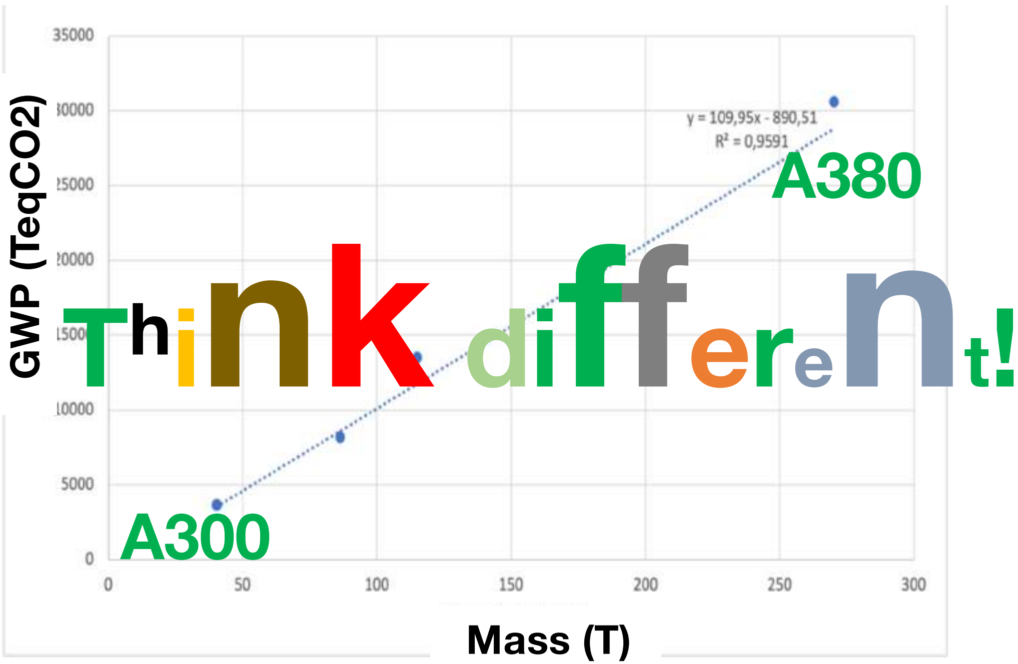
variable	value	units
MTOW	5700	kg
wing surface	34	m^2
engine power	298	kW
motor power	652	kW
battery weight	1607	kg
fuel capacity	500	kg
cruise hybridisation	0.71	
climb hybridisation	0.785	
descent hybridisation	0.337	
GWP	0.712	$kgCO_2eq/km$



Conclusions

- We present three differents MDO problems with new disciplines such as control, stability or LCA
- Ecodesign will be a hard constraint in the near future for every academic/industrial projects even if: Manufacturing <1% of total aircraft emissions
- **Adding more disciplines definitely complexify the design problem**

--> we are here to solve this ;)



Thank you for your attention!

1. **Le Lamer, Y., Quaglia, G., Bénard, E., & Morlier, J.** (2021). Multifidelity aeroelastic optimization applied to har wing. In I ECCOMAS Thematic Conference on Multidisciplinary Design Optimization of Aerospace Systems (Aerobest 2021)
2. **Faïsse, E., Vernay, R., Vetrano, F., Alazard, D., & Morlier, J.** (2021). Adding control in multidisciplinary design optimization of a wing for active flutter suppression. In AIAA Scitech 2021 Forum (p. 0892).
3. **Faïsse, E., Vernay, R., Vetrano, F., Morlier, J., & Alazard, D.** (2022). Aeroservoelastic wing sizing using integrated structural and control (co-design) optimization. In AIAA SCITECH 2022 Forum (p. 2243).
4. **Odriozola, D. M., Marquier, S., Morlier, J., & Gogu, C.** (2023, July). A preliminary low-fidelity mdo approach for load alleviation through movables on har wing. In II ECCOMAS Thematic Conference on Multidisciplinary Design Optimization of Aerospace Systems (Aerobest 2023)
5. **Duriez, E., Guadaño Martín, V. M., & Morlier, J.** (2023). CO 2 footprint minimization of solar-powered HALE using MDO and eco-material selection. Scientific Reports, 13(1), 11994
6. **Bellier, T., Morlier, J., Bil, C., Urbano, A., & Pudsey, A.** (2023, July). Integration of life cycle assessment methodology as an environment discipline module in multidisciplinary analysis and optimization framework. In II ECCOMAS Thematic Conference on Multidisciplinary Design Optimization of Aerospace Systems (Aerobest 2023)

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