17 July 2025
University of Kaiserslautern-Landau

Multidisciplinary Design Optimization for Next-Generation Sustainable Aircraft

Rauno Cavallaro, PhD

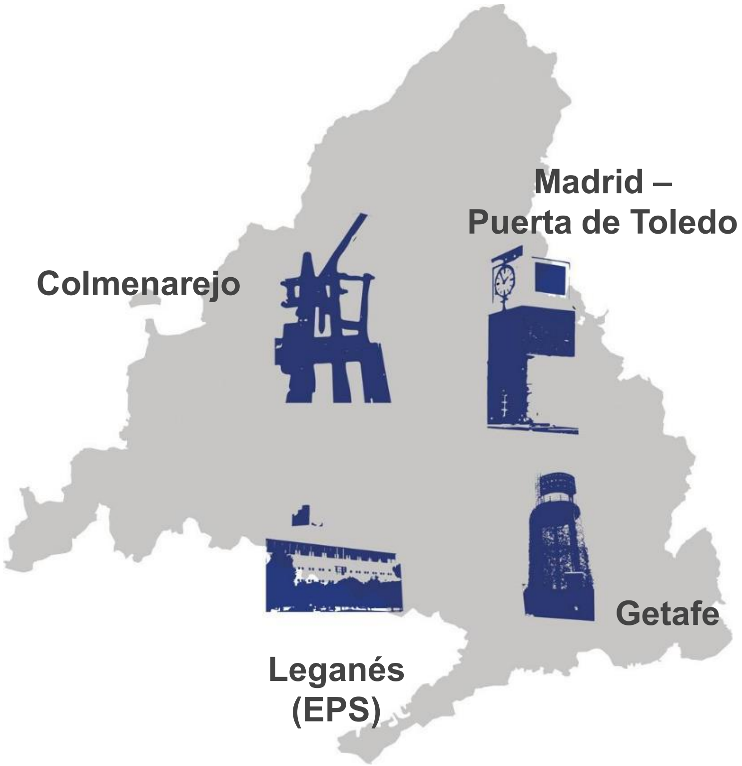
Associate Professor,
Department of Aerospace Engineering,
Universidad Carlos III de Madrid

Scientific Computing
University of Kaiserslautern-Landau

uc3m

Universidad Carlos III de Madrid

- Public, young (created in 1989), and bilingual
  - *73% of degrees in English or bilingual*
  - *2nd ranked public University in Spain (Employability)*
- One of the most international:
  - *23% of students & 14% academics are foreign*
  - *51% student opted for international mobility*
  - *Incoming/outgoing students ~2000 / 2000 (1st in Spain)*
- Well-balanced from a gender perspective:
  - undergraduates: 54% women / 46% men
- Mid-size:
  - undergraduate: 17.000
  - graduate: 5.500
  - academic staff: 2.000



4 campuses in Madrid region

Leganés: **School of Engineering (EPS)**

~45% of UC3M

20 undergraduate degrees

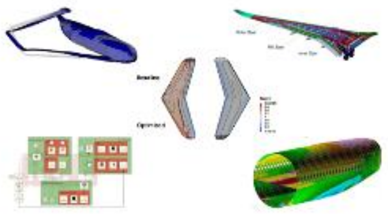
39 master degrees

11 PhD programs

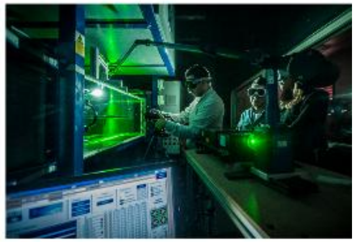
UC3M - Aerospace Engineering Department

- Born in **2010**
- **13** Permanent Professors (35% non-Spanish)
- **~75 people** (counting also Assistant prof., Post-Docs & PhDs students)
- Recognized with prestigious grants/awards:
  - **3 ERC** StG (European Research Council)
  - 1 Ramon y Cajal Fellowship (Spanish Government)
  - **1 Senior** Beatriz Galindo Fellowship (Spanish Government)
  - 3 Leonardo Grants (BBVA Foundation)/
- Covering **6** research areas

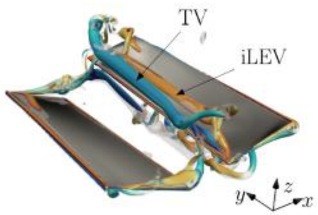
Aeroelastic and Structural Design Lab (ASDLab)



Experimental Aerodynamics and Propulsion Lab



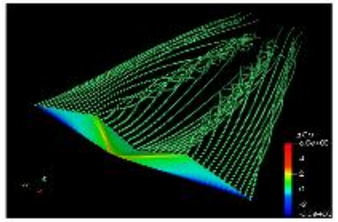
Computational Fluid Dynamics Lab



Plasma and Space Propulsion Team (EP2)

Dynamics and Control in Aerospace Systems

Tethers Applied to Aerospace Engineering



Agenda

uc3m

1. Presentation (UC3M, Aerospace Engineering Department,…)
2. Motivation for Sustainable Aviation
3. MDO for sustainable aviation. Applications
   a. Hybrid-electric Large Aspect Ratio Wings
   b. Highly flexible wings

Context: A Growing Sector with a Growing Footprint

- Air traffic has **rebounded**: 2024 flights at **96% of 2019** levels, emissions at **98%**
- 2025 emissions are projected to exceed 2019 levels **(↑4%).**
- Forecast: +40% flights by 2050 in Europe (~15.4 million flights).
- Aviation contributes **~4% of EU GHG**, **~13.9% of transport emissions**, but **non-CO_2 effects** double its climate impact
- Despite efficiency gains, CO_2 per passenger-km down only **~1–2%** per year.

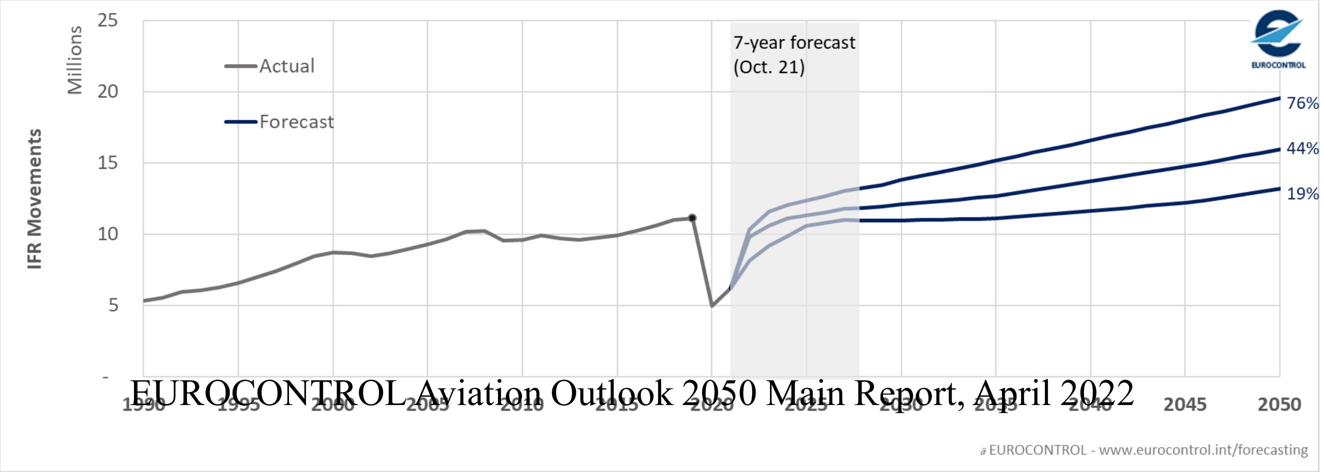
30-YEAR FORECAST 2022-2050

16 MILLION FLIGHTS BY 2050

(RANGE: 13.2-19.6 MILLION)

UP 44% ON 2019

- **10-YEAR LAG** SINCE **PREVIOUS LONG-TERM** FORECAST (2018).
- **MIDDLE-EAST** & **ASIA/PACIFIC:** MOST **DYNAMIC** FLOWS WITH ECAC BY 2050.

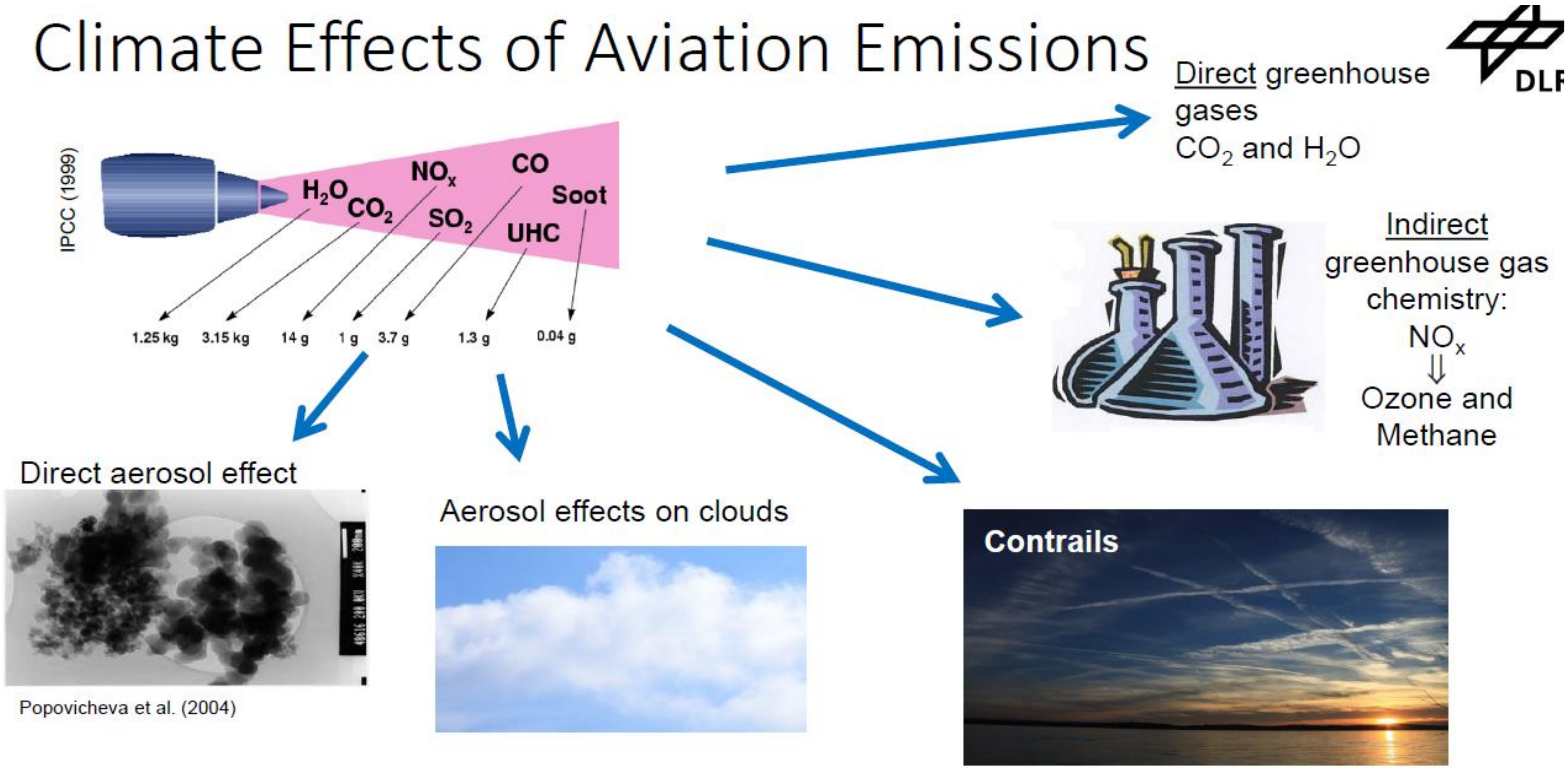


EUROCONTROL Aviation Outlook 2050 Main Report, April 2022

Need to act fast

If some **intermediate goals** are not implemented immediately and **achieved by 2030**, the opportunity for transformation will slip away, leaving the world to face the escalating climate impacts of a rapidly growing aviation sector, which is projected to at least double by 2050.

Not only CO2



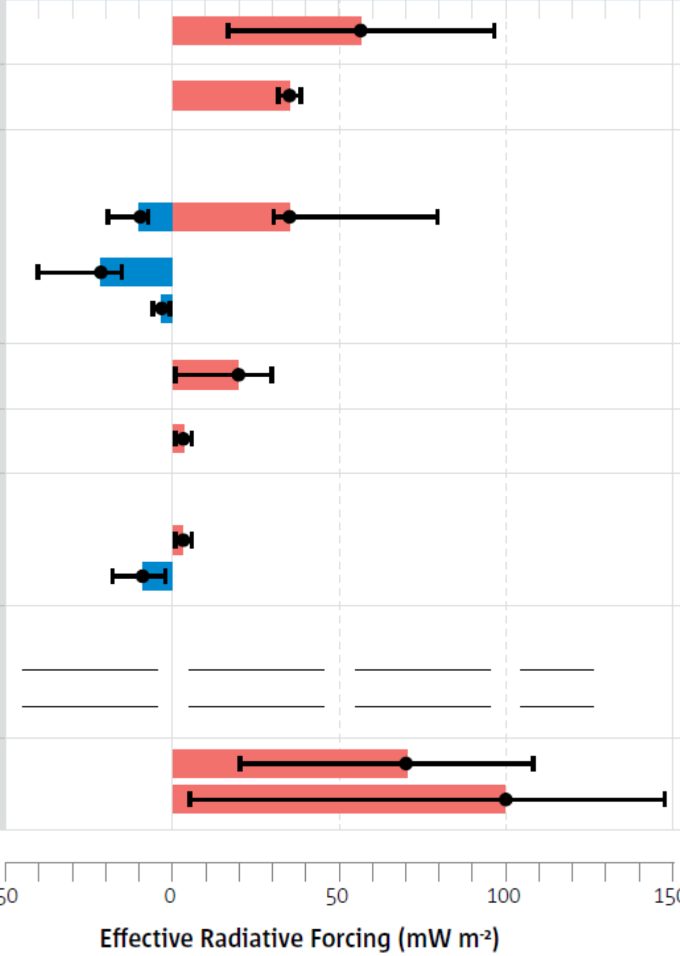
Grewe, V., ECATS Summer School, Blumenthal, September 2023

Not only CO2

uc3m

non-CO2 emissions represent the largest fraction of the total ERF of aviation, at present, **although** the level of uncertainties from the non-CO2 effects is 8 times larger than that from CO2, and the overall confidence levels of the largest non-CO2 effects are ‘low’.

Global Aviation Effective Radiative Forcing (ERF) Terms 1940 – 2018	ERF (mW m⁻²)	RF (mW m⁻²)	ERF/RF	Conf. levels
Contrail cirrus in high-humidity regions	57.4 (17, 98)	111.4 (33, 189)	0.42	Low
Carbon dioxide (CO_2) emissions	34.3 (28, 40)	34.3 (31, 38)	1.0	High
Nitrogen oxide (NO_X) emissions				
Short-term ozone increase	49.3 (32, 76)	36.0 (23, 56)	1.37	Med
Long-term ozone decrease	-10.6 (-20, -7.4)	-9.0 (-17, -6.3)	1.18	Low
Methane decrease	-21.2 (-40, -15)	-17.9 (-34, -13)	1.18	Med
Stratospheric water vapor decrease	-3.2 (-6.0, -2.2)	-2.7 (-5.0, -1.9)	1.18	Low
Net for NO_x emissions	17.5 (0.6, 29)	8.2 (-4.8, 16)	–	Low
Water vapor emissions in the stratosphere	2.0 (0.8, 3.2)	2.0 (0.8, 3.2)	[1]	Med
Aerosol-radiation interactions				
– from soot emissions	0.94 (0.1, 4.0)	0.94 (0.1, 4.0)	[1]	Low
– from sulphur emissions	-7.4 (-19, -2.6)	-7.4 (-19, -2.6)	[1]	Low
Aerosol-cloud interactions				
– from sulphur emissions	No best estimates	No best estimates	–	Very low
– from soot emissions			–	
Net aviation (Non-CO_2 terms)	66.6 (21, 111)	114.8 (35, 194)	–	–
Net aviation (All terms)	100.9 (55, 145)	149.1 (70, 229)	–	–

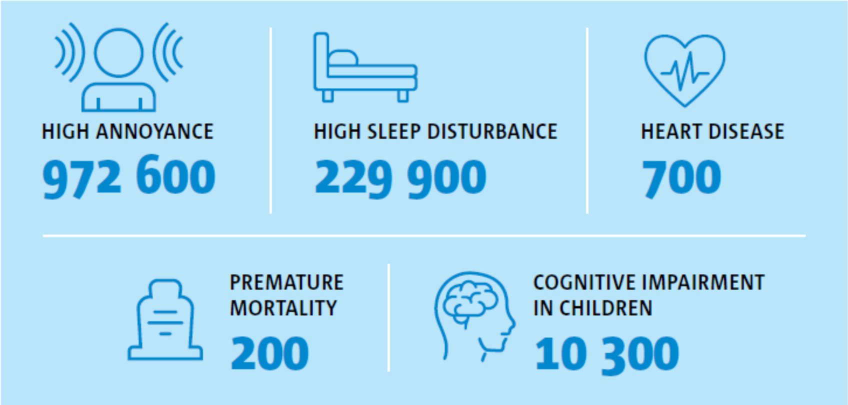


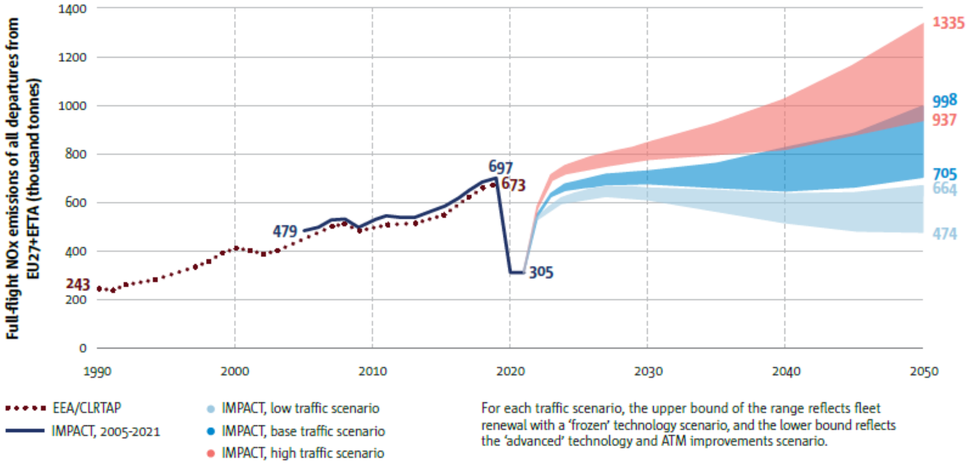
Best Estimates
5 – 95% Confidence

Aviation Environmental Impact

Three main aspects

- Climate change
- Two aspects related to “direct” effects on population living close to airports. Concept of LAQN (Local Air Quality and Noise)
  - **Local Air Quality** (LAQ)
  - **Noise**

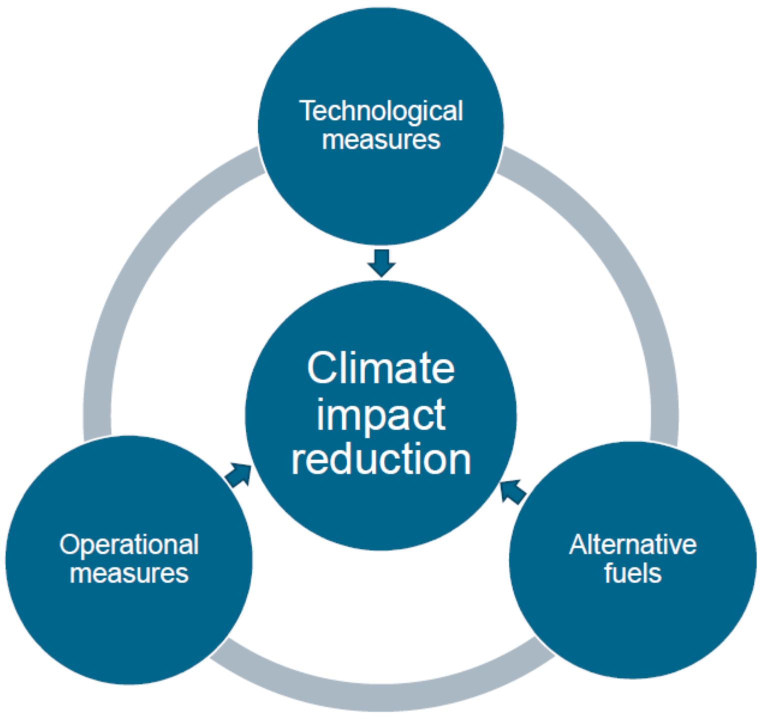




Sustainable Aviation

Sustainable aviation focuses on minimizing the environmental impact of air travel by adopting

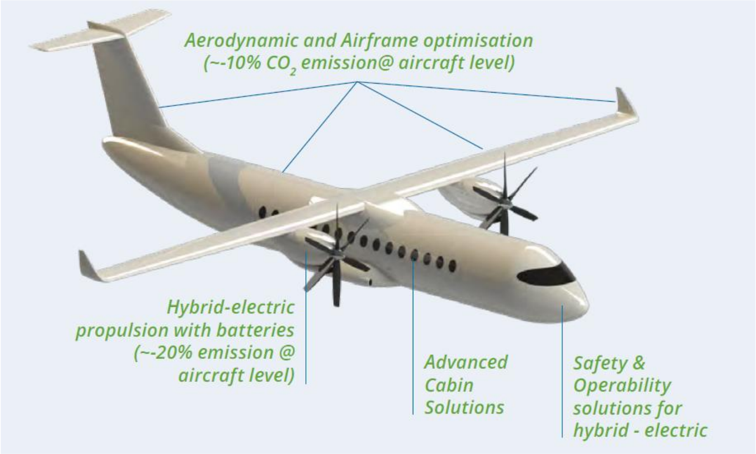
- **Advanced technologies**
  - **Replace old aircraft of fleets**
  - **Next generation aircraft (disruptive technology)**
- **Alternative fuels**, and
- Efficient operations
  - Ground/Flight operations
  - ATC efficiency
  - Exploring innovative technologies like **electric and hydrogen** propulsion.

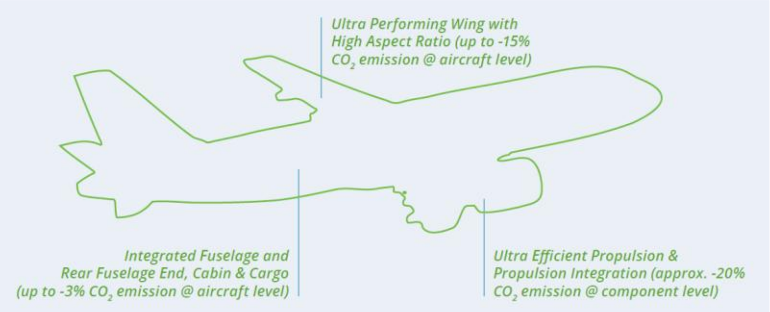


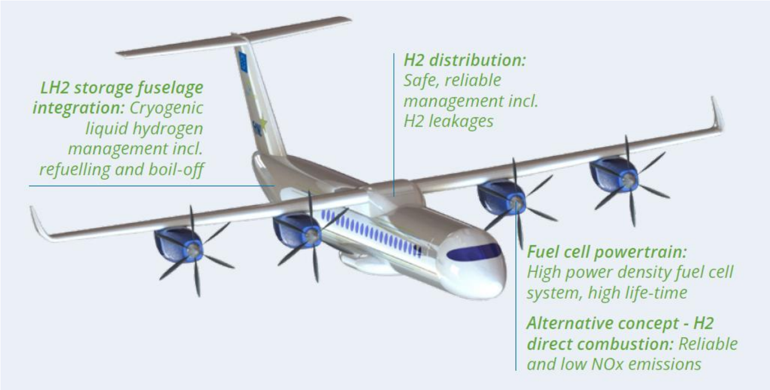

CLEAN AVIATION
Co-funded by the European Union
Clean Aviation's aircraft concepts
Entry-Into-Service in 2035
Ultra-efficient Regional aircraft
Hydrogen powered aircraft
Ultra-efficient Short and Medium Range aircraft
-30% CO_2*
-86% CO_2* incl. SAF
-100% CO_2*
-30% CO_2*
-86% CO_2* incl. SAF
6
* non-CO_2 effects not yet quantified

Designing Disruptive Aircraft: A Multidisciplinary Challenge

- Decarbonization goals demand **disruptive architectures**
  - hybrid-electric, hydrogen
  - novel configurations
- **Break with legacy**
  - no historical data
  - no baseline designs
  - Multiple **tightly coupled** disciplines
    - Aerodynamics, structures, propulsion, thermal management, systems, …
- **Sustainability** adds new **dimensions**:
  - emissions, energy
  - lifecycle
  - regulatory constraints.







In hybrid-electric systems, propulsion sizing depends

- on thermal management,
- which in turn affects weight and drag.

H2 aircraft, the LH2 tank volume and placement impact

- the aerodynamic shape,
- center of gravity, and
- structural layout simultaneously.

The answer: Multidisciplinary Design and Optimization

uc3m

No Historical Data = Need for Physics-Based, Integrated Models

- Legacy aircraft had empirical decoupling
  - *"this works because it always worked."*
- Disruptive aircraft lack validated trends
  - models must be fully coupled
  - and physics-based from the start
- Optimization must happen in this complex, high-dimensional space
  - enter MDO.

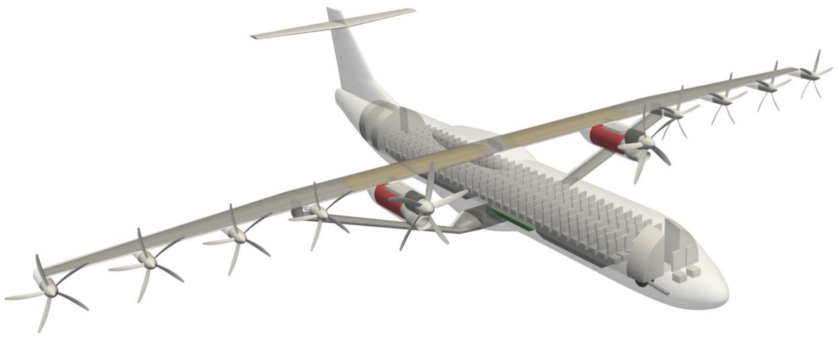
While aircraft have always required coordination between disciplines, disruptive designs amplify these dependencies to the point where **traditional sequential approaches become insufficient.**

MDO isn't new, what's new is that **it's now indispensable**. Legacy aircraft "tolerated" approximation. Sustainable aircraft, with tight energy and emission constraints, do not.

Applications

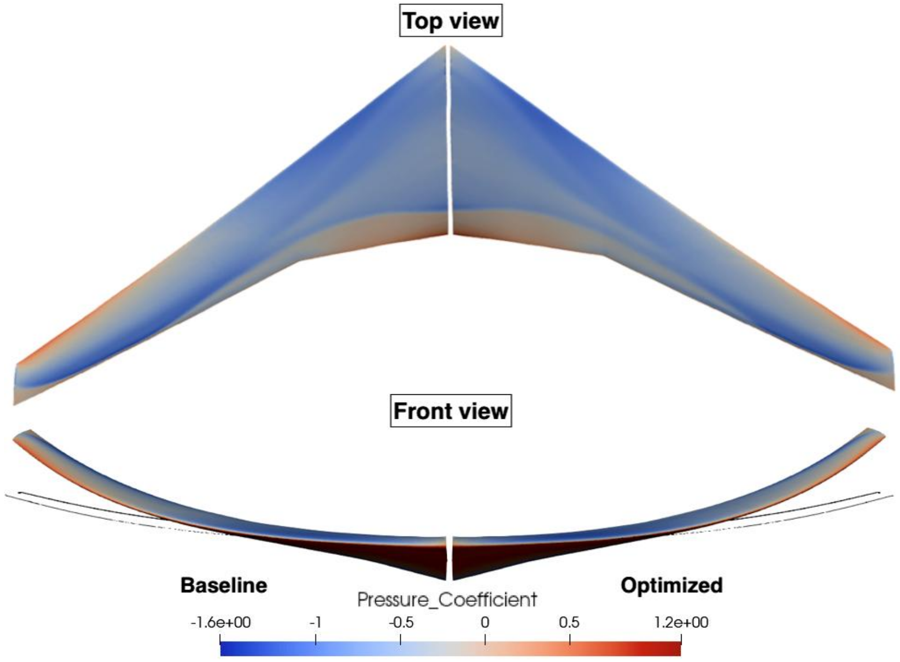
Application 1

- Improving Local Air Quality and Noise
- Hybrid-electric powertrain
- Strut-braced wing
- New Operations (trajectories)



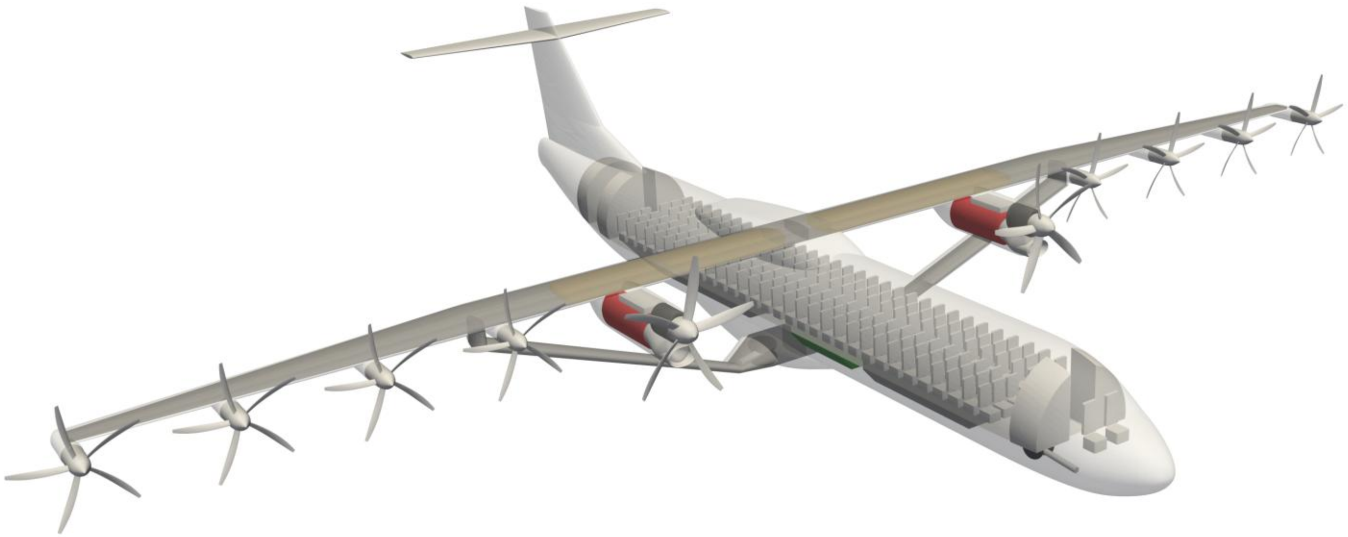
Application 2

- Highly-flexible wings
  - Emission reduction



Application 1 - INDIGO

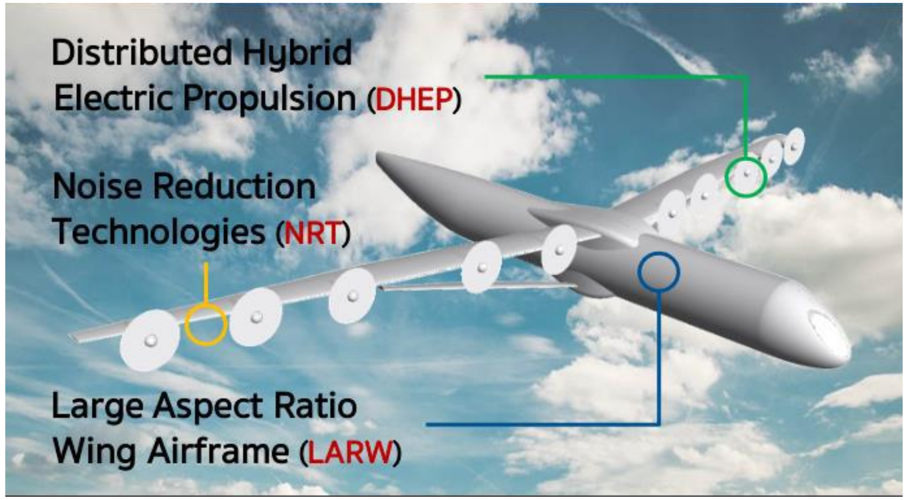
uc3m



INDIGO project

HORIZON-CL5-2022-D5-01-12: Towards a silent and ultra-low local air pollution aircraft

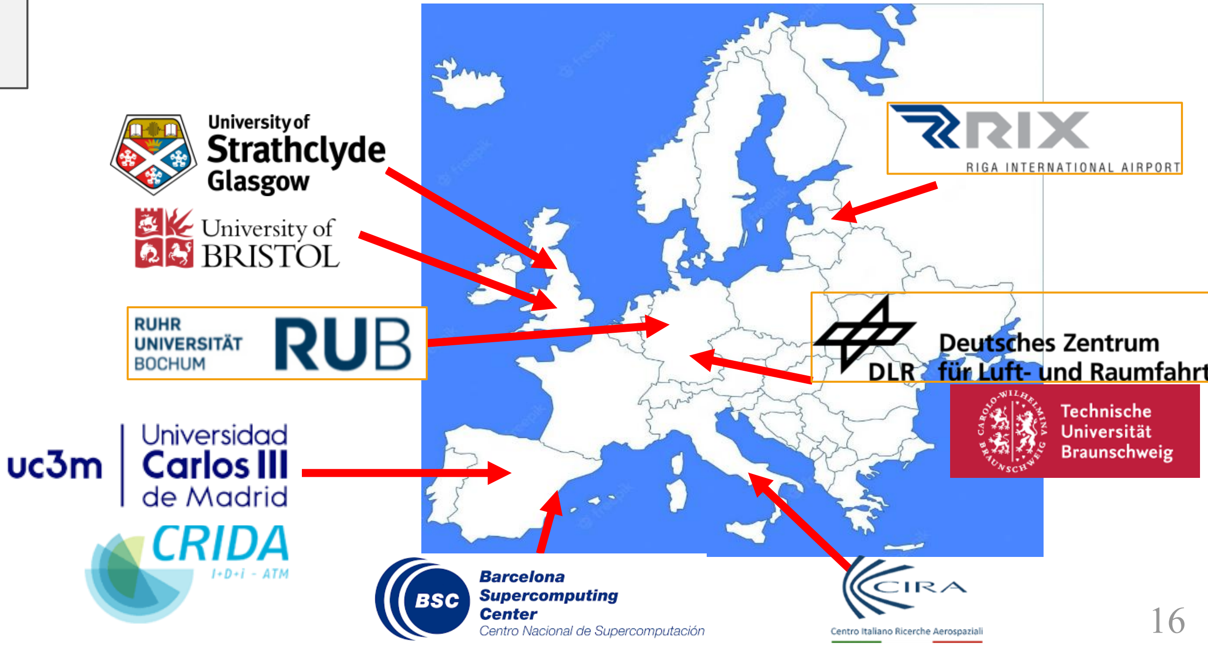
- "Deliver **transformative technologies** that will allow a step change in the reduction **of local air quality** (**LAQ**) impact **below 900m above ground level around airports**"
- "Deliver transformative technologies towards **a silent aircraft operations around airports**" (**NOISE**)



INDIGO

***IN**tegration and **D**igital demonstration of low-emission a**I**rcraft technolo**G**ies and airport **O**perations*

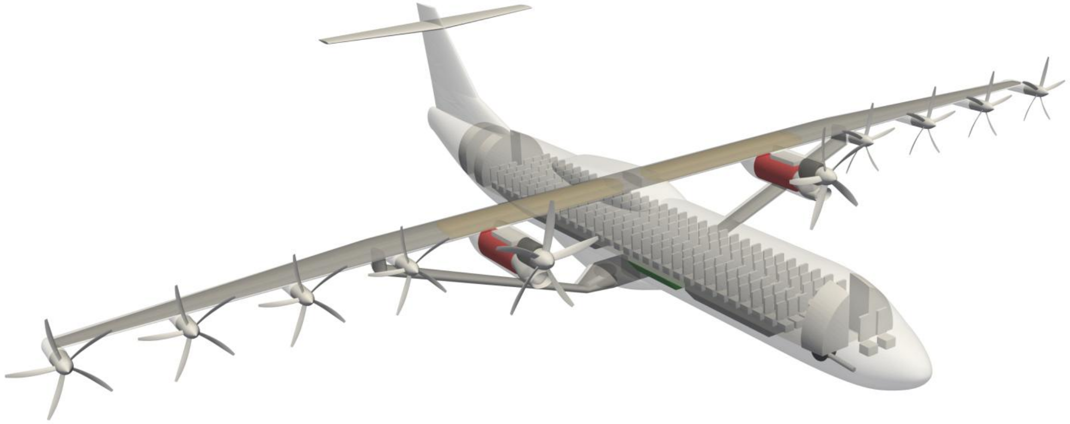
- **10** partners (8 beneficiaries + 2 associated).
- Total funding **4.4m€** (EU funding 3,1 m€ + UKRI 1,3 m€)
- 7 WPs , 15 Deliverables; 36 months

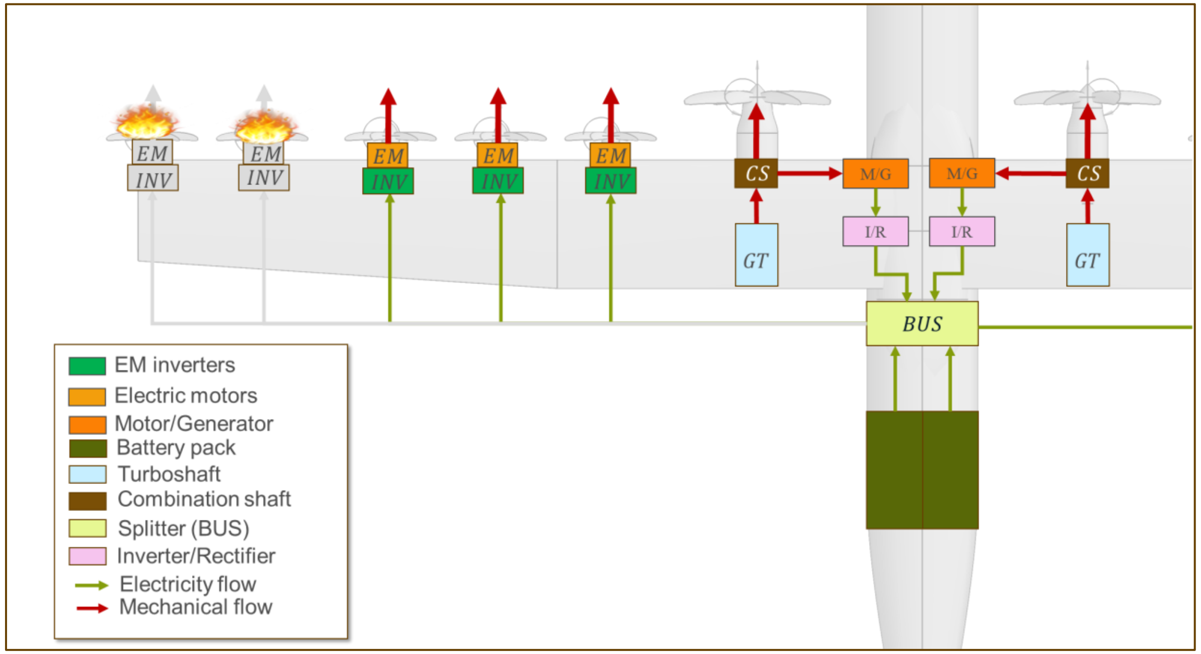


Funded by the European Union

Contents

- **Introduction**
- Methodology
- Optimization campaign

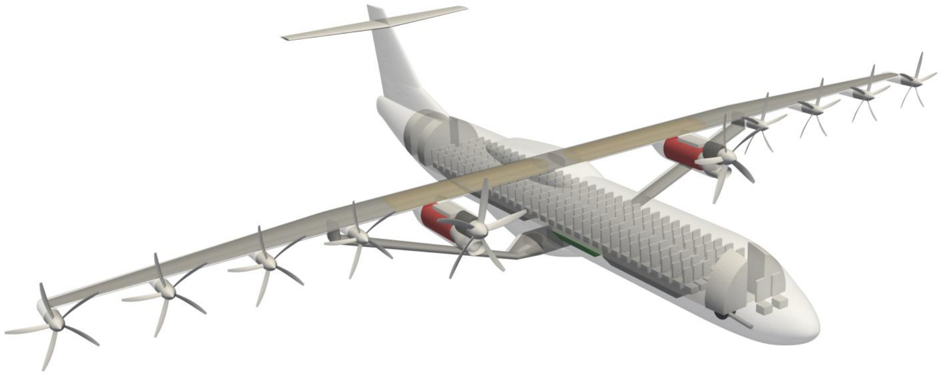


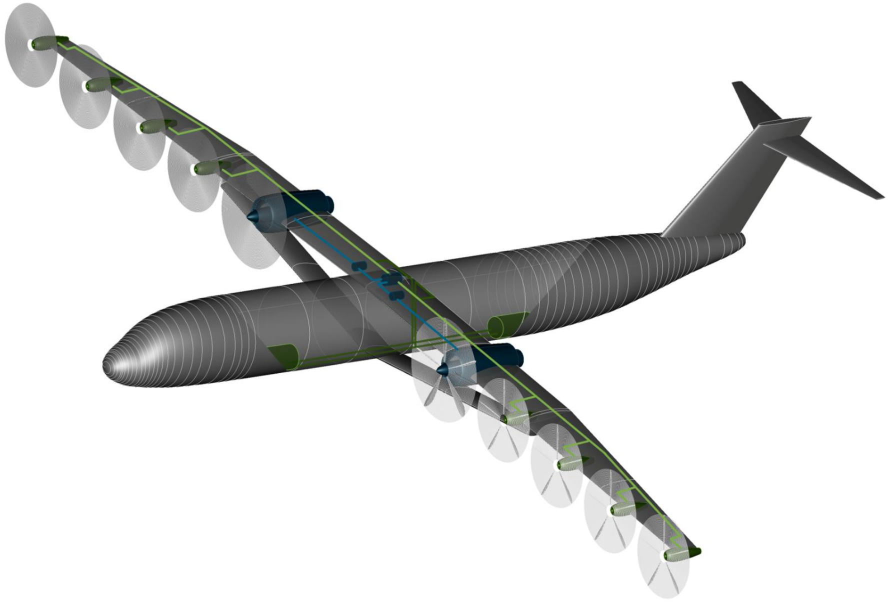


Funded by the European Union

Technological challenges

- **Large Aspect Ratio Wings (LARW)**
  - **Strut-braced wing** aircraft
  - Offers possible better integration of DHEP
- **Hybrid Electric Propulsion**
  - Go as **electric as possible below 900m**
  - Electric technologies still lagging for **full electric** trips (for MTOW of **A320** and design range **1000nm**)
  - Many powertrain architectures (serial, parallel)
- **Distributed Electric Propulsion (DEP)**
  - Synergistic with noise reduction
  - Blowing effects



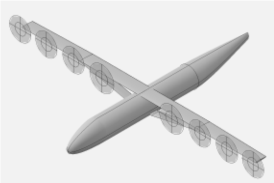
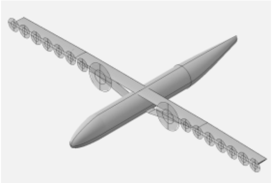


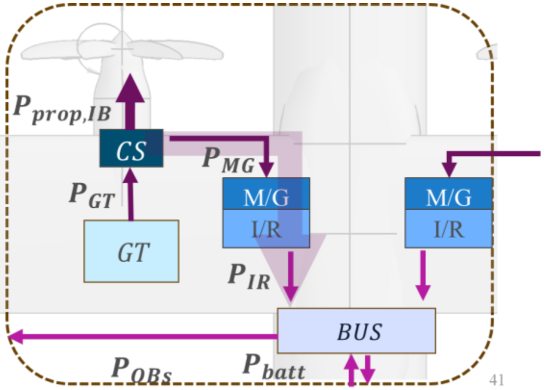
Funded by the European Union

Technological challenges

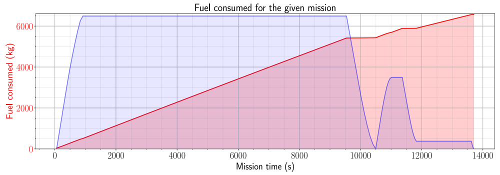
Deliverable 1.1
Provide an interim LARW-DHEP baseline

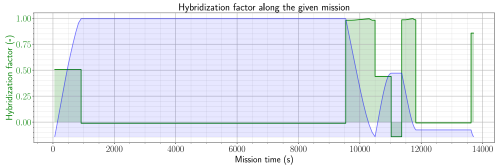
Deliverable 5.1
Preliminary design under Uncertainties



- **How many propellers?**
- **Which powertrain architecture?**
- **Battery capacity?**
- **How to distribute the 2 sources of energy along the mission?**
- **Wing planform to integrate better the DHEP**
- **How to balance conflicting needs (LAQN vs block fuel)**
- **Technology uncertainties and robust design**
- **Minimize impact on surroundings on real trajectories**



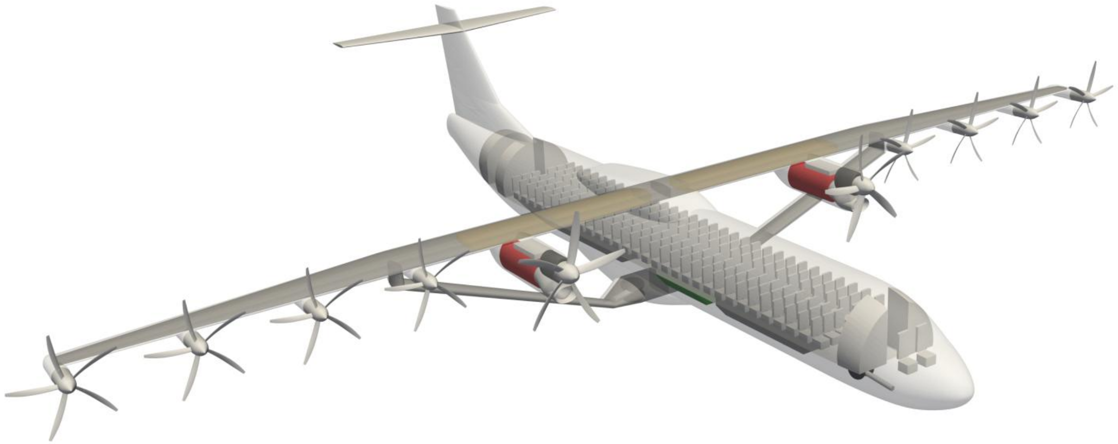


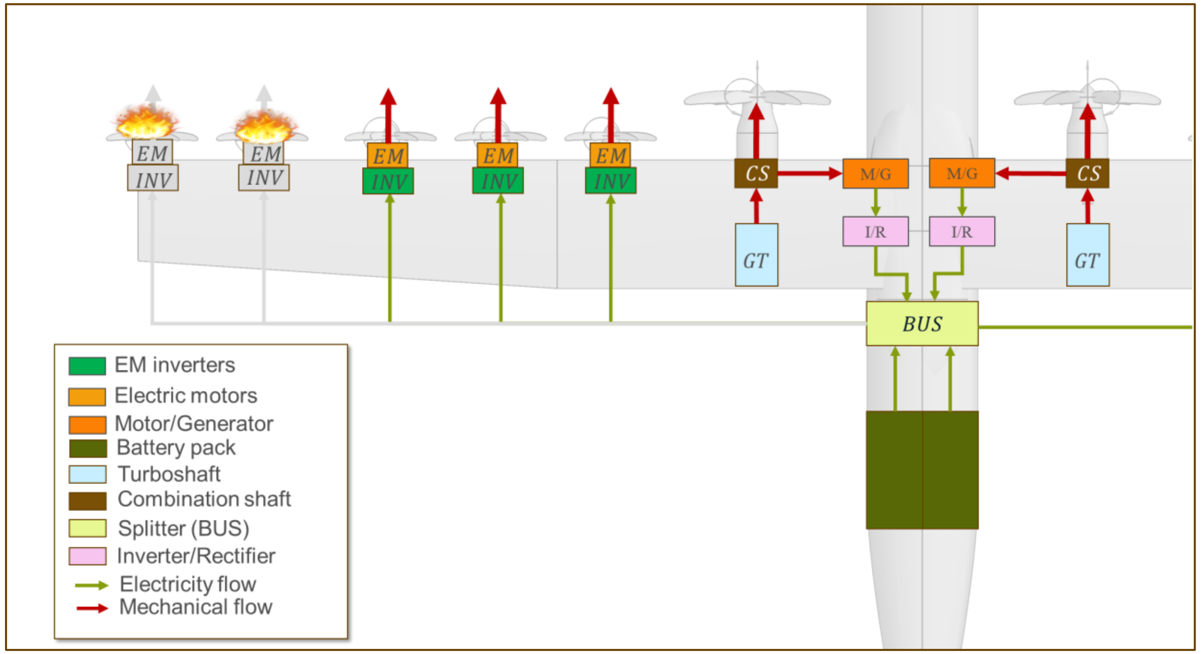
MDO

Funded by the European Union

Contents

- Introduction
- **Methodology**
- Optimization campaign
- Results





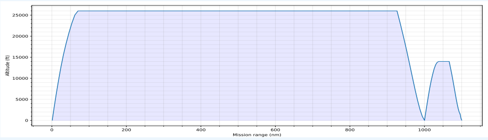
Funded by the European Union

Methodology - MDAO

MDAO platform (MOTIVATION - Mdao fOr susTaInable aViATION)

TLDR

Mission and range



Design variables

- Component ratings
- Prop diameters and RPM
- Wing planform
- Hybridization factor/thrust splitting

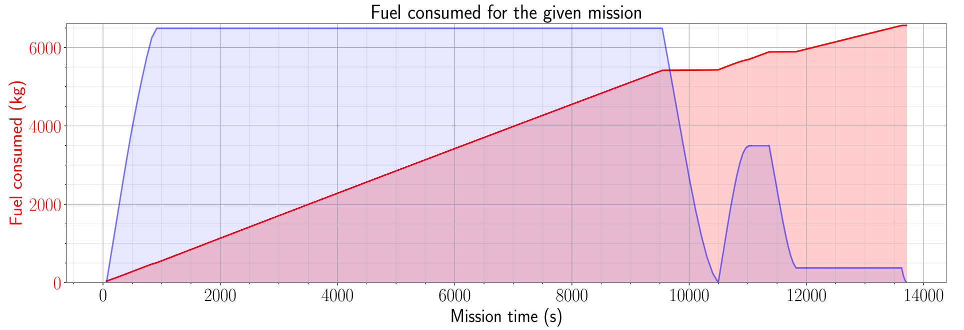
Design constraints

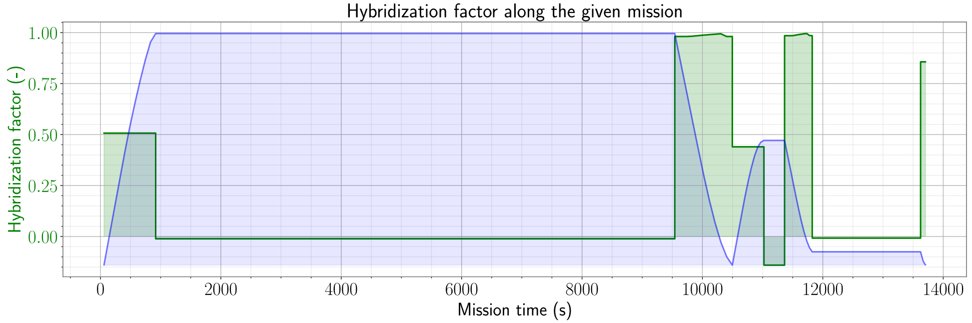
- Sizing margins
- Throttles (Gas turbine and Electric motors)
- Battery residual SOC
- Propellers gaps
- TOFL and RLD
- OEI Certification gradients

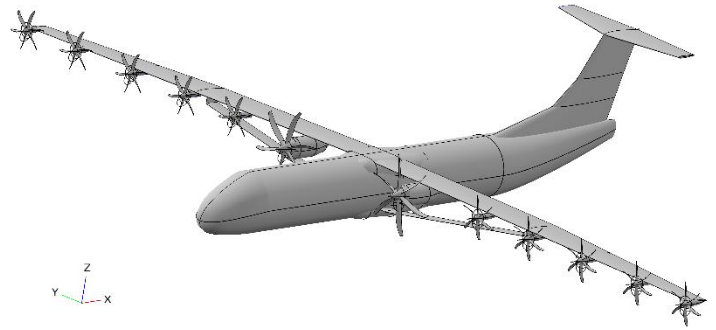
Objective function(s)
min $\Phi_i(x)$

MOTIVATION

- Forked from ***OpenConcept*** (2019)
- **Flexibility**:
  - different **powertrains**
  - **discipline modules** (fidelity)
- **Powerful:**
  - **large optimization problems**
  - **avoiding a-priori decisions** (extremely important as legacy-experience is missing).







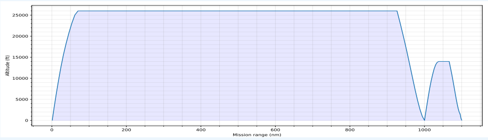
Funded by the European Union

Methodology - MDAO

MDAO platform (TOPAZ - Tool for Optimizing Powerplants and Aircraft with Zero-emissions)

TLDR

Mission and range



Design variables

As before +

- Htp/Vtp sizing, wing positioning

Design constraints

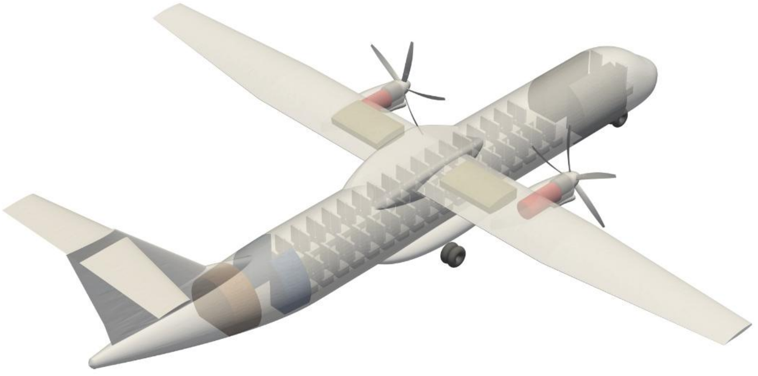
As before +

- Volume (integration of batteries)
- Trim (high-low speed)
- Stability
- Thermal management

Objective function(s)
$\min \boldsymbol{\Phi}_i(\boldsymbol{x})$

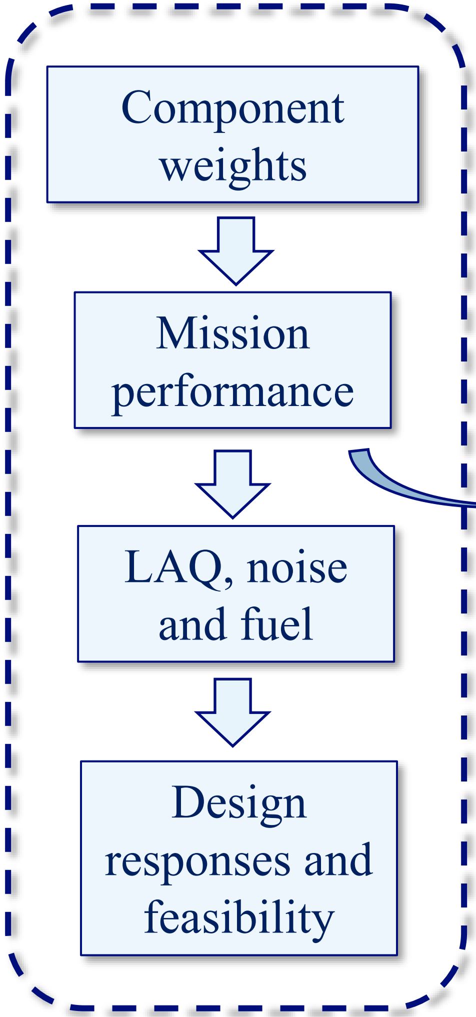
GEMSEO

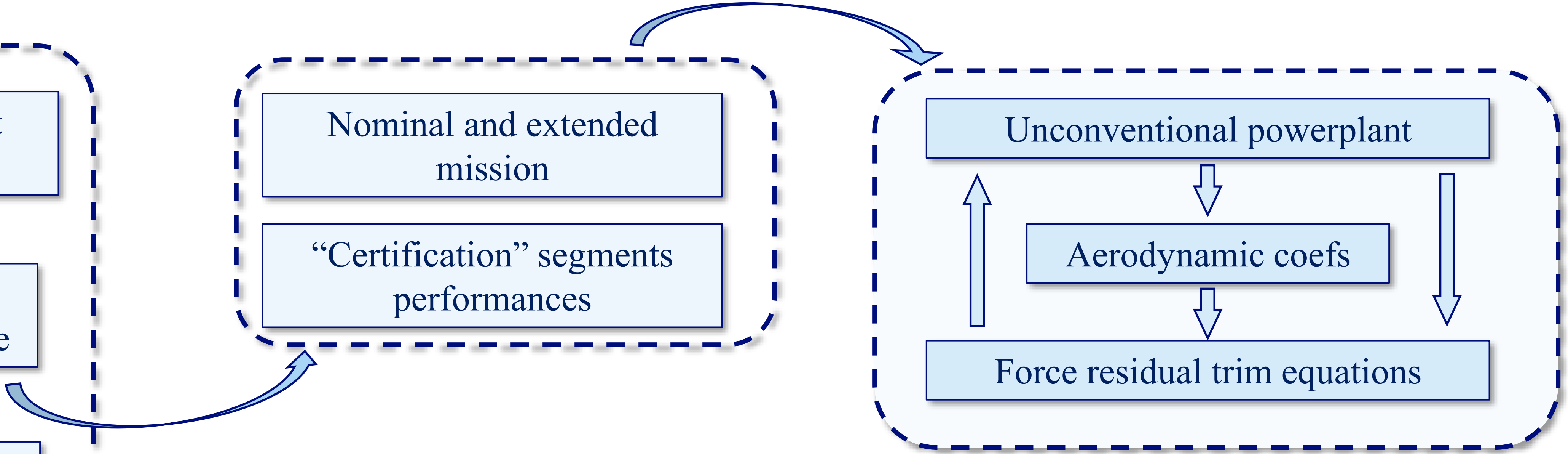
- **Flexibility**:
  - different **powertrains**
  - **discipline modules** (fidelity)
- **Powerful:**
  - **large optimization problems**
  - **avoiding a-priori decisions** (extremely important as legacy-experience is missing).
- JAX-AD for sensitivities



Funded by the European Union

MDAO frameworks building blocks





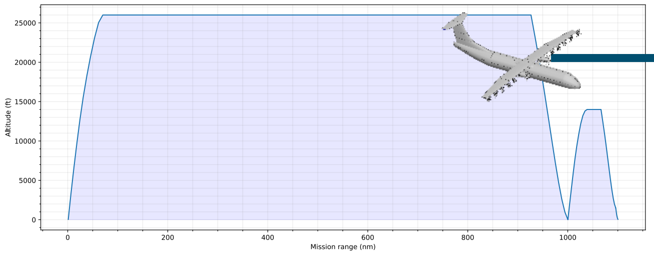
Equilibrium of all forces: coupling effects (DEP and blowing)

- WP1 - Use “**minimal” fidelity models** for large design space exploration
- WP5 - Use “**mid/high-fidelity** models on a reduced design space. Uncertainties.
- Define the mission as **FAR/CS25 compliant**, considering takeoff, landing and certification segments (climb gradients) – **Regulations yet to be defined for hybrid-electric aircraft!**
- Solve the **strong couplings** from the introduction of new technologies.

Funded by the European Union

Dynamic equilibrium

Convergence of residual



HF, ψ

$$\mathcal{R}_{vertical} = \boldsymbol{W} \cdot \cos(\gamma) - q \cdot S_{ref} \cdot (\boldsymbol{CL_{\alpha}} \cdot \boldsymbol{\alpha} + \boldsymbol{CL_0})$$

$$\mathcal{R}_{horizontal} = \boldsymbol{T} - \boldsymbol{W} \cdot \sin(\gamma) - q \cdot S_{ref} \cdot (\boldsymbol{CD_0} + \boldsymbol{CD_{\alpha}} \cdot \boldsymbol{\alpha} + \boldsymbol{CD_{\alpha\alpha}} \cdot \boldsymbol{\alpha^2})$$

throttles

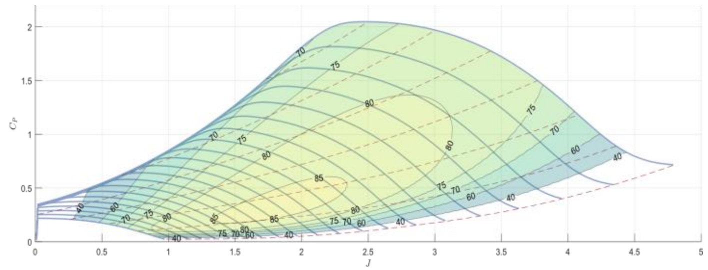
$\delta_{t_{OB}}$ δ_{gt} $\delta_{t_{IB}}$

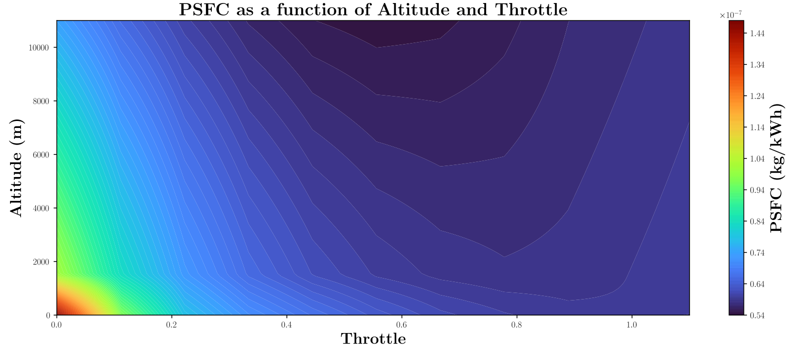
$\dot{m}$

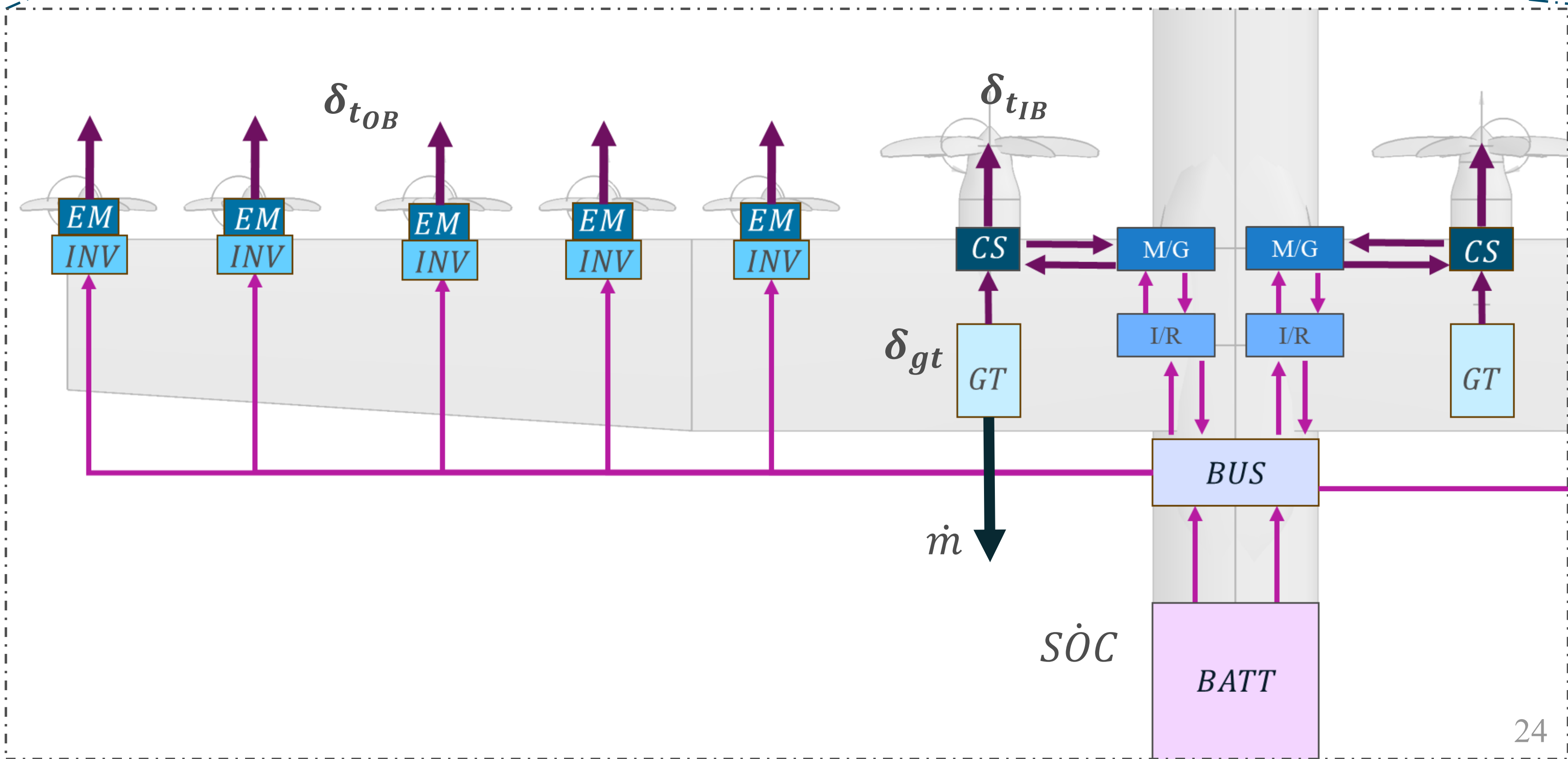
$S\dot{O}C$

Powerplant

tighter coupling





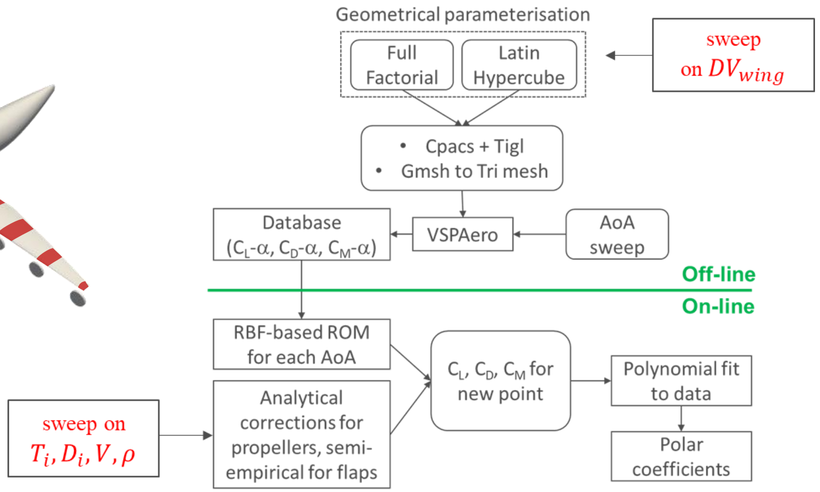


Funded by the European Union

Disciplines - Aerodynamics (UST, DLR)

Low-fi

- ROM
  - VLM (VSPAero)
  - Analytical correction for propeller blowing
  - Semi-empirical equations for flap, etc…

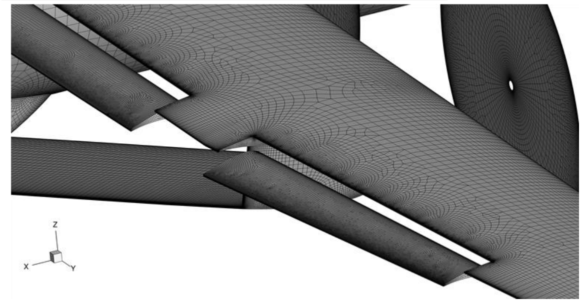


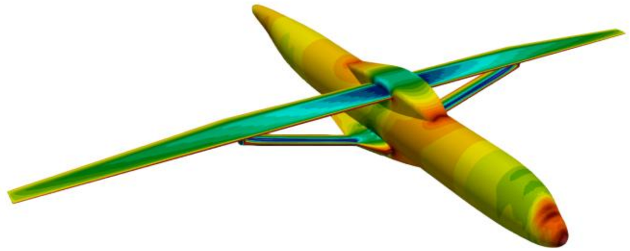
$$\begin{cases} C_L = C_{L_0} + C_{L_\alpha}\,\alpha \\ C_D = C_{D_0} + C_{D_\alpha}\,\alpha + C_{D_{\alpha\alpha}}\alpha^2 \\ C_m = C_{m_0} + C_{m_\alpha}\,\alpha + C_{m_{\alpha\alpha}}\alpha^2 \end{cases}$$

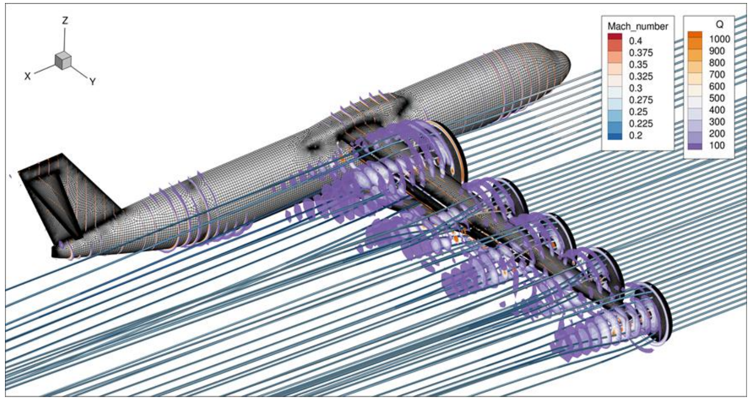
$$C_{L_x},\, C_{D_x} = f(\,DV_{wing}, T_i, D_i, V, \rho)$$

High-fi

- Multi-fi Surrogate Model (SM)
  - Hi-fi SU2+TAU
  - 6 SM for 6 polars (2 high-speed, 3 Low-speed)
  - Propeller blowing







Flight Case Visualization (not trimmed), Starting Point for Trim Routine

Funded by the European Union

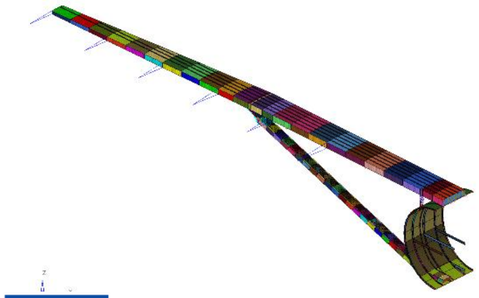
Discipline - Structures (UC3M)

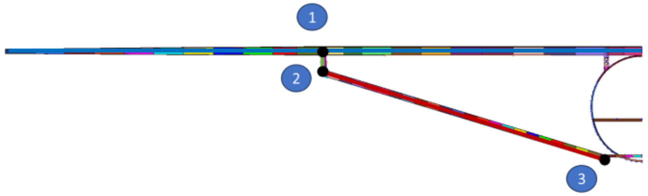
Low-fi

- Weight breakdown
- Classic semi-empirical formula, FLOPS. However,
  - Structural weight: coefficients calibration based on gFEM structural sizing (optimization)
  - Weight of powerplant system as regression on Max Power – Weight curves [RUB, UST, TUBS]

$$W = OEW + W_{PL} + W_F + W_{batt}$$

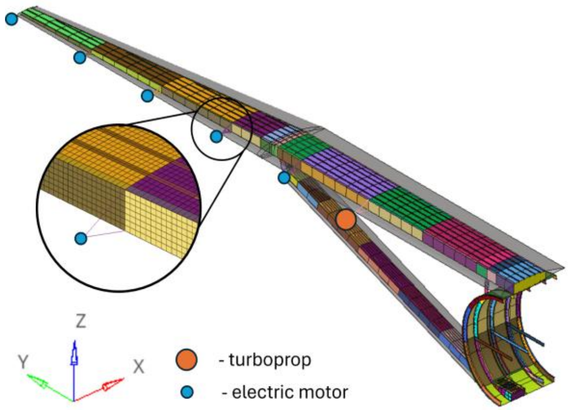
$$OEW = W_{struct} + W_{sys} + W_{furnishing} + W_{operitems} + W_{ppsys}$$

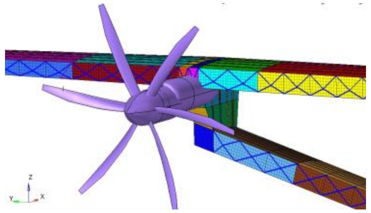


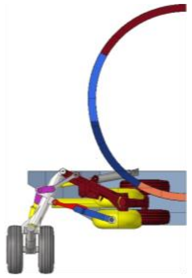


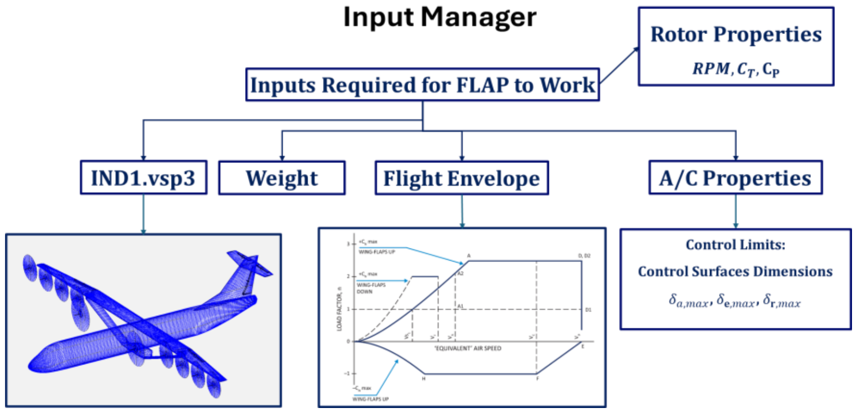
High-fi

- SM for lifting system weight
- gFEM
  - Loads (bookcases)
  - Flutter





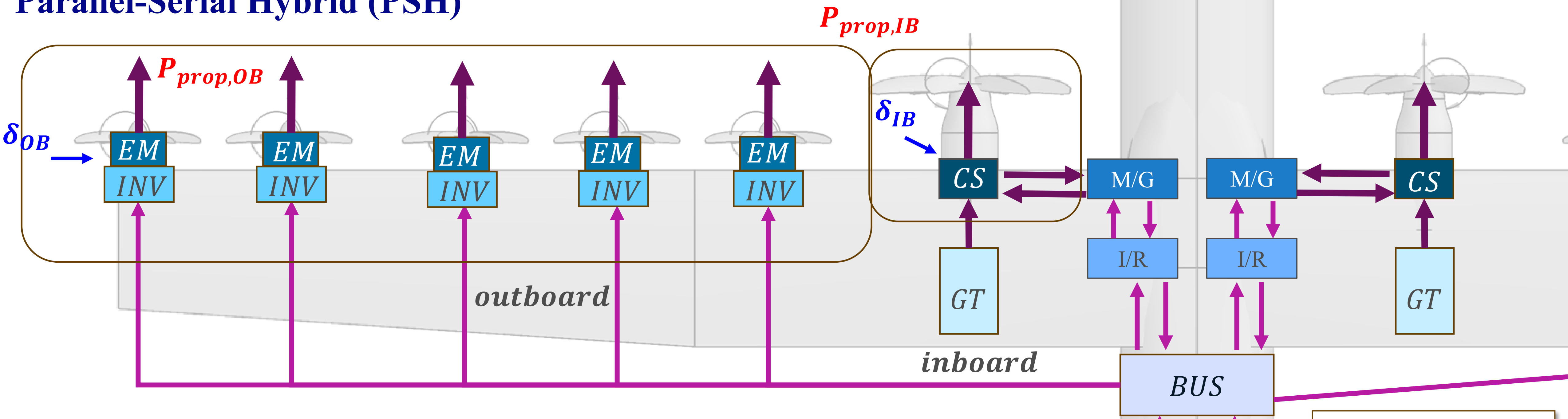




Funded by the European Union

Powertrain modelling (RUB, UST, TUBS, UC3M)

Parallel-Serial Hybrid (PSH)



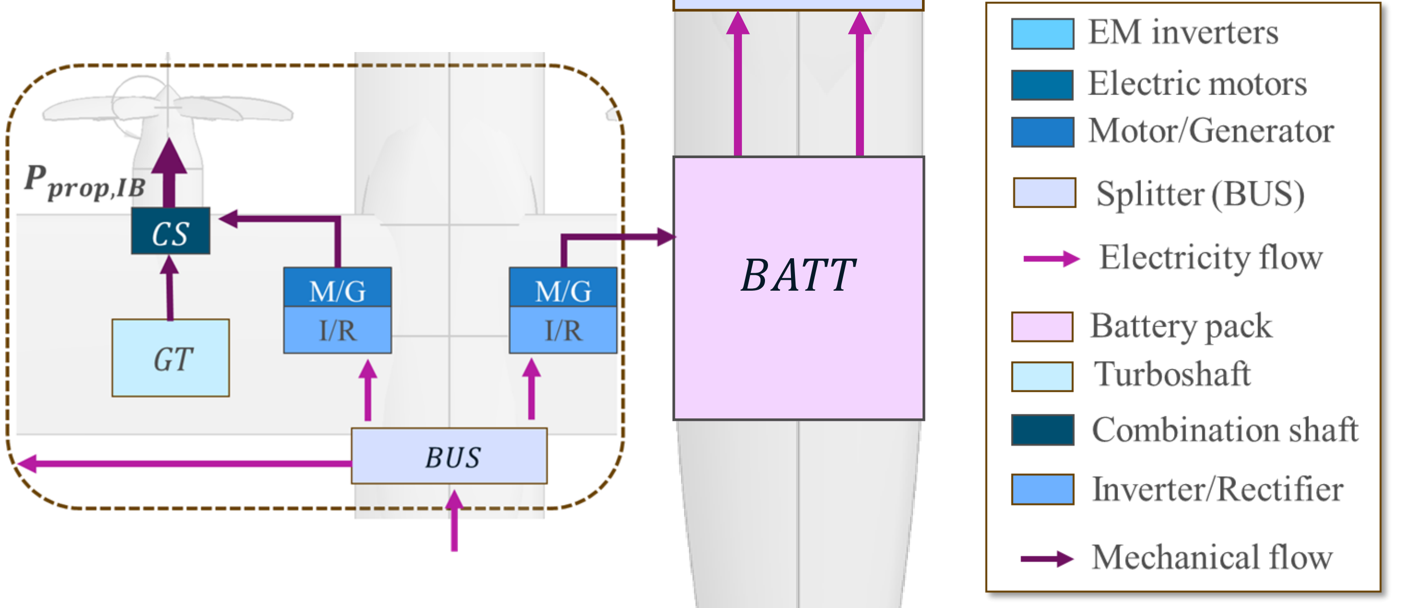
Power fraction ratio - Design Variable

$$\delta_{OB} = \delta_{IB} \cdot \boldsymbol{\psi}$$

Hybridization @ CS - Design Variable

$$HF^* = \frac{P_{out,MG}}{P_{prop,IB}}$$

$\delta_{IB/OB}$ → Fraction of Max Power ("throttle") – state variable



Funded by the European Union

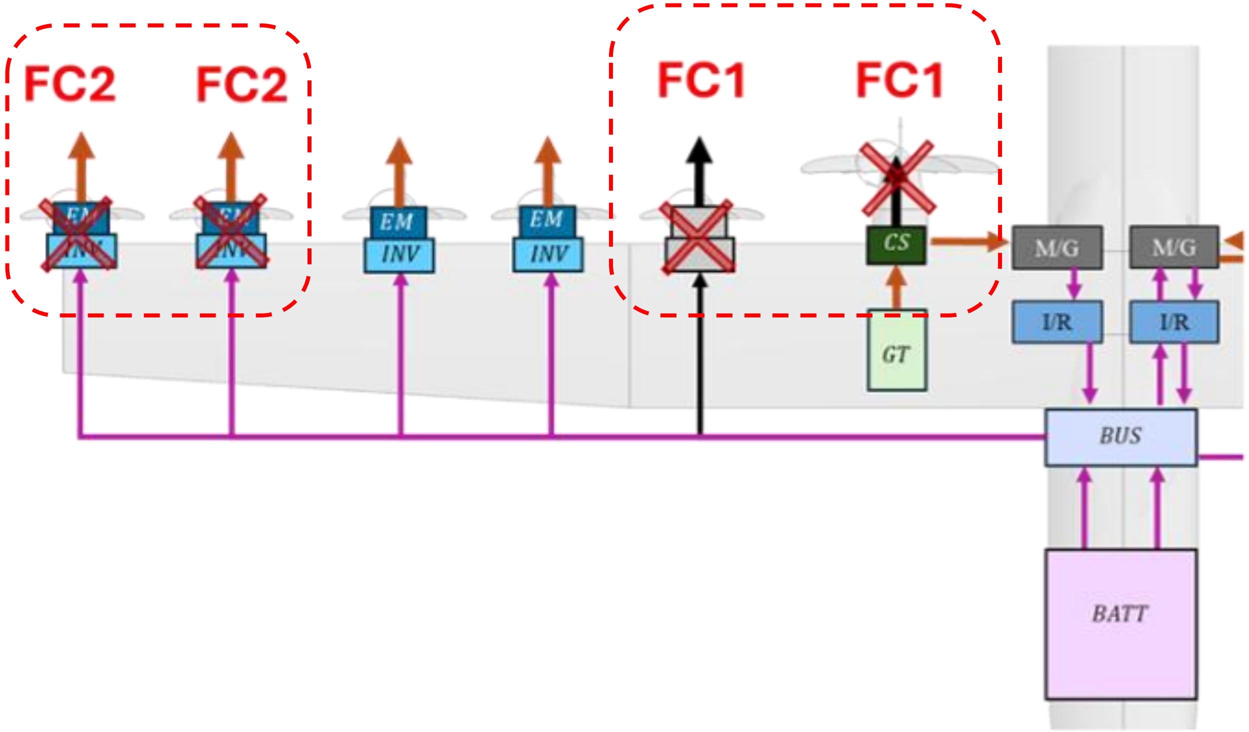
Failure cases

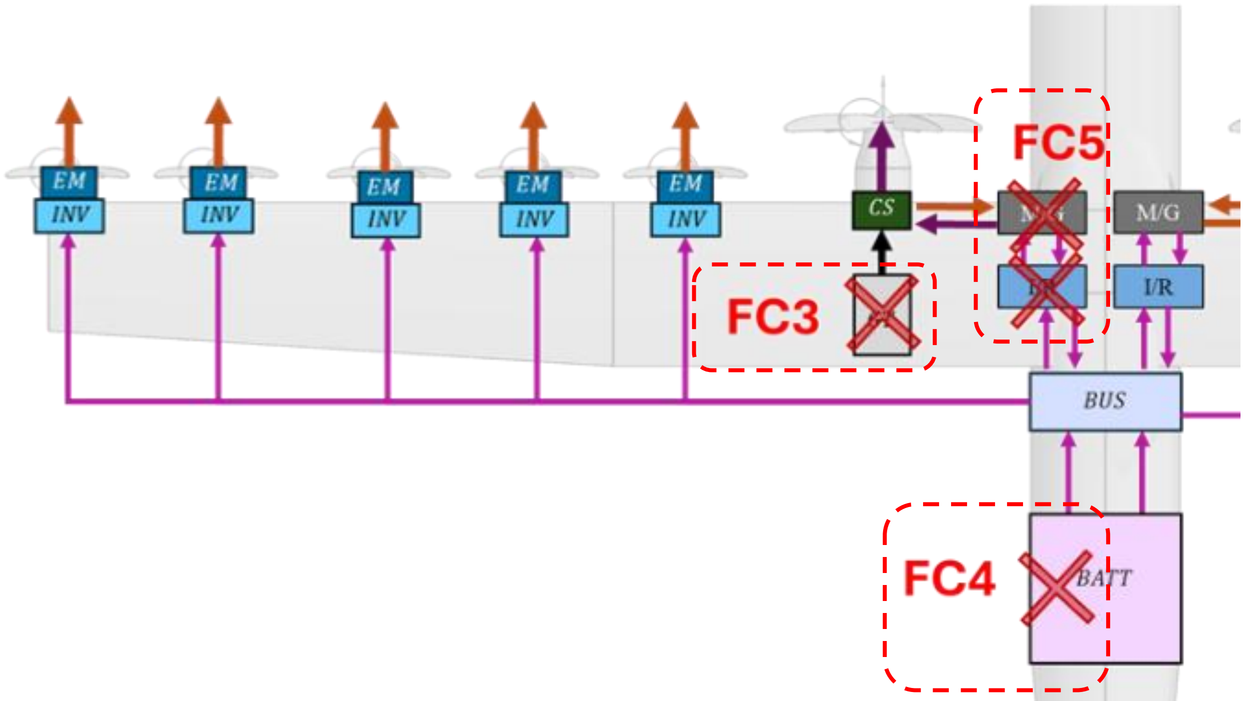
Lack of Thrust

- **FC1 - 2 most-inboard propellers**
- **FC2 - 2 most-outboard propellers**

Lack of Power

- **FC3 – 1 Gas Turbine Out**
- **FC4 – 50% Battery pack Out**
- **FC5 – 1 Electric Motor/Generator Out**

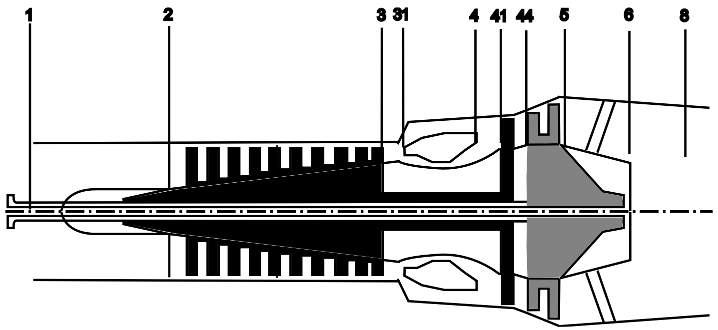




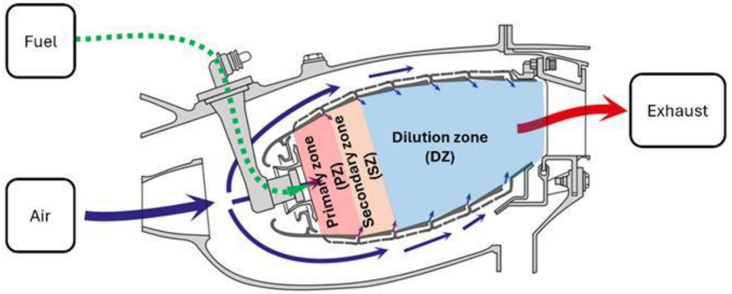
Funded by the European Union

Powertrain Modeling (RUB, TUBS, UST)

Gas Turbine (TUBS/RUB)



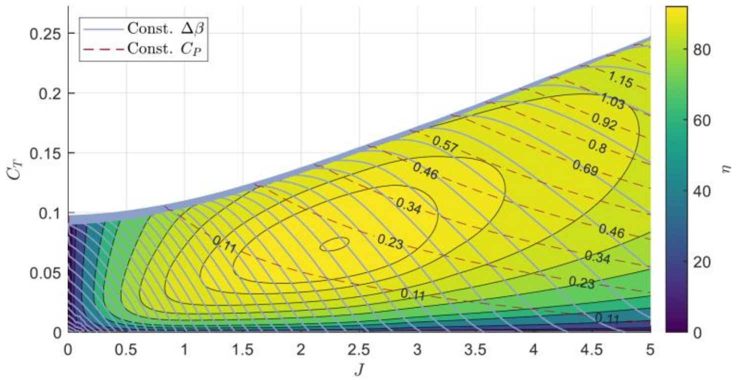
Combusiton Chamber (RUB)



For a certain power profile

- Sizes the thermal components
- Evaluate weight, PSFC
- $NO_x, CO, HC, PM..$

Propeller Aerodynamics (TUBS)



For a certain thrust profile

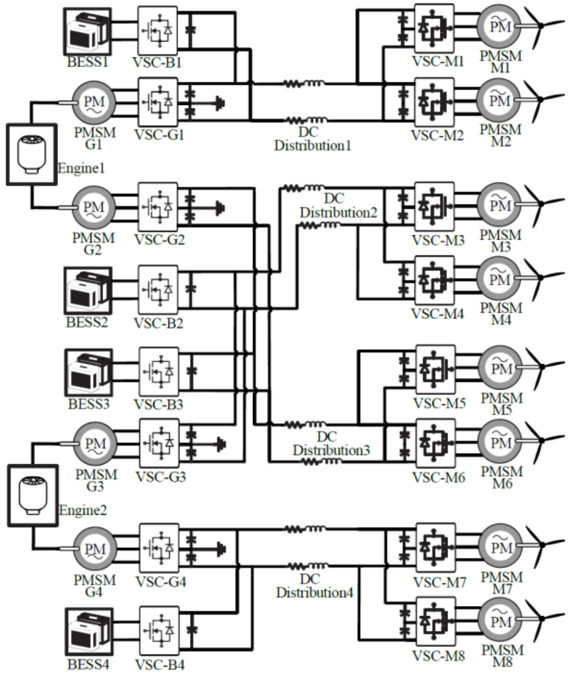
- Sizes the propellers
- Different Disk loadings

All given as SMs

Electric Power System (UST)

For a certain power profile

- Sizes electric system
- Outputs weight, efficiencies
- Includes transient-simulation and failure rates

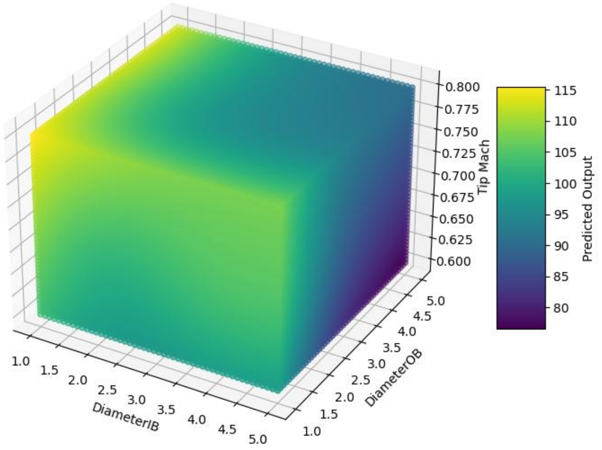


Funded by the European Union

Noise (UBR, DLR)

Low-fi

- **SM**
  - **IMMIS+** provided by partner DLR for noise assessment
  - **EPNL** (effective perceived noise level) as function of the propeller **diameters, tip Mach** number and **Thrust** (different for the IB and OB propellers)



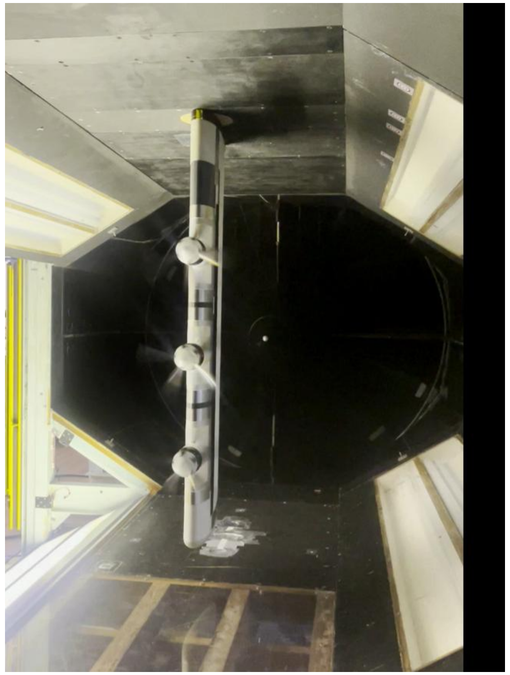
High-fi

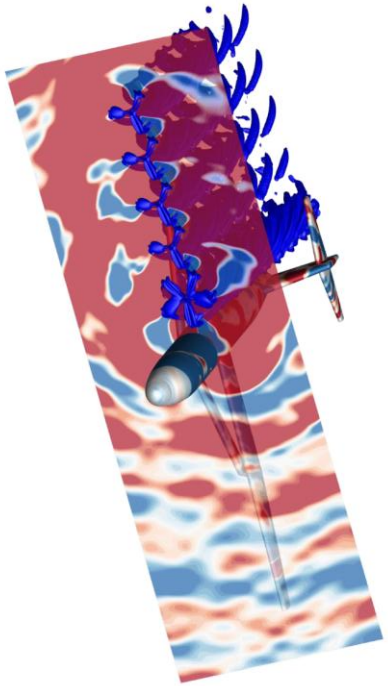
Experimental activity

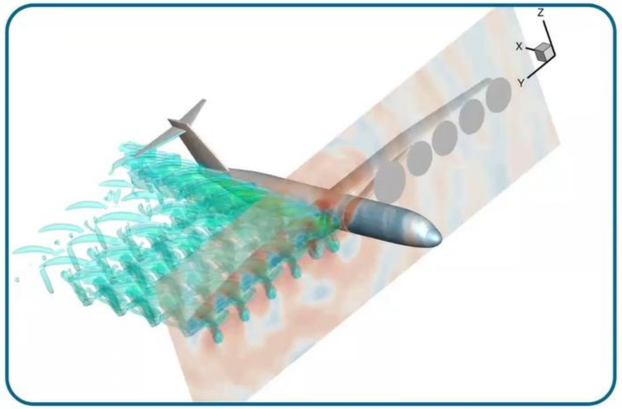
- Propeller-wing
- Propeller-propeller
- Phase shifting
- Used to calibrate the CAA solvers

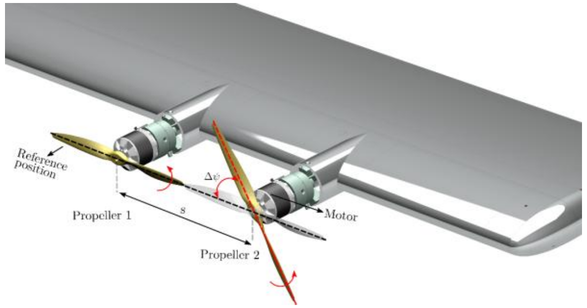
CAA

- Multifidelity
- CFD
- LBM
- **Calibrated on wind tunnel**
- Used on post MDO for fine-tuning
- Used for impact assessment







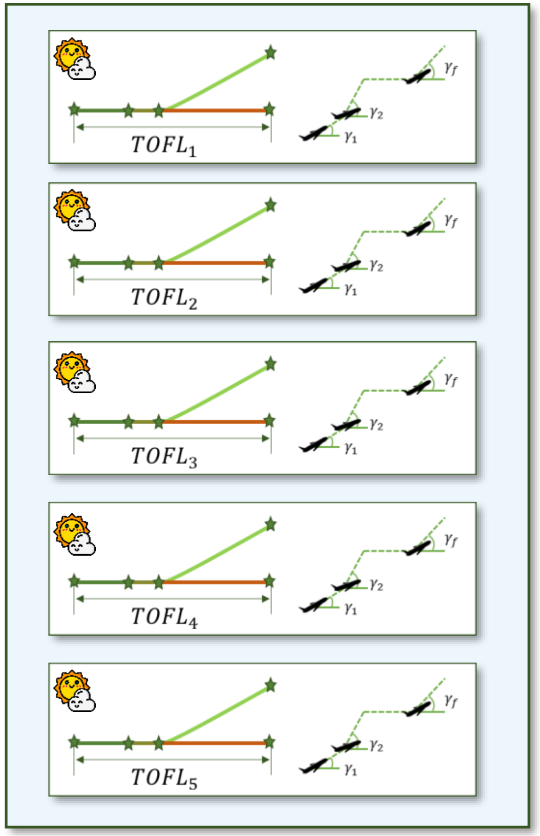


Funded by the European Union

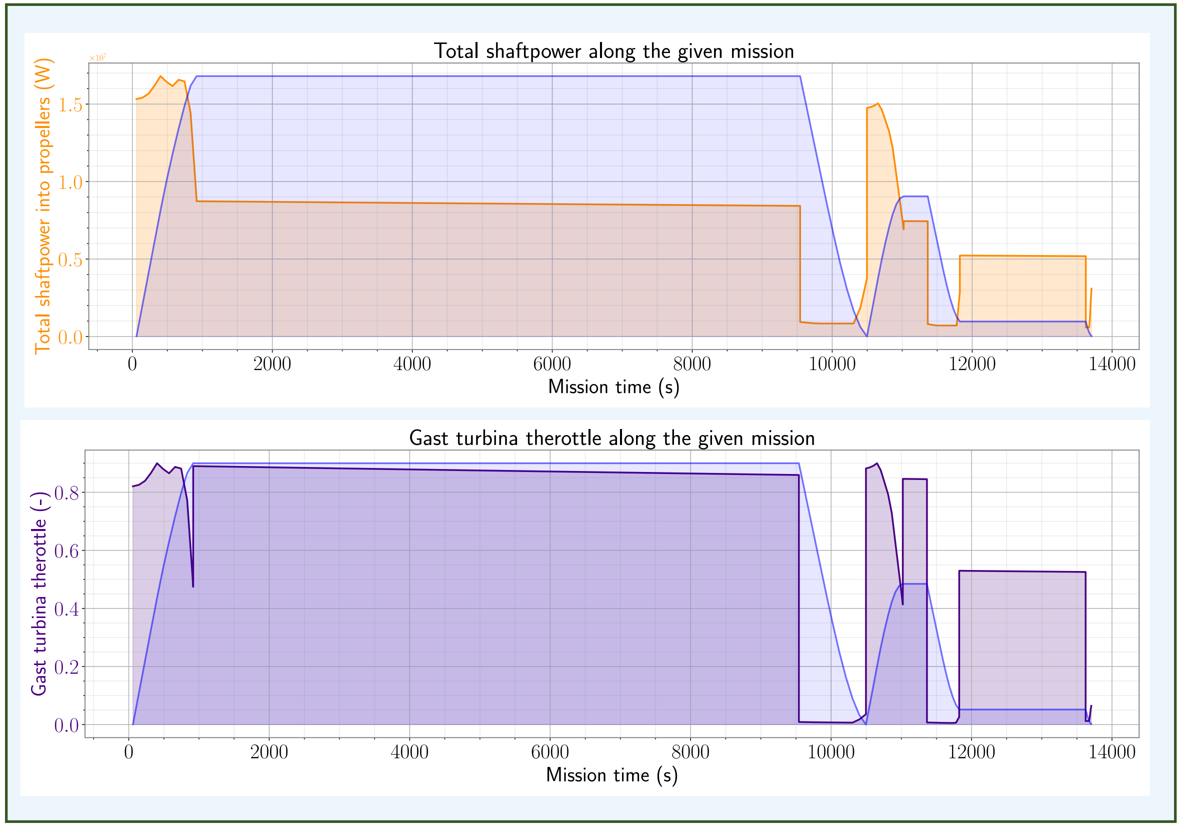
Mission module

- **Mission (Nominal + Diversion)**
- **TOFL and RLD Evaluation (wet/dry, failure conditions, inspired by FAR/CS25)**
- **Climb Gradients (failure conditions, inspired by FAR/CS25)**

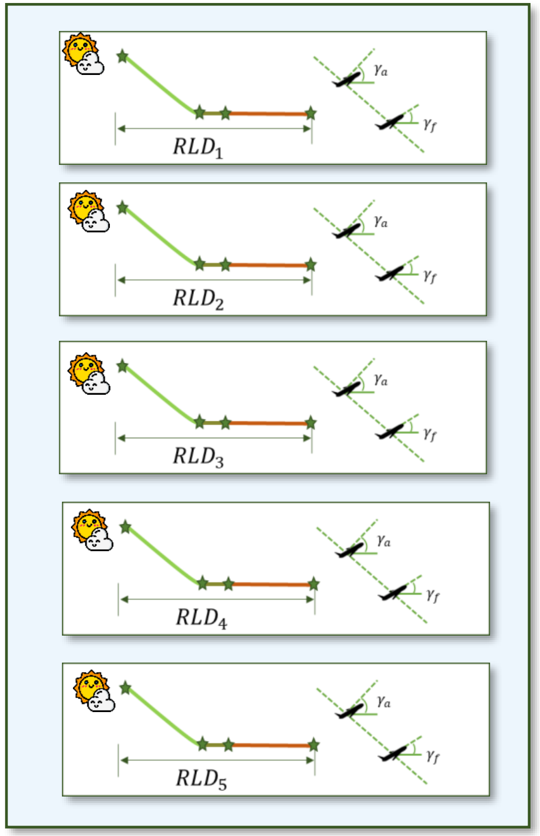
Takeoff and climb segments



Main and extended certification mission



Approach and landing segments

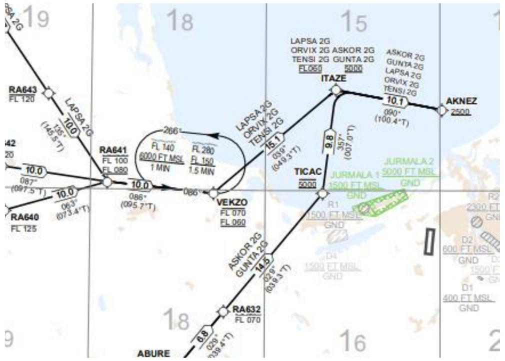


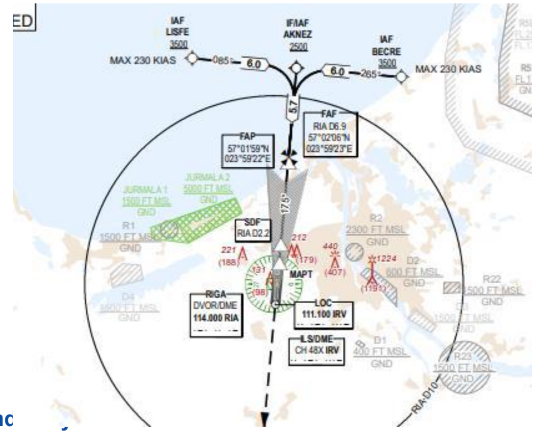
Funded by the European Union

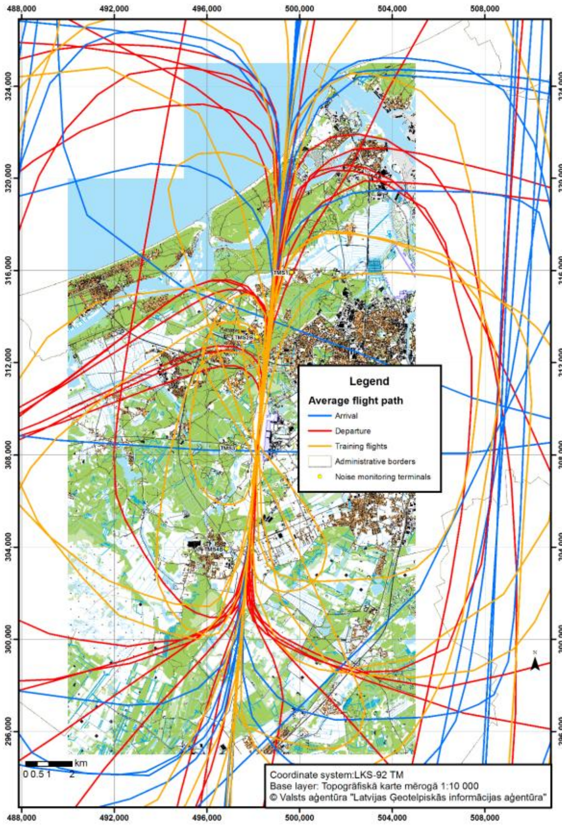
Mission and Impact (CRIDA, RIX, BSC)

Airport trajectories

- RIGA, Madrid, Barcelona, Dortmund
- Trajectories
  - Most flown
  - Better/Worst
    - LAQ
    - Noise

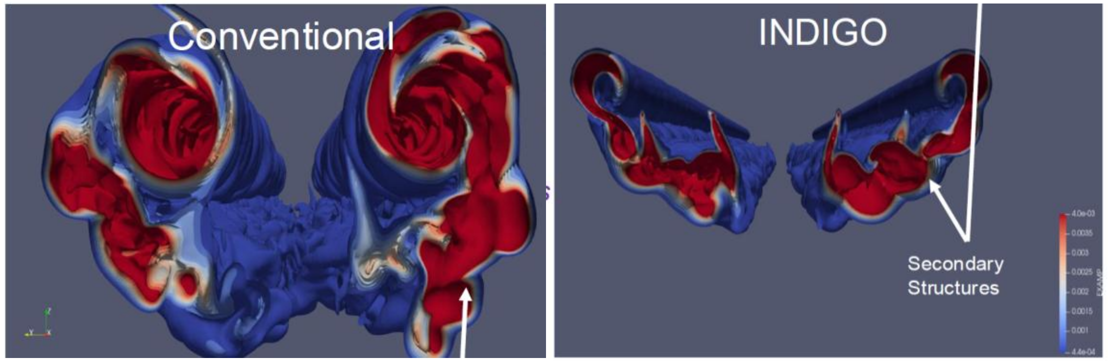






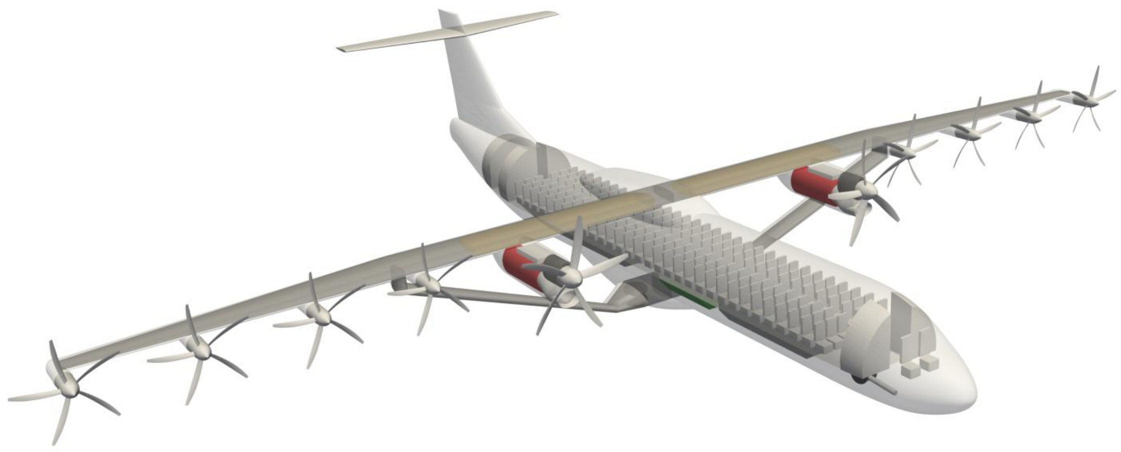
Pollutant Dispersion

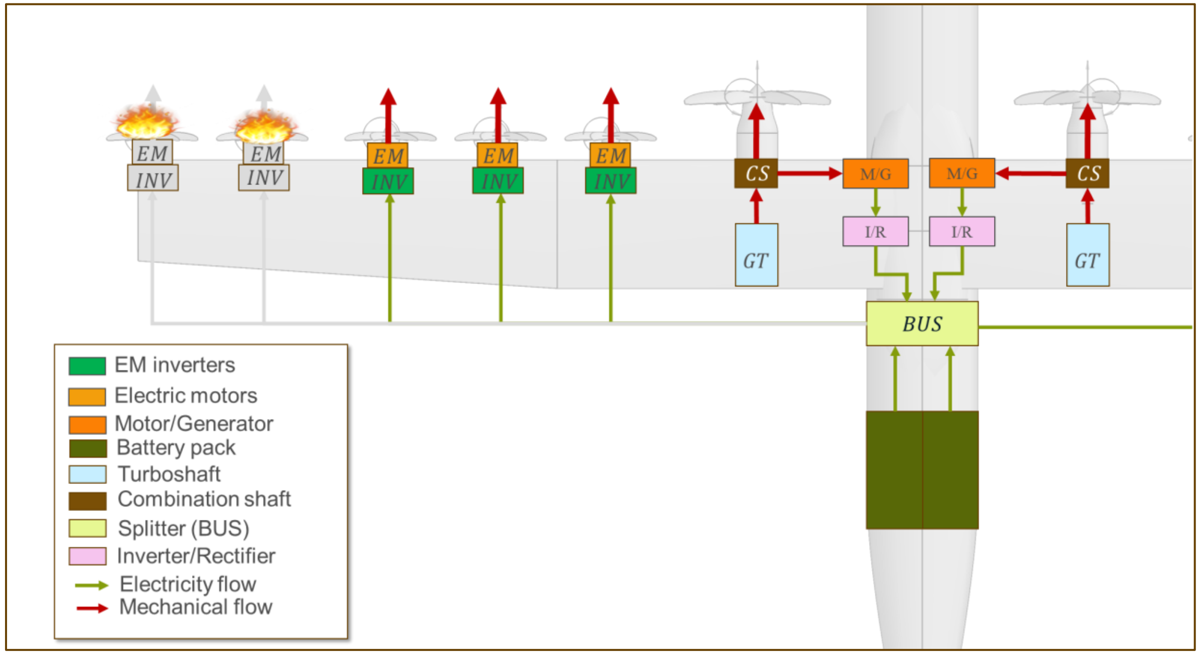
- LES modelling of vortices dynamics
- Assessment of pollutant concentration in populated areas
- Calibration of available methods on INDIGO's aircraft
- **Used after MDO**



Func... European Union

- Introduction
- Methodology
- **Optimization campaign**



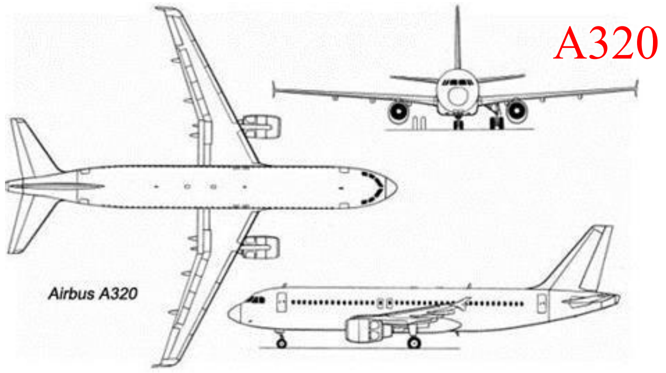


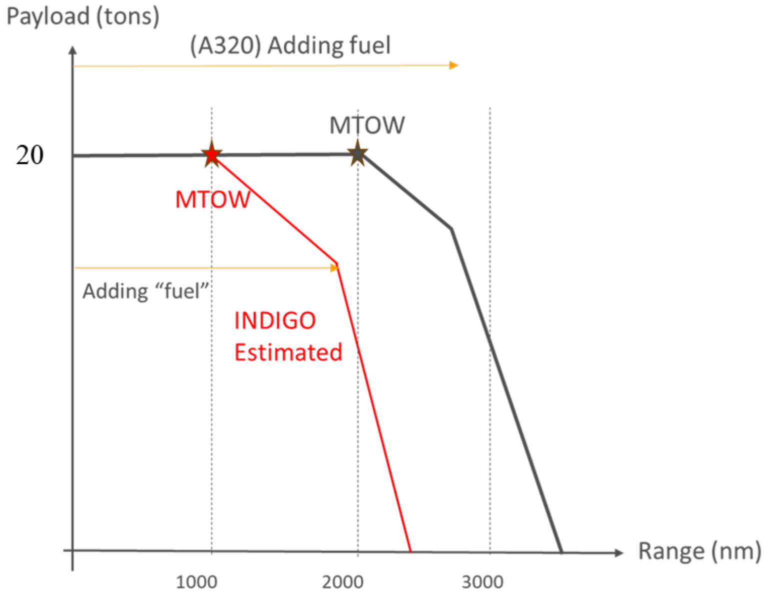
Funded by the European Union

D1: Low-fi Optimization Campaign

Reference vs Indigo Aircraft

	INDIGO	A320
MTOW	79 t	79 t
MPW	20 t	20 t
Wing Area	122.6 m^2	122.6 m^2
Range @ Max Payload	1000 nm	~2000-2500 nm
Cruise altitude	6000 m	~ 11000 m
Mach @ cruise	0.6	0.78





Funded by the European Union

D1: Low-fi Optimization Campaign

Optimization problem

$$\begin{cases} \min_{x} obj(x) \\ \text{subject to } g(x) \le 0 \\ h(x) = 0. \end{cases}$$

$$obj = F^* + \alpha \cdot G^* + \beta \cdot N^*$$

F^* :	Non-dimensional block fuel along the **nominal mission**
G^*:	Non-dimensional fuel burn **below 900m**
N^*:	Non-dimensional **noise measure**

Viability (block fuel)

LAQN metrics (operations below 900)

- **Gaseous part**
  - Integration of fuel burn
  - NOx, CO2 and other derivatives can be evaluated as byproduct
- **Noise Part**
  - EPNL

Optimization algorithm: SNOPT

α → relevance of **fuel burn below 900m** (indicators of Gaseous Emissions)

β → relevance of **noise** (indicators of emitted Noise)

Funded by the European Union

D1: Low-fi Optimization Campaign

Optimization problem

$$\begin{cases} \min_{x} obj(x) \\ \text{subject to } g(x) \leq 0 \\ \qquad\qquad h(x) = 0. \end{cases}$$

- **Airframe**
  - Wing planform DVs
  - Other wing and strut outer-mold line DVs (but airfoils class is fixed)
- **Powertrain**
  - Max **power of electric** and **thermal** components
  - Propeller design, **Diameter** and $\boldsymbol{M_{tip}}$ (RPMs as consequence) and **solidity** of the blade.
  - Hybridization factors $\boldsymbol{HF}$ along mission segments
  - Relative propeller power/thrust $\boldsymbol{\psi}$ along mission segments

Design variable	Units	Lower	Upper	Design variable	Units	Lower	Upper
Wing Planform							
AR	-	*15*	*25*	*Taper ratio*	-	*0.31*	*0.33*
Twist @ wing root	*deg*	*-3*	*3*	*Twist @ wing tip*	*deg*	*-5*	*1*
Twist @ strut	*deg*	*-3*	*3*	*Strut chord*	-	*0.906*	*1.597*
t/c @ root	-	*12%*	*18%*	*t/c @ tip*	-	*9%*	*14%*
Powerplant components							
Turboshaft	hp	3000	40000	Electric motor	hp	500	40000
Combination gearbox	hp	1000	100000	Inverter	hp	500	10000
Inverter/rectifier/generator assembly	hp	500	40000	Battery Weight	kg	10	100000
Propellers							
Propeller IB diameter	m	1.5	5	Propeller OB diameter	m	1.5	5
Propeller IB TipM	-	0.5	0.78	Propeller OB TipM	-	0.5	0.78
Propeller IB solid_factor	-	0	1	Propeller OB solid_factor	-	0	1
Ground and flight phases							
HF (initial)	-	-20	1	HF (final)	-	-20	1
psi (initial)	-	0.2	10	psi (final)	-	0.2	10

Total:
186 DVs

Funded by the European Union

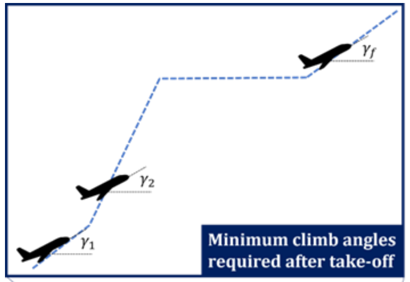
D1: Low-fi Optimization Campaign

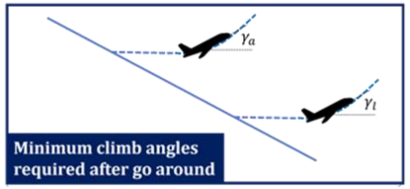
Optimization problem

$$\begin{cases} \min\limits_{x} obj(x) \\ \text{subject to } g(x) \leq 0 \\ \qquad\qquad h(x) = 0. \end{cases}$$

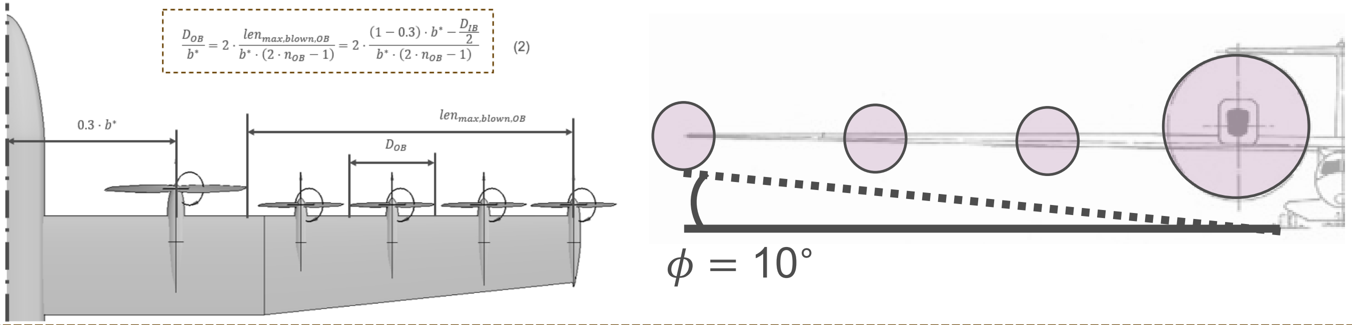
Total:
~5500 constraints

- **Performance and Airworthiness**
  - TOFL< target TOFL (2190 m)
  - LFL< target LFL
  - Climb gradients
  - Yawing constraints (failure case 2)
  - $C_p \leq 1.2$ (far from stall)
- **Geometric**
  - Gap between propellers (non-overlapping)
  - Clearance during roll maneuver
- **MDA Feasibility**
  - Power < Power Rating (for all components)
  - SoC of battery > 0.2 (can recharge!)

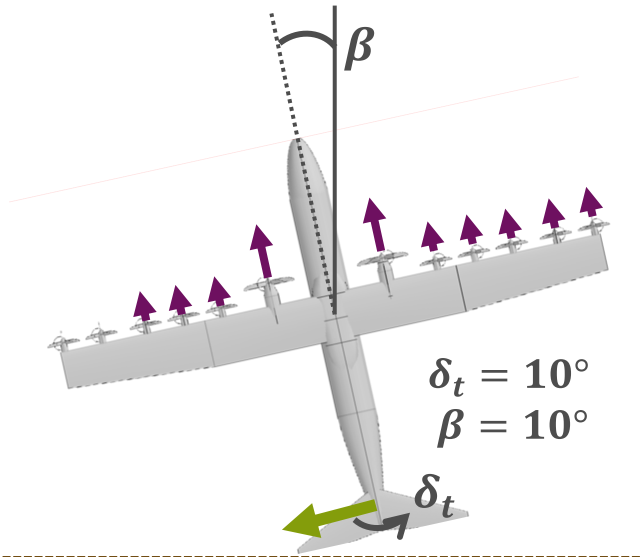




Propeller clearance

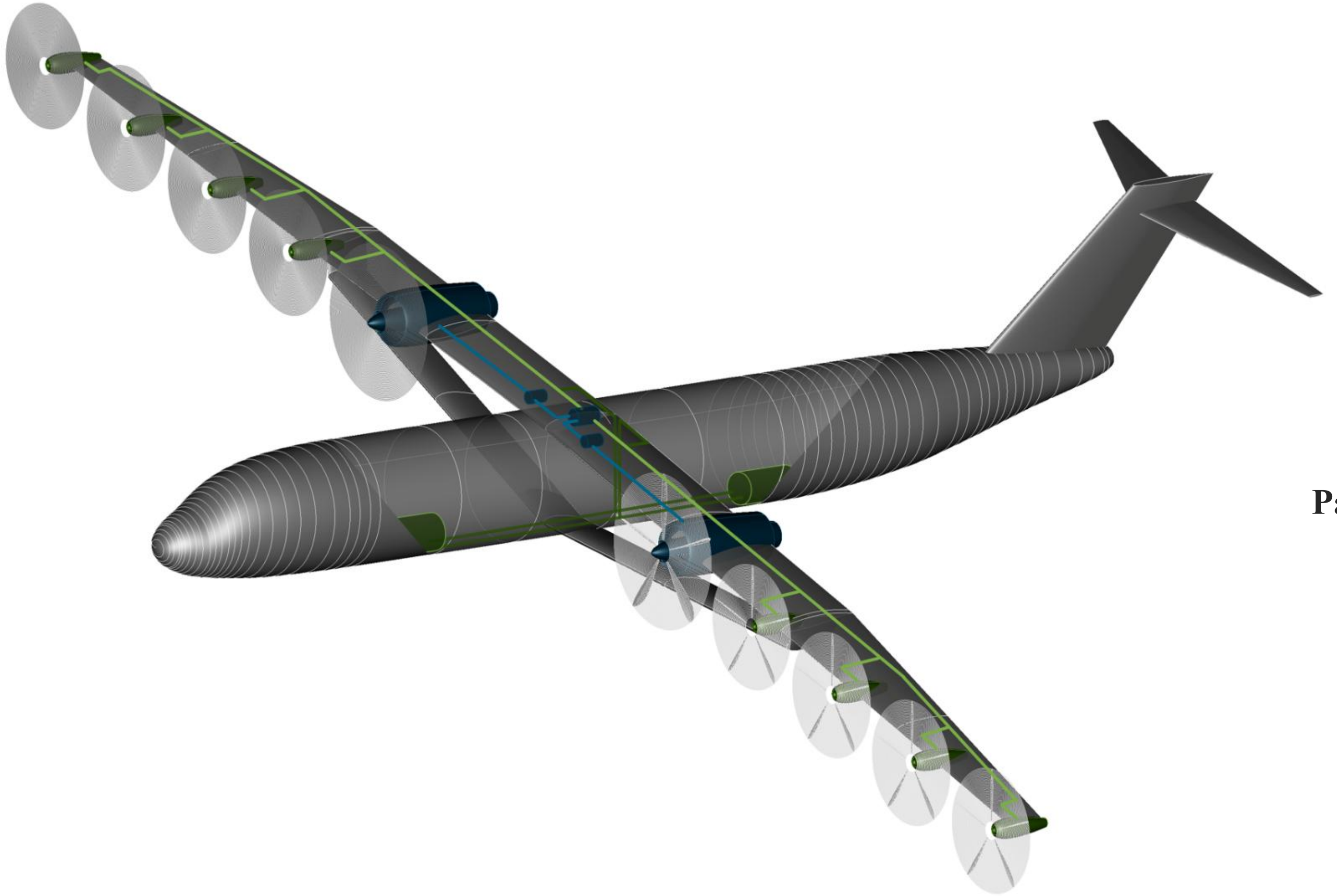


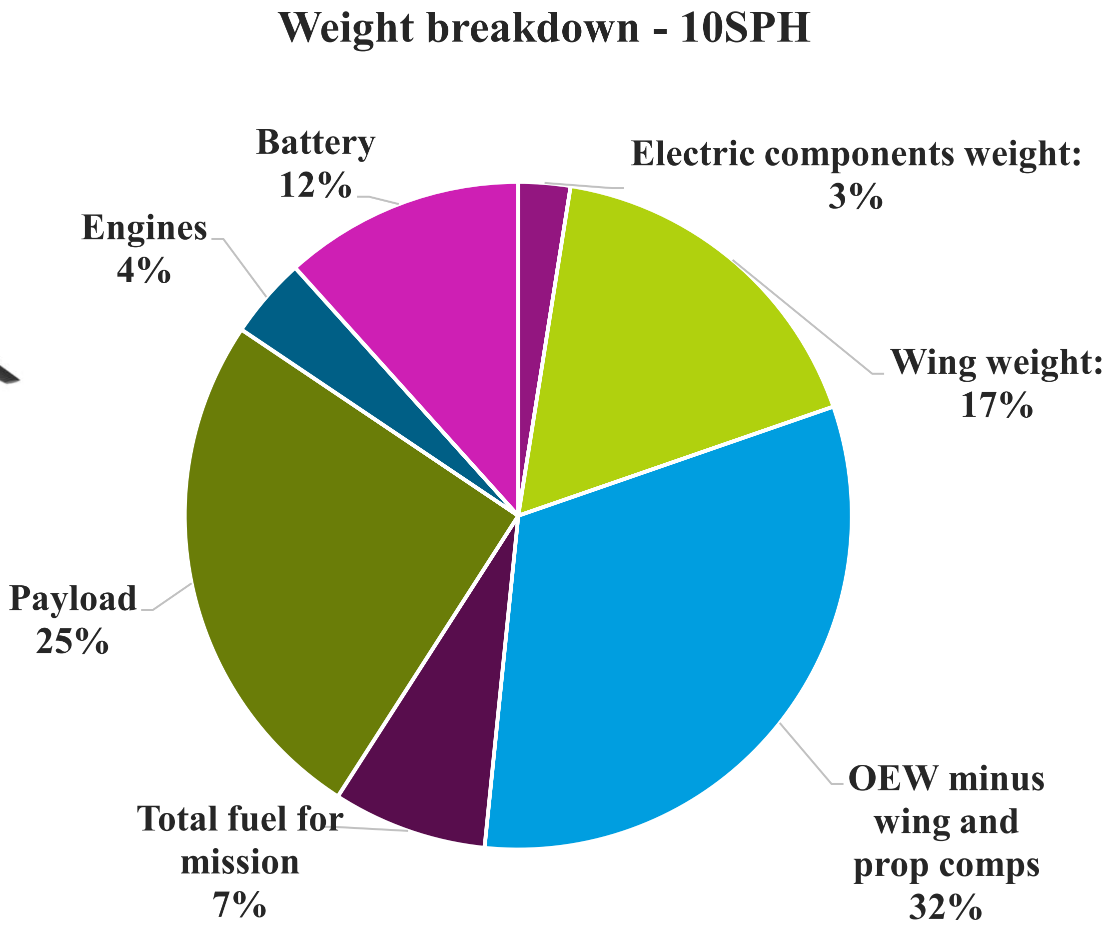
Yawing constraint during FC2:



Funded by the European Union

INDIGO aircraft baseline





Funded by the European Union

uc3m

INDIGO Baseline design parameters

Variable	units	Value	Variable	units	Value
Propeller IB diameter	m	5	Comb gearbox weight	kg	103.4
Propeller OB diameter	m	4.0	Dimenional Aspect ratio	None	21.6
Propeller IB mach number	None	0.6	Dimensional Taper ratio	None	0.4
Propeller OB mach number	None	0.6	Dimensional Wing root twist	deg	-3.0
Propeller IB solid fraction	None	0.7	Dimensional Wing tip twist	deg	-5.0
Propeller OB solid fraction	None	0.3	Dimensional Strut twist	deg	1.6
Inverter rating	MW	1.7	Dimensional Strut chord	m	1.6
Inverter rectifier rating	MW	1.8	Dimensional Root thickness	None	0.2
Engine rating	MW	**6.7**	Dimensional Tip thickness	None	0.1
Electric motor rating	MW	**1.6**	Trip fuel	kg	4530.4
Gearbox rating	MW	2.0	Total fuel	kg	5912.4
Battery weight	kg	**9215.8**	OEW	kg	43871.7
Inverter weight	kg	94.1	**Wing weight**	kg	**13577.7**
Inverter rectifier motor weight	kg	196.0	Mean EPNL	None	74.9
Engine weight	kg	1547.6	Fuel burnt below 900m	kg	72.4
Motor weight	kg	79.2			

Comparison with A320

- Same Payload (specific pollution)
- Same Mission Range

	INDIGO	A320	Improv %
Block fuel [kg]	4530.5	6479.7	30.1
Fuel burn < 900m [kg]	72.4	227.6	68.2
Noise (avg TO EPNL) [dB]	77.5	83.5	6.0 dB

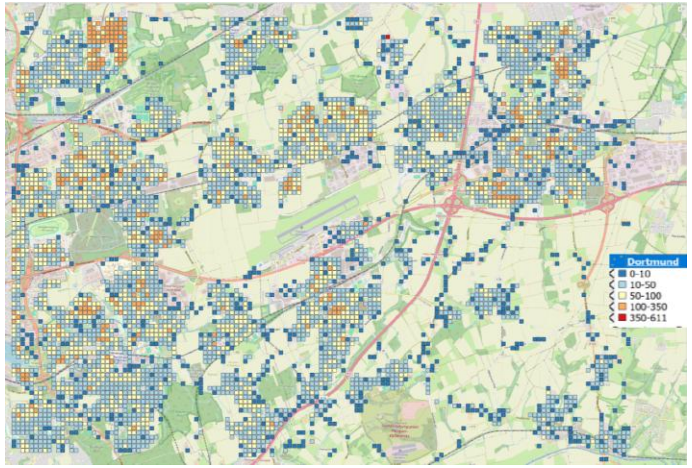
Funded by the European Union

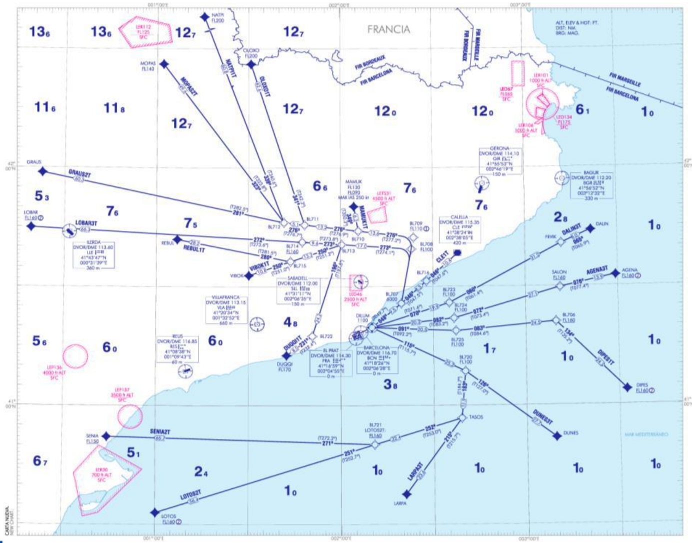
uc3m

Next steps – HiFi MDOUU

INDI GO!

$$obj = F^* + \alpha \cdot G^* + \beta \cdot N^*$$





LAQN metrics (operations below 900)

- Gaseous and Noise concentrations measures (**weighted by population density**)
- Surrogate model
- **Gaseous part**
  - AeroMOD (emitted → air dispersion → concentration)
  - NOx, CO2 and other derivatives weighted by health impact
- **Noise Part**
  - EPNL in **populated regions**!

Multi-missions

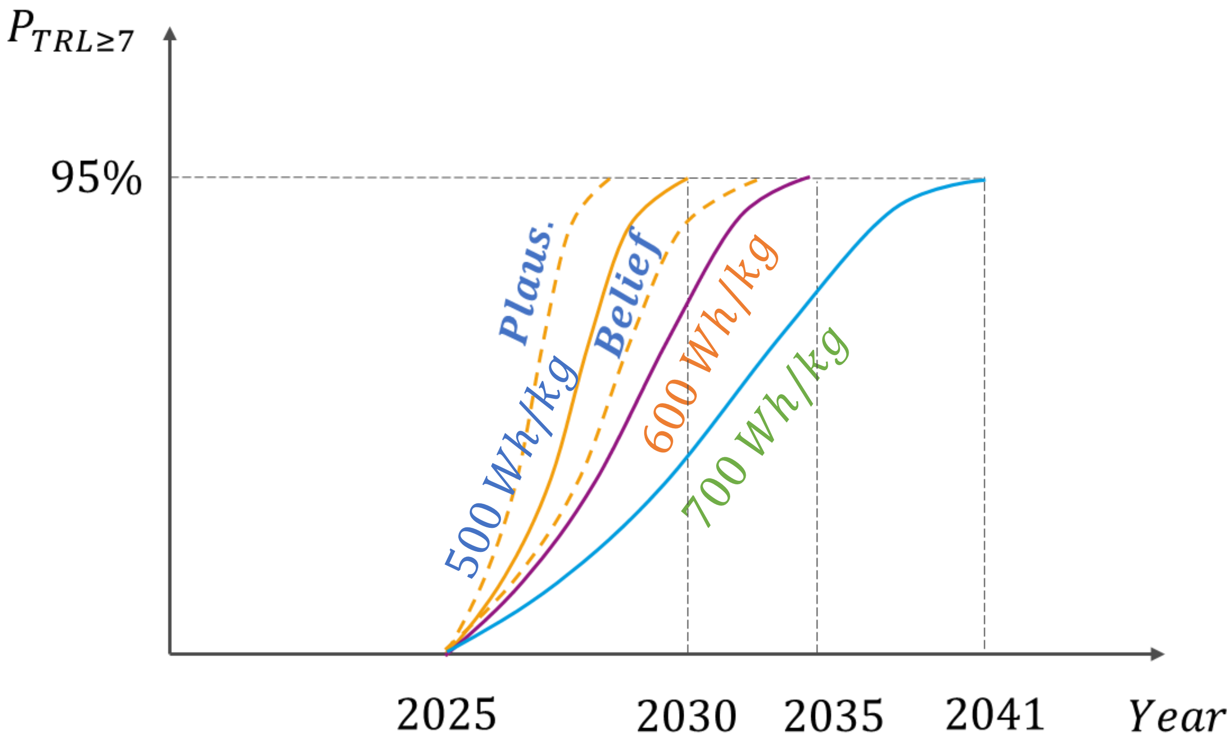
- 20 TO trajectories
- 20 LA trajectories

Funded by the European Union

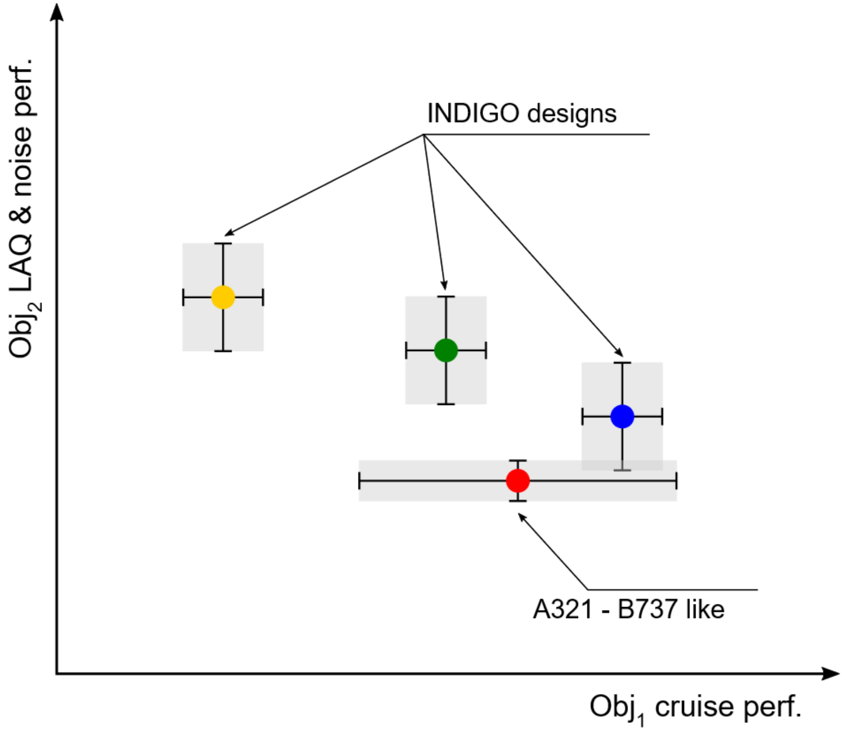
Next steps – HiFi MDOUU

Uncertainties

- On batteries technological level (energy/power density)



Dempster-Shafer evidence theory to determine optimistic (plausibility) and pessimistic margins of a given required battery feature.



Funded by the European Union

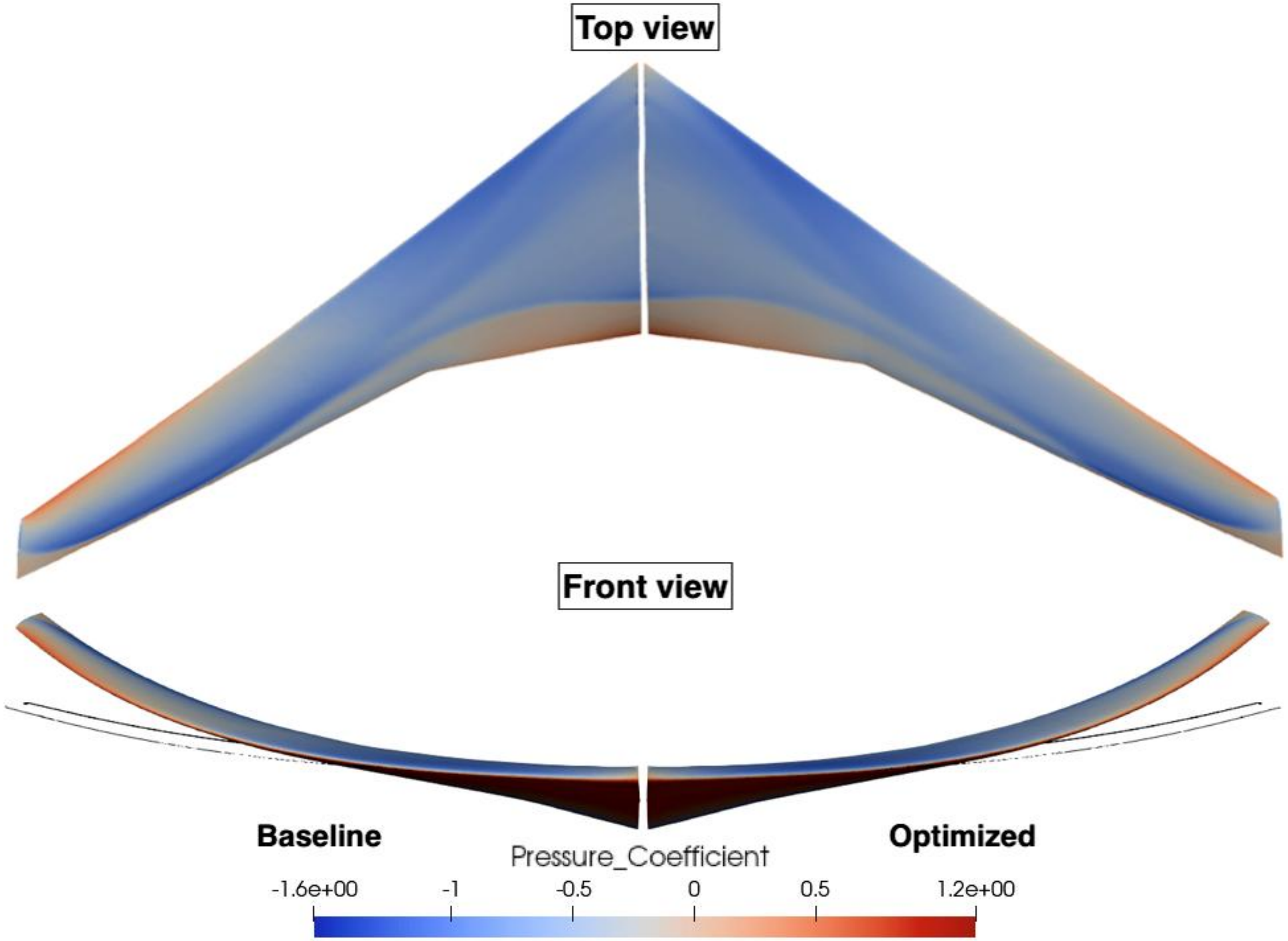
Acknowledgements

Website: https://indigo-sustainableaviation.eu/

LinkedIn: linkedin.com/company/ indigo-he-project/

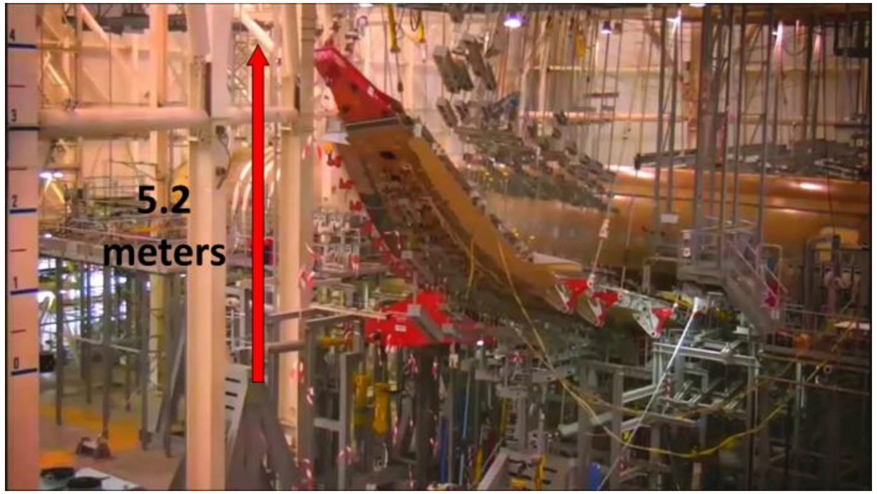
The activities described in this paper have been carried out under the project **INDIGO** (Integration and Digital Demonstration of Low-emission Aircraft Technologies and Airport Operations), coordinated by **Universidad Carlos III de Madrid**.

INDIGO project has received fundg from the European Climate, Infrastructure and Environment Executive Agency (CINEA) under the Horizon Europe programme under grant agreement No 101096055. in

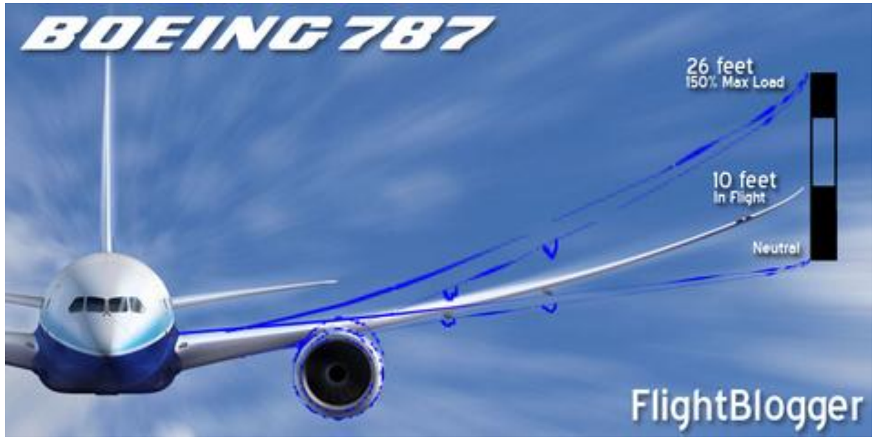

Top view
Front view
Baseline
Optimized
Pressure_Coefficient
-1.6e+00
-1
-0.5
0
0.5
1.2e+00

Highly-flexible wing case

- **New generation** of aircraft → more **efficient** design:
  - **Unconventional** configurations with large AR, and/or
  - **Lighter** and more **flexible** aircraft structures.
- Expected **significant** wing **deflections** while in operation: strong **aeroelastic** (aero-structural) **coupling**.
- Required adequate **analysis** approaches.
- High-fidelity earlier to reduce time-to-market and/or risks.
- Not only analysis but design and (coupled) **optimization**



A350 ultimate load wing deflection



Cruise and and ultimate load wing deflections of the B787

10% semi-span wing tip deflection in flight.

High-fidelity aerostructural optimization. How?

- Employ **high-fidelity** solvers into coupled **aerostructural optimization** processes:
  - **Larger cost** per evaluation of aeroelastic solutions.
  - **High-sensitivity** with respect to **small geometric features** → **higher number** of Design Variables (**DVs**) needed to exploit potential of high-fidelity optimization.
- Influence on the optimization approach:
  - Gradient-based optimization is an appealing choice
  - **Adjoint method** makes gradient calculation almost **independent** on the number of **DVs** (as opposed to other strategies)
- Highly **modular**: each discipline solver is self-contained and communicates at high level by means of an orchestrator.

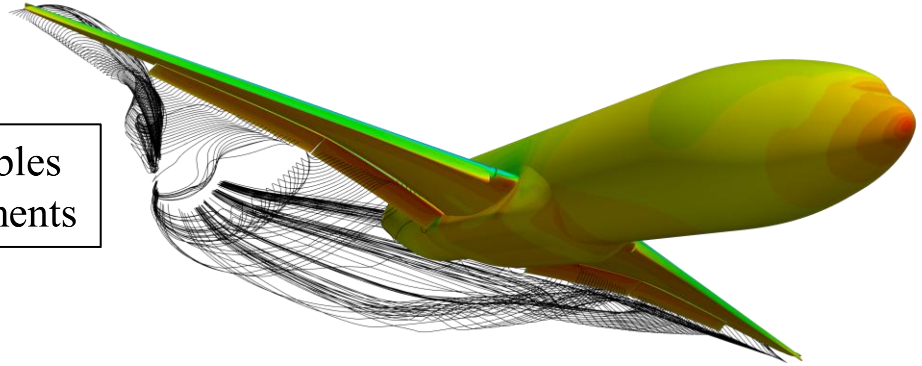
→ **Adjoint method**

CFD solver (SU2)

- Flow models: **Euler**, **RANS,** etc.
- **(Arbitrary Lagrange Euler) ALE** formulation.

$$\mathcal{F}(\mathbf{w},\mathbf{z}) = \frac{\partial \mathbf{w}}{\partial t} + \nabla \cdot \mathbf{F}^c(\mathbf{w},\mathbf{z}) - \nabla \cdot \mathbf{F}^v(\mathbf{w},\mathbf{z}) - \mathbf{Q}(\mathbf{w},\mathbf{z}) = \mathbf{0}$$

$\boldsymbol{w}$ → flow conservative variables
$\boldsymbol{z}$ → volume mesh displacements



Fluid mesh deformation solver (SU2)

- **Linear** (pseudo-)**elastic** volume deformation method.

$$\mathcal{M}(\mathbf{z},\mathbf{u_f}) = \mathbf{K_m} \cdot \mathbf{z} - \tilde{\mathbf{f}}(\mathbf{u_f}) = 0$$

$\boldsymbol{u_f}$ → displacements at the surface

Implementation

- C++ core.
- Top level functions wrapped in Python.
- Handling **AD** by means of **CoDiPack** library.
- Hybrid MPI-MP parallelization

- ADL, Stanford University
- P&P, TU Delft
- SciComp, TU Kaiserslautern
- CREA Lab, Politecnico di Milano
- Imperial College London MTFC Group,
- University of Liege
- van der Weide Group, U. of Twente
- New Concepts in Aeronautics Lab, ITA
- Strathclyde University
- Robert Bosch LLC
- ECN part of TNO
- Universidad Carlos III de Madrid (UC3M)

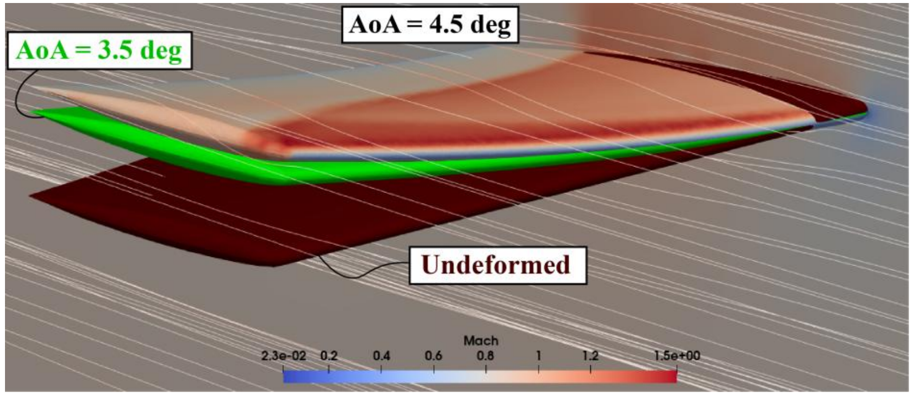
Solvers: Structures

In-house Structural FE solver (pyAUGUSTO)

- Shells (Plate & membranes), beams, nonlinear rigid elements
- Geometric **nonlinearities** (large displacements)

$$S(\boldsymbol{u_s}) = \boldsymbol{f_s} - \boldsymbol{f_{int}}(\boldsymbol{u_s}) = \boldsymbol{0}$$

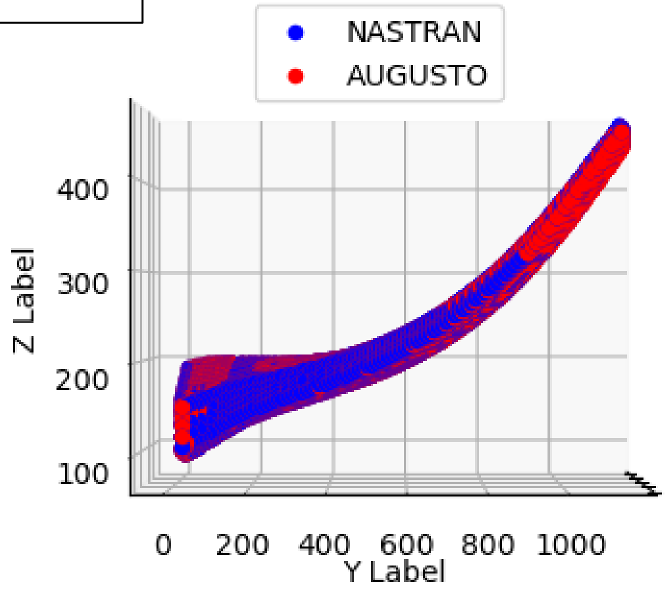
$\boldsymbol{u_s}$ → structural displacements variables
$\boldsymbol{f_s}$ → applied forces



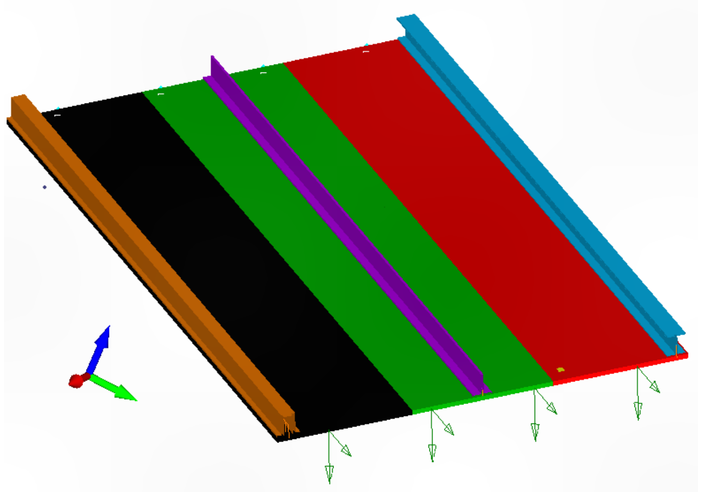
ONERA M6 test case at aeroelastic equilibrium with different AoAs.

Implementation

- C++ core.
- Top level functions wrapped in Python.
- Developed to handle **AD** by means of **CoDiPack** library.
- MPI parallelism



Very flexible NASA CRM deflection



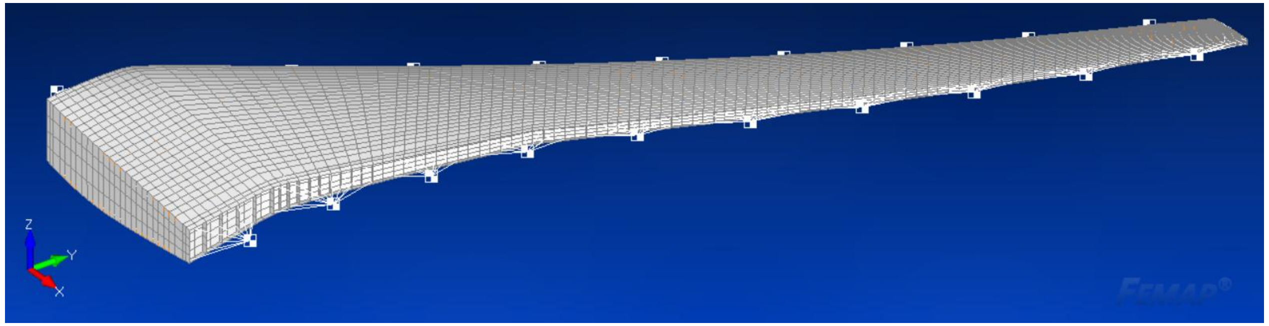
Stiffened panel

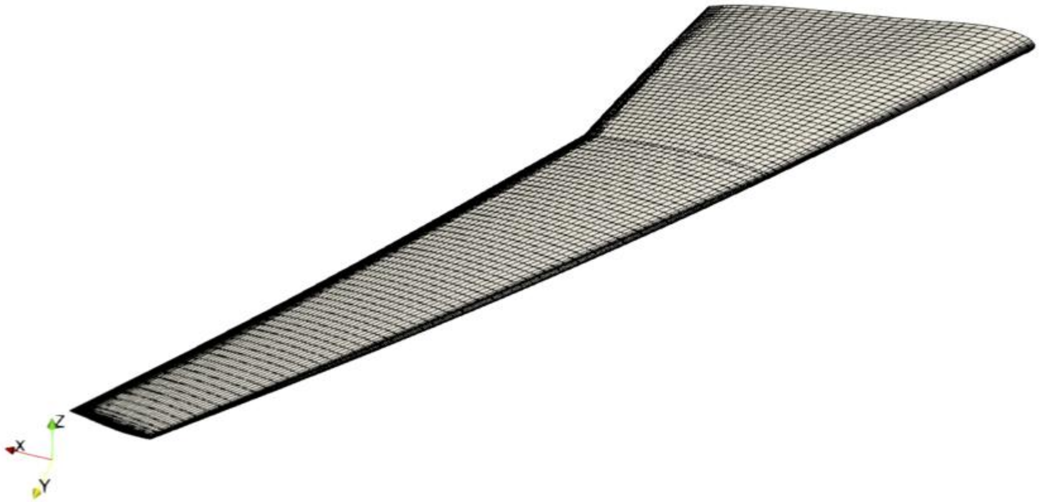
Solvers: Spline

Interfacing method (MLS)

- Transfer information between non-conformal grids*.
- Based on **Radial Basis Functions**.

$$\begin{cases} \boldsymbol{u_f} = \boldsymbol{H}_{MLS}\, \boldsymbol{u_s} \\ \boldsymbol{f_s} = \boldsymbol{H}^{T}_{MLS}\, \boldsymbol{f_f} \end{cases}$$





<u>Implementation</u>

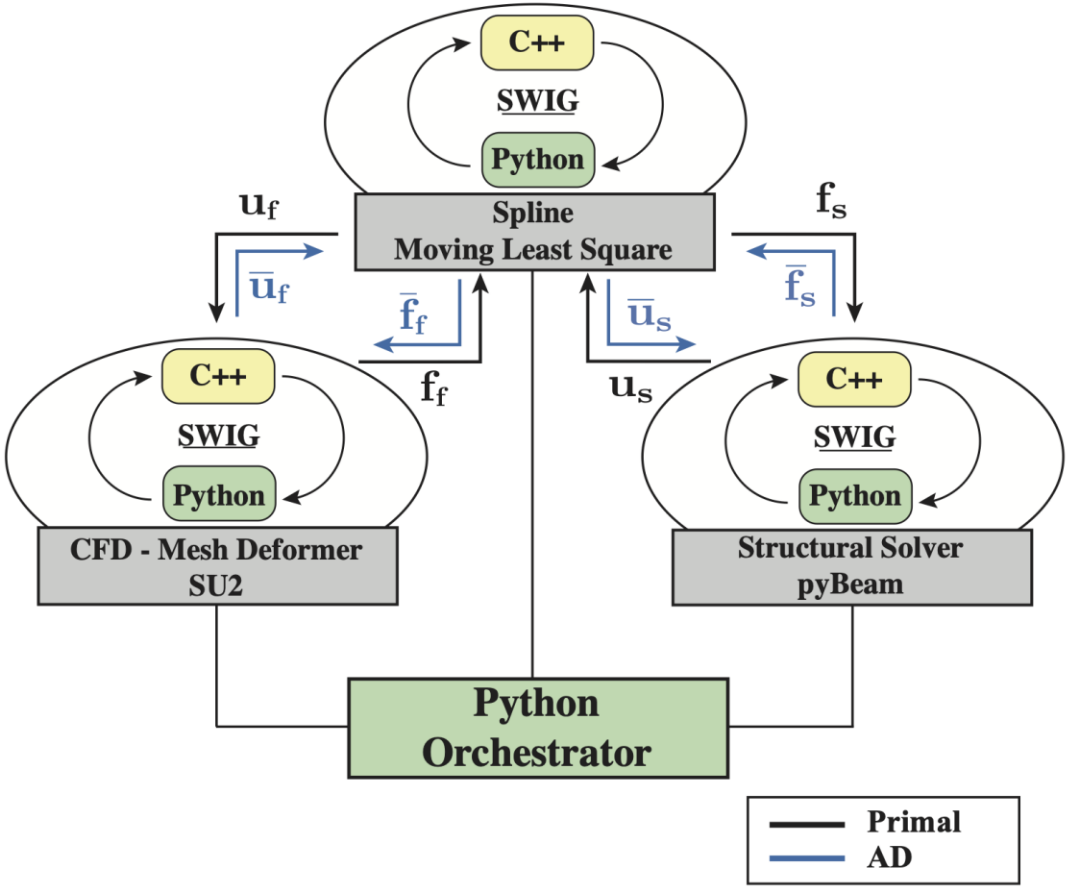
- **C++** core.
- Top level functions wrapped in **Python**.
- **Ad-hoc developed**.

*Quaranta G, et al (2005) A conservative mesh-free approach for fluid structure problems in coupled problems. In: International conference for coupled problems in science and engineering, Santorini, Greece. pp 24–27

Coupling method (Orchestrator)

- **3-field** formulation.
- **Block Gauss-Seidel** (BGS) iterative solution strategy.
- **Relaxation** of displacements to ensure convergence.
- Primal and dual.

$$\mathcal{G}(\mathbf{u_s}, \mathbf{w}, \mathbf{z}) = \begin{cases} \mathcal{S}(\mathbf{u_s}, \mathbf{w}, \mathbf{z}) = 0, \\ \mathcal{F}(\mathbf{w}, \mathbf{z}) = 0, \\ \mathcal{M}(\mathbf{u_s}, \mathbf{z}) = 0, \end{cases}$$



Implementation

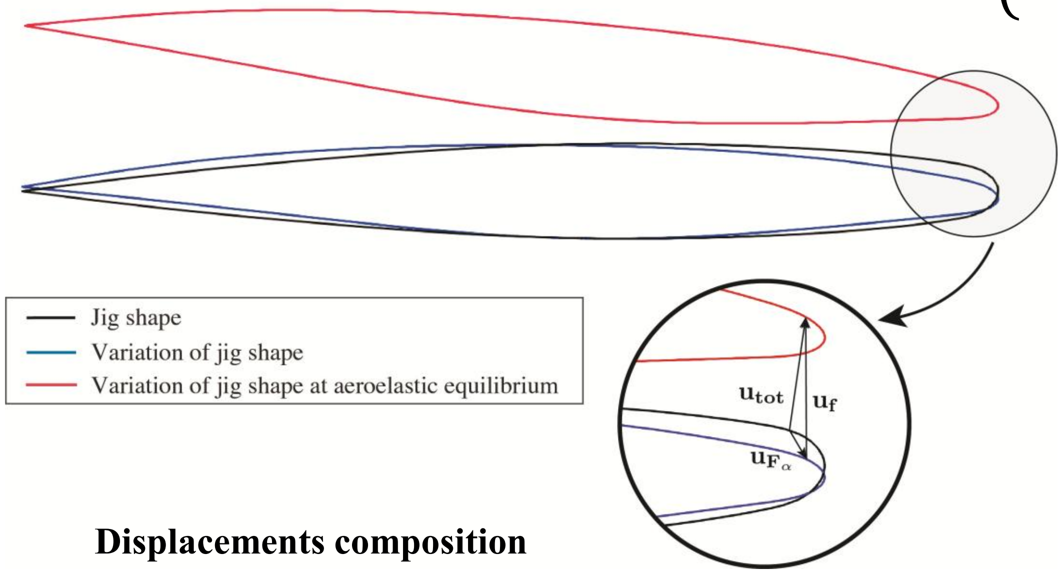
- **Python** coded.
- Wraps solvers (primal/dual problems).
- Interfaces with **optimizer**.
- **Ad-hoc developed**.

Aerostructural optimization problem

Application: wing-shape aerostructural optimization (2021)

- **Response (objective/constraints)**
  - **Fluid:** drag coefficient
- **DVs:**
  - **Geometric** (variation of wing jig shape)

$$
\begin{cases}
\min_{u_{F\alpha}} \quad J = C_D(w,z) \\
\text{subject to}
\begin{cases}
F(w,z) - w = 0 & \textbf{Fluid solver} \\
F_f(w,z) - f_f = 0 & \textbf{Force calculation (on the wing surface)} \\
M(u_{tot}) - z = 0 & \textbf{Mesh deform. solver} \\
H^T f_f - f_s = 0 & \textbf{Force transfer} \\
S(u_s, f_s) - u_s = 0 & \textbf{Struct. solver} \\
H\, u_s - u_f = 0 & \textbf{Struct. disp. transfer} \\
u_{tot} - u_f - u_{F_\alpha} = 0 & \textbf{Displacement composition}
\end{cases}
\end{cases}
$$



Displacements composition

	State variables
$\mathbf{u_s}$	Structural displacements
$\mathbf{w}$	Flow conservative variables
$\mathbf{z}$	Volume mesh displacements
$\mathbf{f_f}$	Fluid loads
$\mathbf{f_s}$	Structural loads
$\mathbf{u_f}$	Displacements of wing surface due to deflection
$\mathbf{u_{tot}}$	Cumulative displacements of wing surface

uc3m

Adjoint equations and objective gradient

$$\bar{w}^T = \frac{\partial J}{\partial w} + \bar{w}^T \frac{\partial F}{\partial w} + \bar{f_f}^T \frac{\partial F_f}{\partial w}$$

$$\frac{\partial J}{\partial f_f} - \bar{f_f}^T + \bar{f_s}^T H^T = 0$$

$$\frac{\partial J}{\partial z} + \bar{w}^T \frac{\partial F}{\partial z} + \bar{f_f}^T \frac{\partial F_f}{\partial z} + \bar{z}^T = 0$$

$$\frac{\partial J}{\partial f_s} - \bar{f_s}^T + \bar{u_s}^T \frac{\partial S}{\partial f_s} = 0$$

$$\bar{u}_s^T = \frac{\partial J}{\partial u_s} + \bar{u}_s^T \frac{\partial S}{\partial u_s} + \bar{u_f}^T H$$

$$\frac{\partial J}{\partial u_f} - \bar{u}_f^T - \bar{u}_{tot}^T = 0$$

$$\frac{\partial J}{\partial u_{tot}} + \bar{z}^T \frac{\partial M}{\partial u_{tot}} + \bar{u}_{tot}^T = 0$$

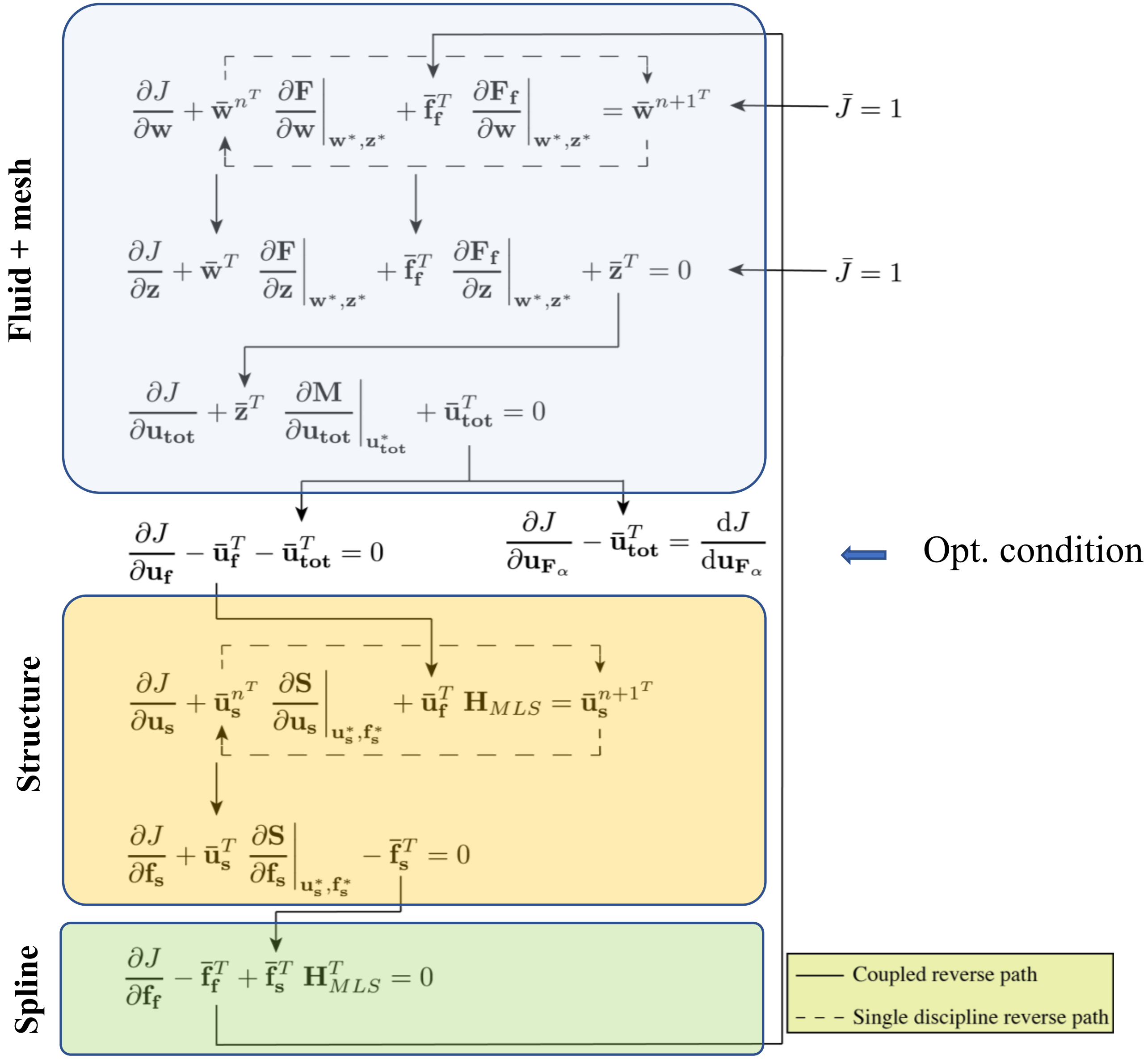
$$\boldsymbol{\frac{dJ}{du_{F_\alpha}} = \frac{\partial \mathcal{L}}{\partial u_{F_\alpha}} = \frac{\partial J}{\partial u_{F_\alpha}} - \bar{u}_{tot}^T}$$

How to solve this system of equations?

- Main blocks are
  - CFD and mesh solvers, coupled within **SU2**
  - CSD solver
  - Interface module
- A monolithic solution is not efficient (different physics are better treated by dedicated solvers), not convenient/viable (memory to store the computational graph)
- Ideally, different solvers treat a block of these equations.
- Coupling due to dependency of adjoint equation of one solver to adjoint variables calculated in other solvers

Aerostructural optimization problem

Adjoint and objective gradient



Iterative solution:

- At the **discipline solver level** (nonlinear primal solver in FP).
- At the **interdiscipline level** (source term exchanged through orchestrator).

	State variables
$\mathbf{u_s}$	Structural displacements
$\mathbf{w}$	Flow conservative variables
$\mathbf{z}$	Volume mesh displacements
$\mathbf{f_f}$	Fluid loads
$\mathbf{f_s}$	Structural loads
$\mathbf{u_f}$	Displacements of wing surface due to deflection
$\mathbf{u_{tot}}$	Cumulative displacements of wing surface

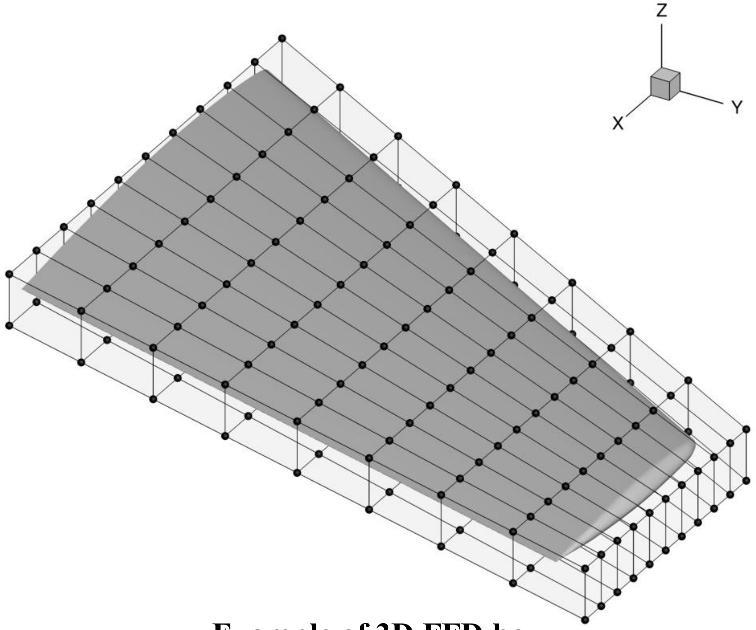
With minimum effort on the workflow it is possible to:

- Select **different responses (objective function/constraint)**
- Add different **DVs**.

Aerostructural optimization problem

Aerostructural wing shape optimization

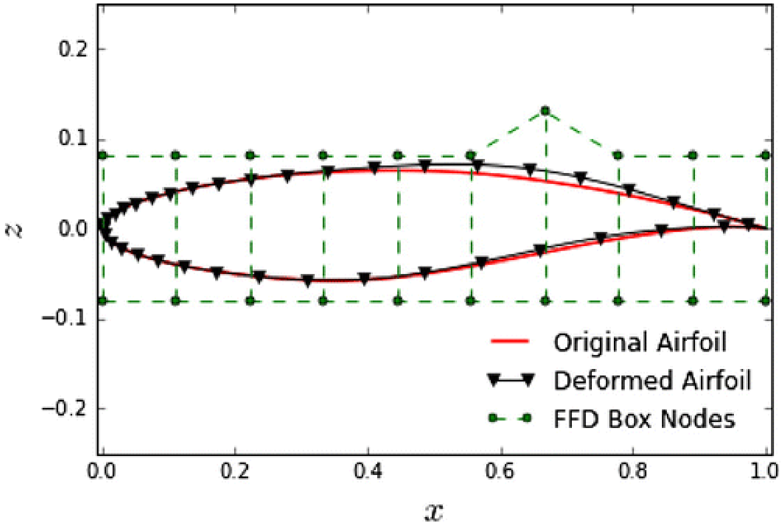
- Algorithm: Sequential Least Square Quadratic Programming **(SLSQP).**
- **Free Form Deformation** (FFD) technique.
- **FFD box** discretized with given number of **Control Points** (CP), which are the DVs given to optimizer.



Example of 3D FFD box

Constraints

- Geometric constraints (e.g., t/c) and their gradients evaluated by SU2 module **SU2_GEO**.
- Prescribed $\boldsymbol{C_L}$ accommodated internally by SU2 (not treated at optimization level).



2D FFD technique on airfoil*

uc3m

Importance of considering aerostructural coupling

Two optimization strategies:

- Aerodynamic Wing Shape Optimization (**AWSO**).
  - **Rigid** configuration.
  - **No aerostructural coupling** in primal/dual problems.
- **Aerostructural** Wing Shape Optimization (**ASWSO**).
  - Configuration at aeroelastic equilibrium: **flying shape**.
  - **Aerostructural coupling** in primal/dual problem.
  - **Intermediate approach:** aerostructural coupling in the primal problem only

AWSO optimum is, compared, **at aeroelastic equilibrium,** to the **ASWSO optimum**.

Asymptotic flow conditions

- $C_L = 0.5;\ M_\infty$=0.85.

Application: NASA CRM

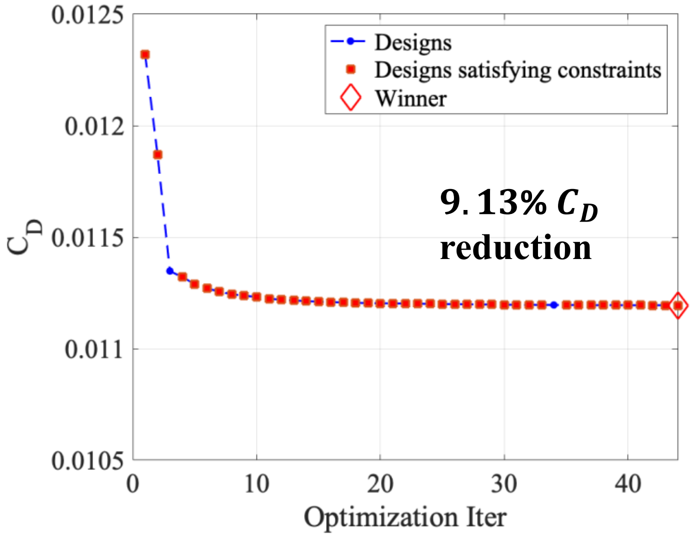
uc3m

Optimization of the CRM

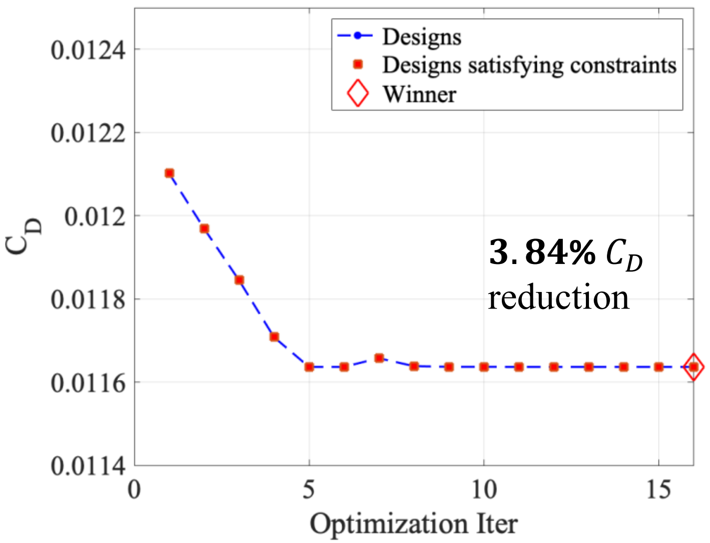
Aerodynamic constraints		
C_L	$=$	0.5
Geometric constraints		
t/c (sec. at 0.34% span)	$\geq$	15.6%
t/c (sec. at 16.32% span)	$\geq$	12.5%
t/c (sec. at 27.01% span)	$\geq$	11.2%
t/c (sec. at 38.49% span)	$\geq$	10.4%
t/c (sec. at 49.76% span)	$\geq$	10.0%
t/c (sec. at 60.74% span)	$\geq$	9.8%
t/c (sec. at 71.89% span)	$\geq$	9.6%
t/c (sec. at 83.07% span)	$\geq$	9.5%
t/c (sec. at 94.14% span)	$\geq$	9.5%
Number of DVs	$=$	418

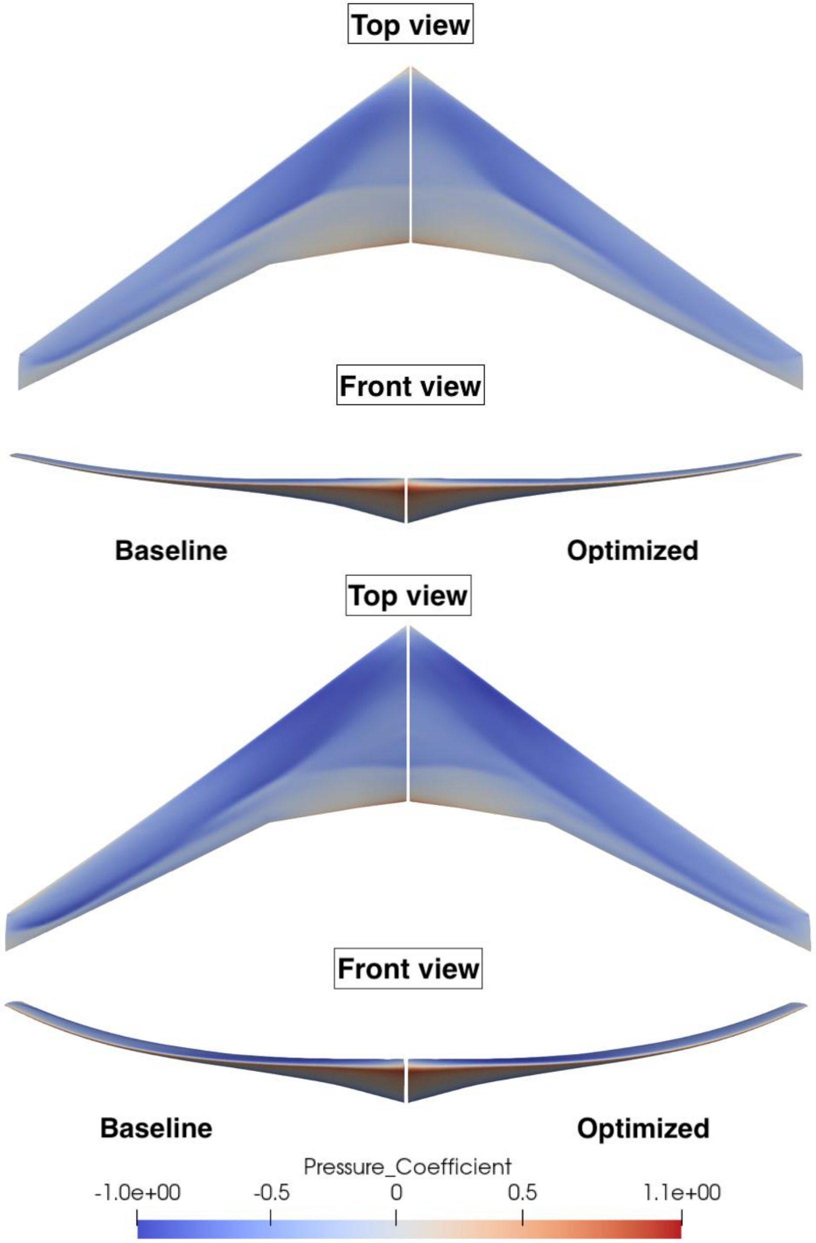
Optimization results

AWSO (Rigid wing)



ASWSO (aerostructural)





AWSO and ASWSO comparison

Configuration	C_D	Diff. %
ASWSO optimum	0.01163	–
AWSO optimum	0.01243	6.87%
Original	0.01210	4.04%

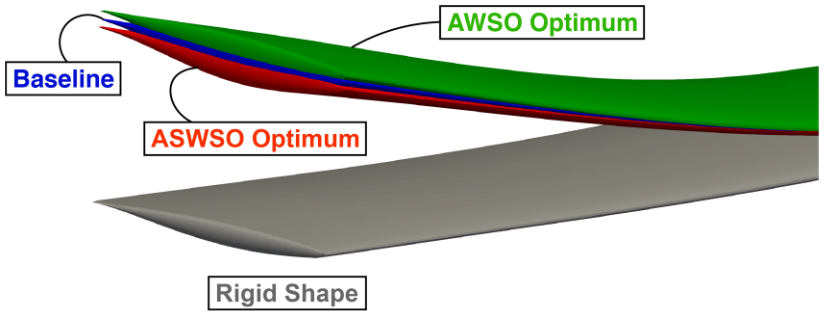
C_D comparison at aeroelastic equilibrium

AWSO optimum performs **worse** than the ASWSO.

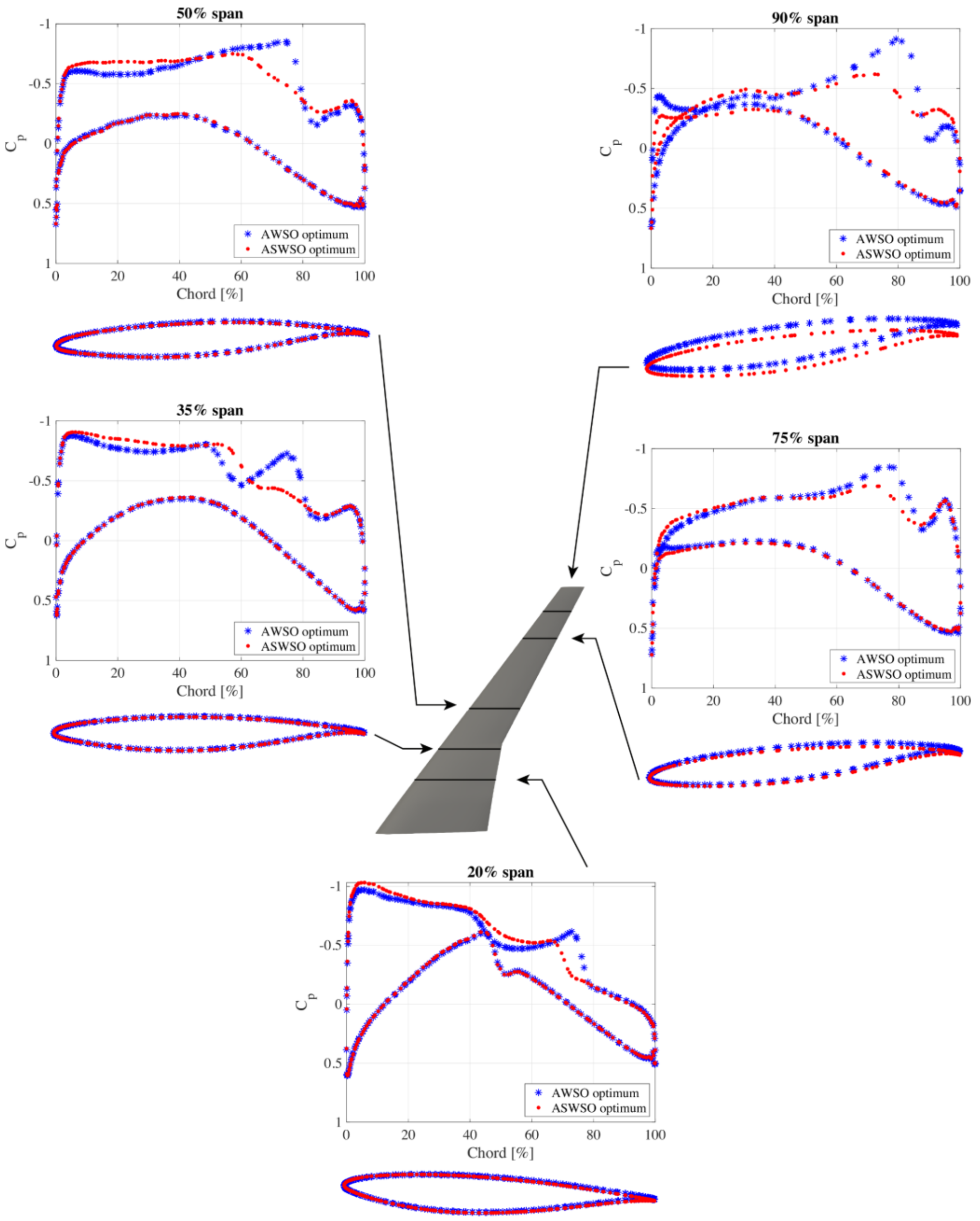
- Optimized for an **off-design** point.

AWSO optimum performs **worse** than the baseline.

For highly flexible wings AWSO doesn't necessarily payback.



Flying shapes comparison



AWSO and ASWSO flying shapes C_p distribution comparison

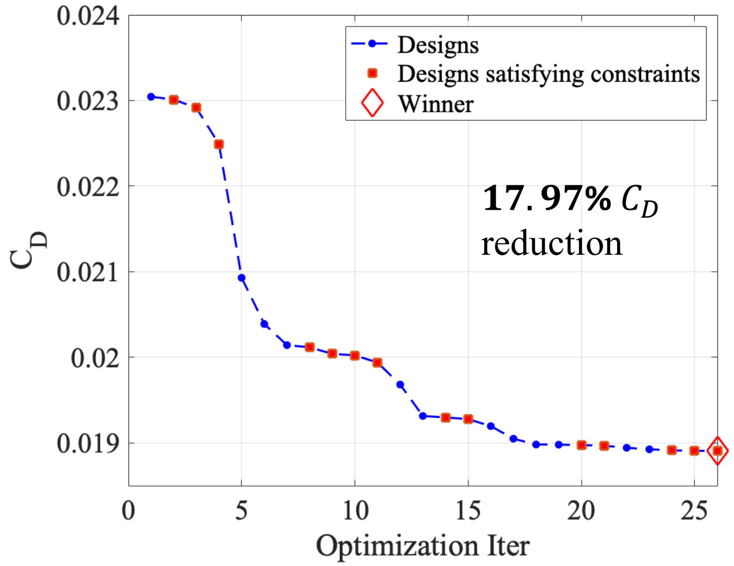
uc3m

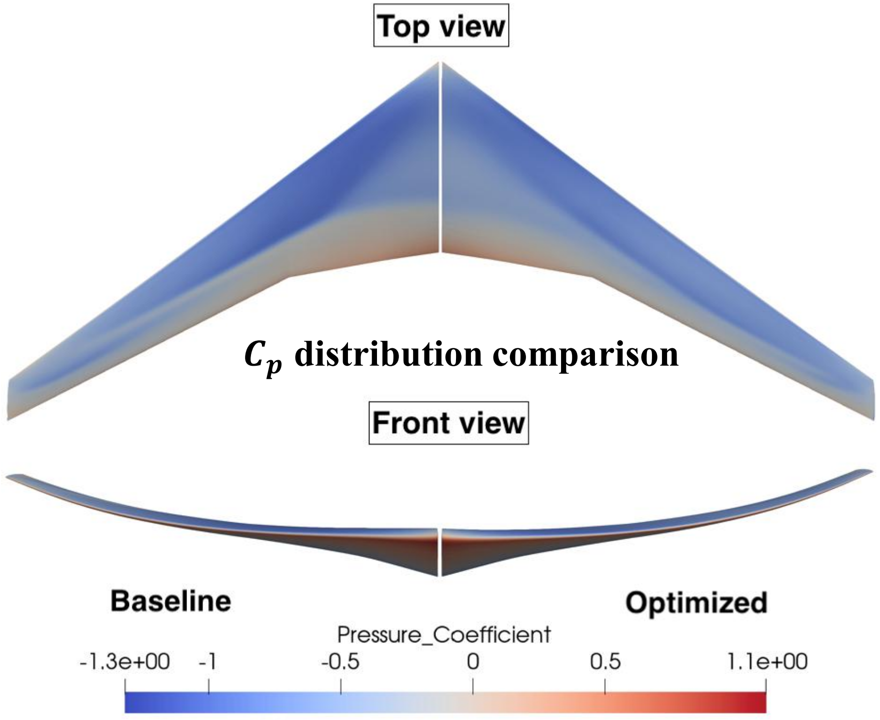
Optimization of the CRM (RANS-SA)

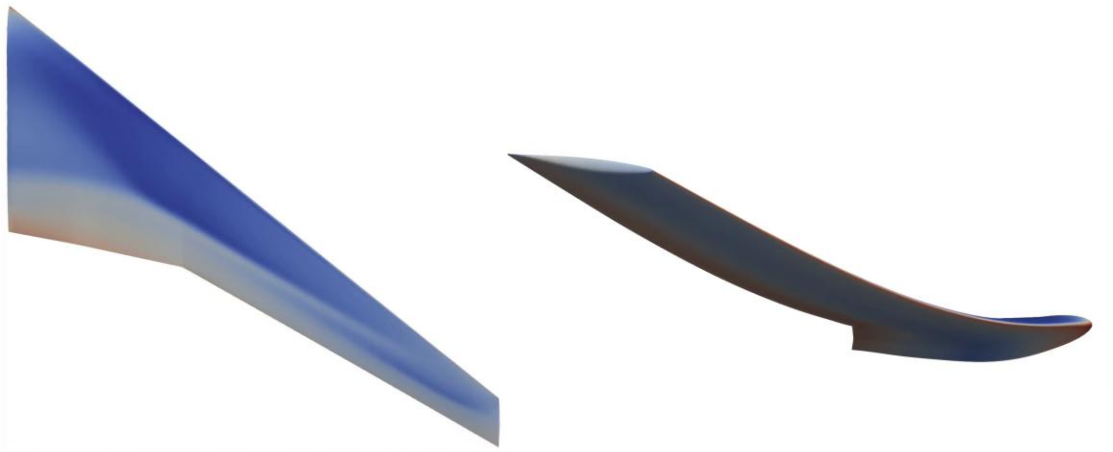
ASWSO (aerostructural)

- **Ideal gas** model.
- **Laminar** viscosity with **Sutherland**'s law.
- **Turbulent** viscosity with **SA** one equation.
- **Full-turbulence** (non-frozen turbulence) adjoint.
- Same aerodynamic and geometric constraints.

Optimization results







Application: Very flexible NASA CRM

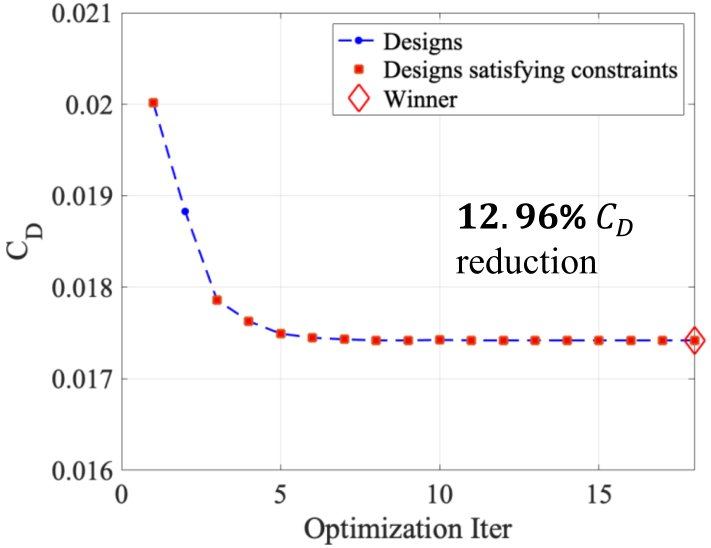
Optimization of the very-flexible CRM (Euler)

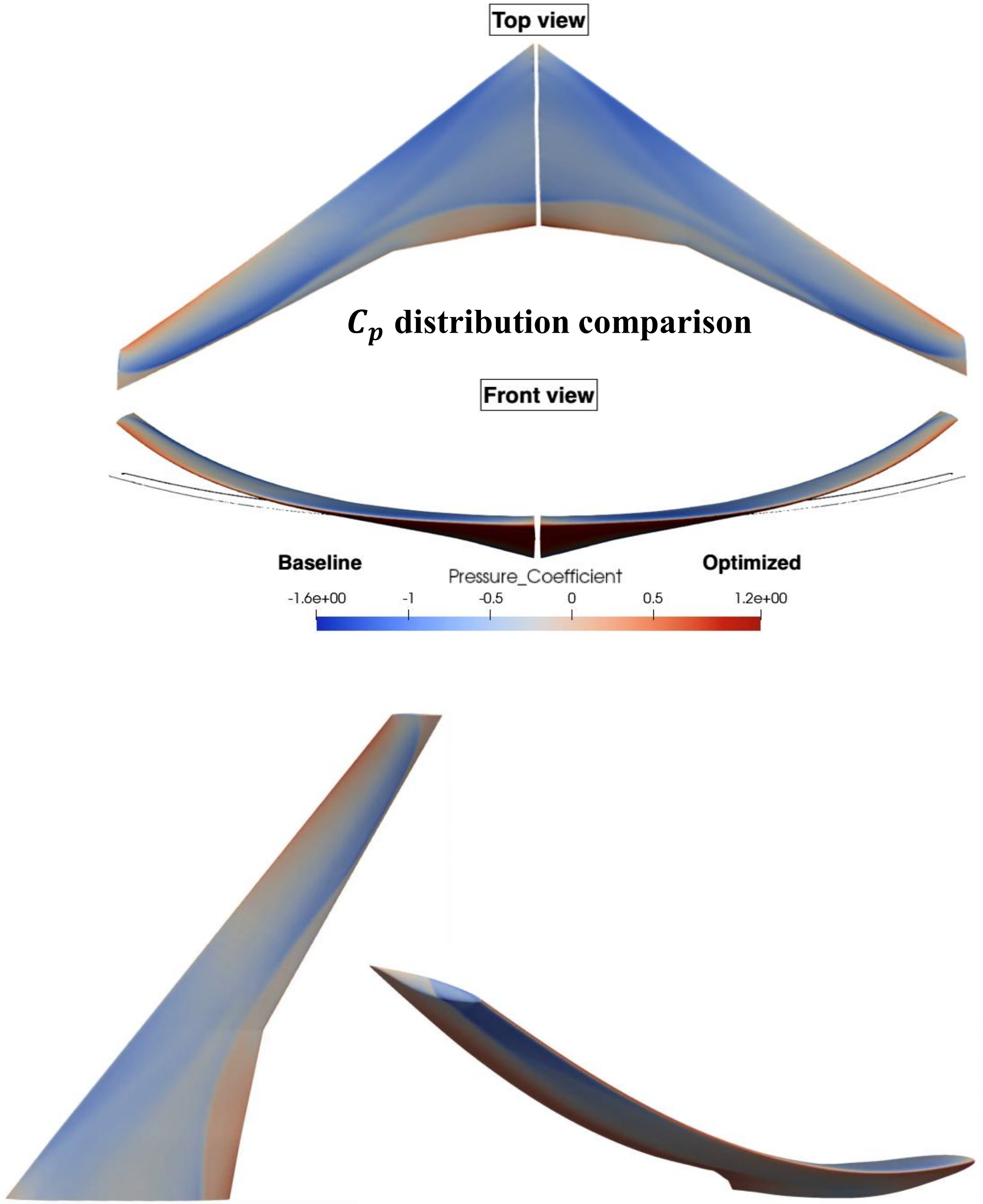
ASWSO (aerostructural)

Aerodynamic constraints		
C_L	$=$	0.5
Geometric constraints		
t/c (sec. at 0.34% span)	$\geq$	15.6%
t/c (sec. at 16.32% span)	$\geq$	12.5%
t/c (sec. at 27.01% span)	$\geq$	11.2%
t/c (sec. at 38.49% span)	$\geq$	10.4%
t/c (sec. at 49.76% span)	$\geq$	10.0%
t/c (sec. at 60.74% span)	$\geq$	9.8%
t/c (sec. at 71.89% span)	$\geq$	9.6%
t/c (sec. at 83.07% span)	$\geq$	9.5%
t/c (sec. at 94.14% span)	$\geq$	9.5%
Number of DVs	$=$	418

Wing stiffness tuned to have ~**14%** of semi-span wing tip deflection at aeroel. equilibrium.

Optimization results



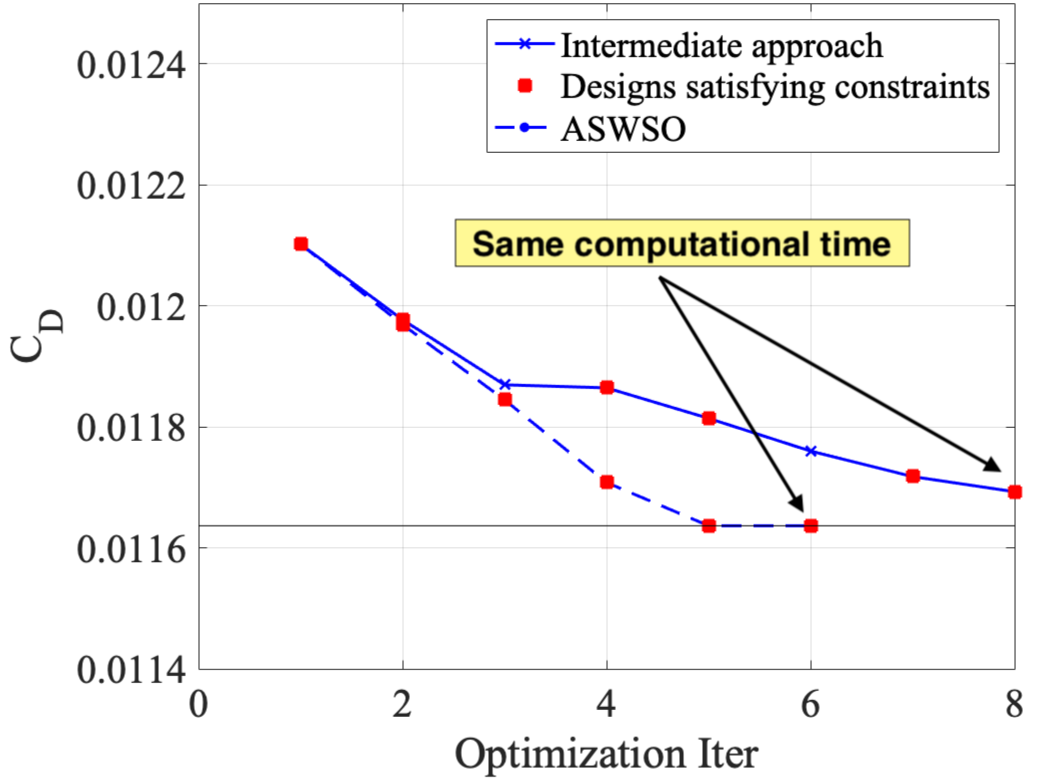


Coupled gradients vs uncoupled gradients

ASWSO (aerostructural)

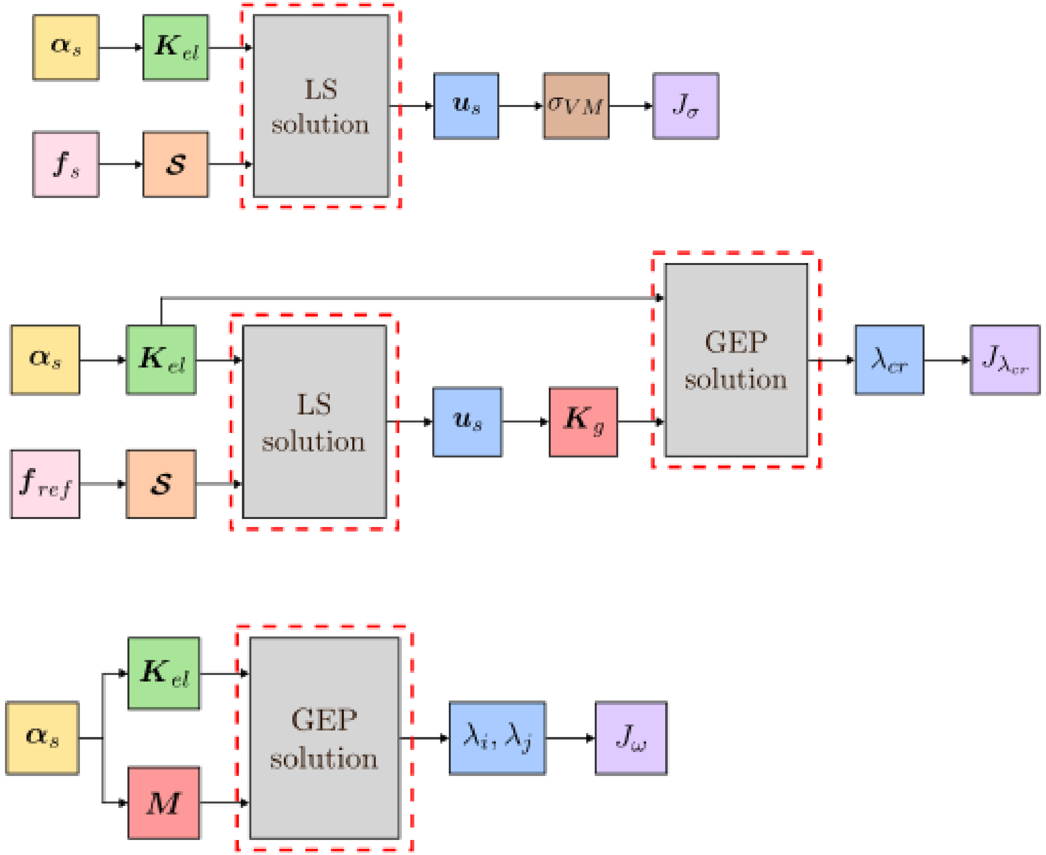
- **Fully-coupled** approach (coupled primal and adjoint problem)
  - Discrete-exact gradients
  - More complex; gradient evaluation more costly
- Intermediate approach: gradients **without aerostructural coupling**
  - Inexact gradients
  - Simpler; cheaper gradient evaluation

- For a given **computational budget**, **fully-coupled** approach is providing a better result
- For more flexible wing, the approximated gradient can be too imprecise, and determine failure of the optimization problem.



Current work

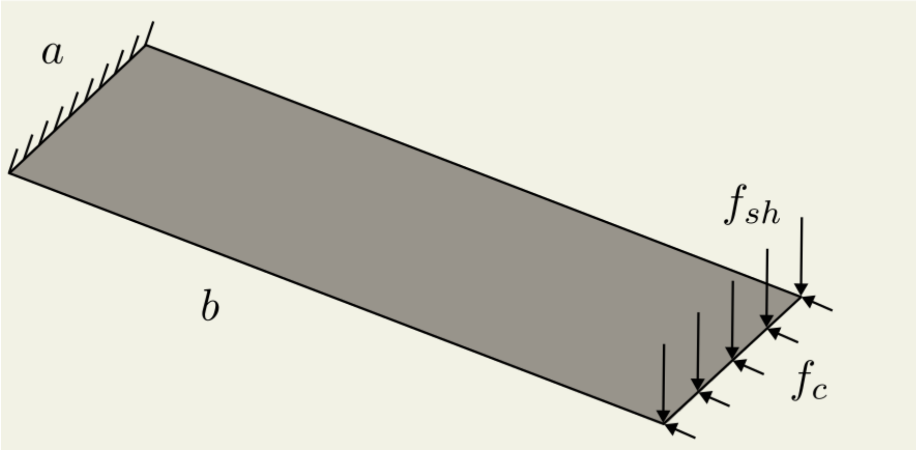
- **Improvement of FE solver.**
- **AD-based adjoints**
  - **Stresses**
  - **Buckling**
  - **Free Vibration modes (step towards flutter)**

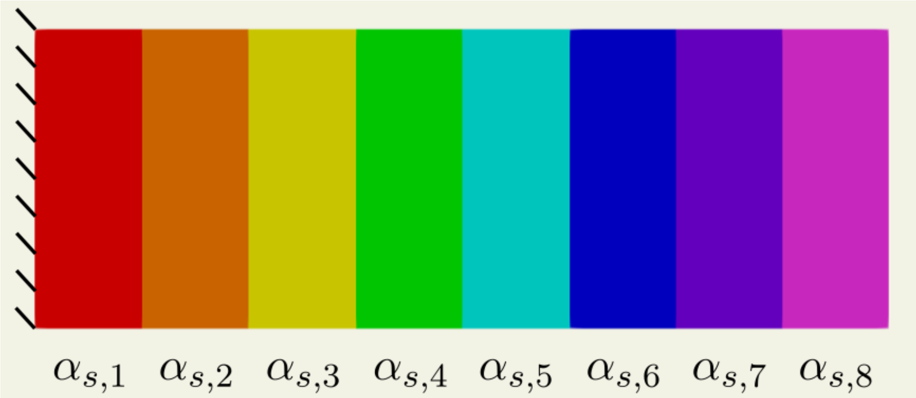


Governing equations	$c_i \leq 0$
$\mathcal{S} = K_{el}u_s - f_s = 0$	$J_\sigma = KS(g_i) = \frac{1}{\rho_{KS}}\log\sum_{i=1}^{n} e^{\rho_{KS}\cdot g_i} \leq 0$ $(where\ \ g_i = \frac{\sigma_i^{VM}}{\sigma_{ADM}} - 1)$
$(K_{el} - \omega_k^2 M)\phi_k = 0$	$J_\omega = \rho_\omega \frac{(\omega_j - \omega_i)_{init}}{\omega_j - \omega_i} - 1 \leq 0$
$(K_{el} + \lambda_k^{cr} K_g)\phi_k^{cr} = 0$	$J_{\lambda_{cr}} = \rho_{\lambda_{cr}} \frac{(\lambda_1^{cr})_{init}}{\lambda_1^{cr}} - 1 \leq 0$

	Primal problem	Adjoint statement
Linear system	$K_{el}u_s = f_s$	$K_{el}^T s = \frac{\partial J}{\partial u_s}$ $\bar{K}_{el} \mathrel{+}= -s \cdot u_s$ $\bar{\mathcal{S}} \mathrel{+}= s$
Generalised eigenvalue problem	$A\phi_k = \lambda_k B\phi_k$	$\bar{A} \mathrel{+}= \phi_k\phi_k^T$ $\bar{B} \mathrel{+}= -\lambda_k \bar{A}$

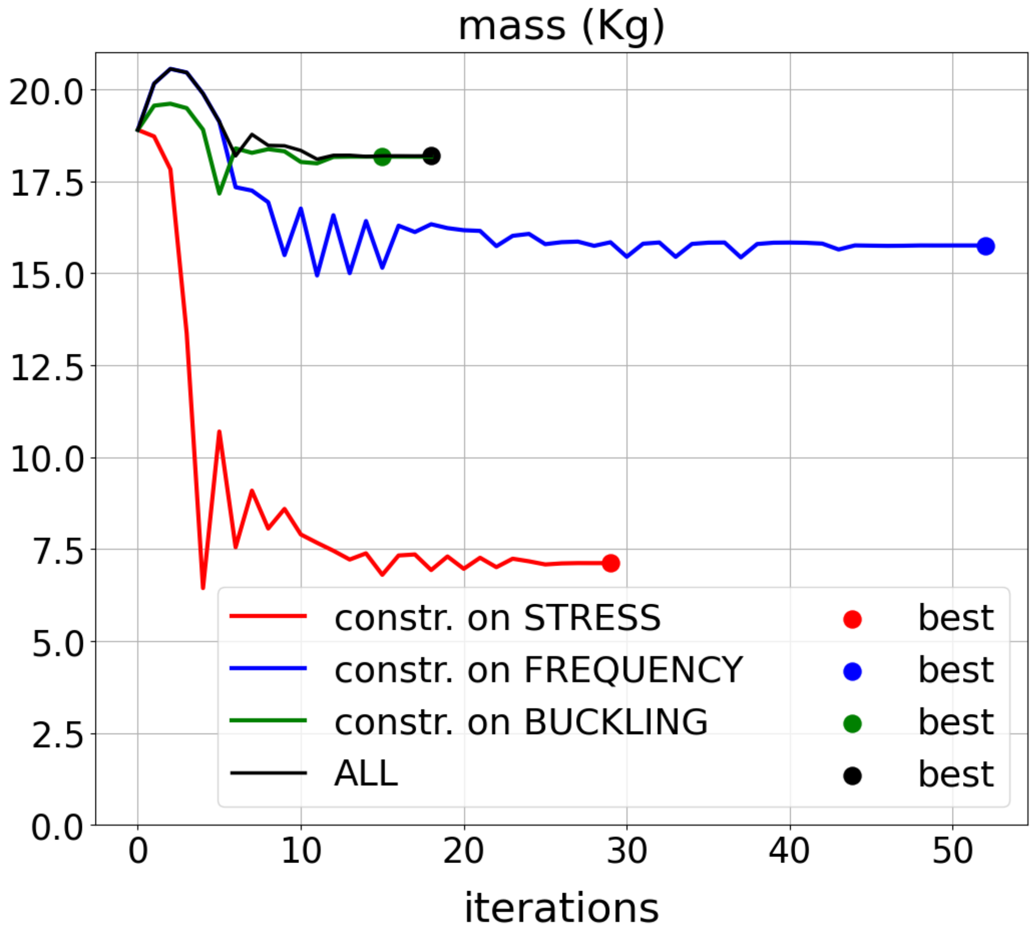
Structural optimisation – testcase 1



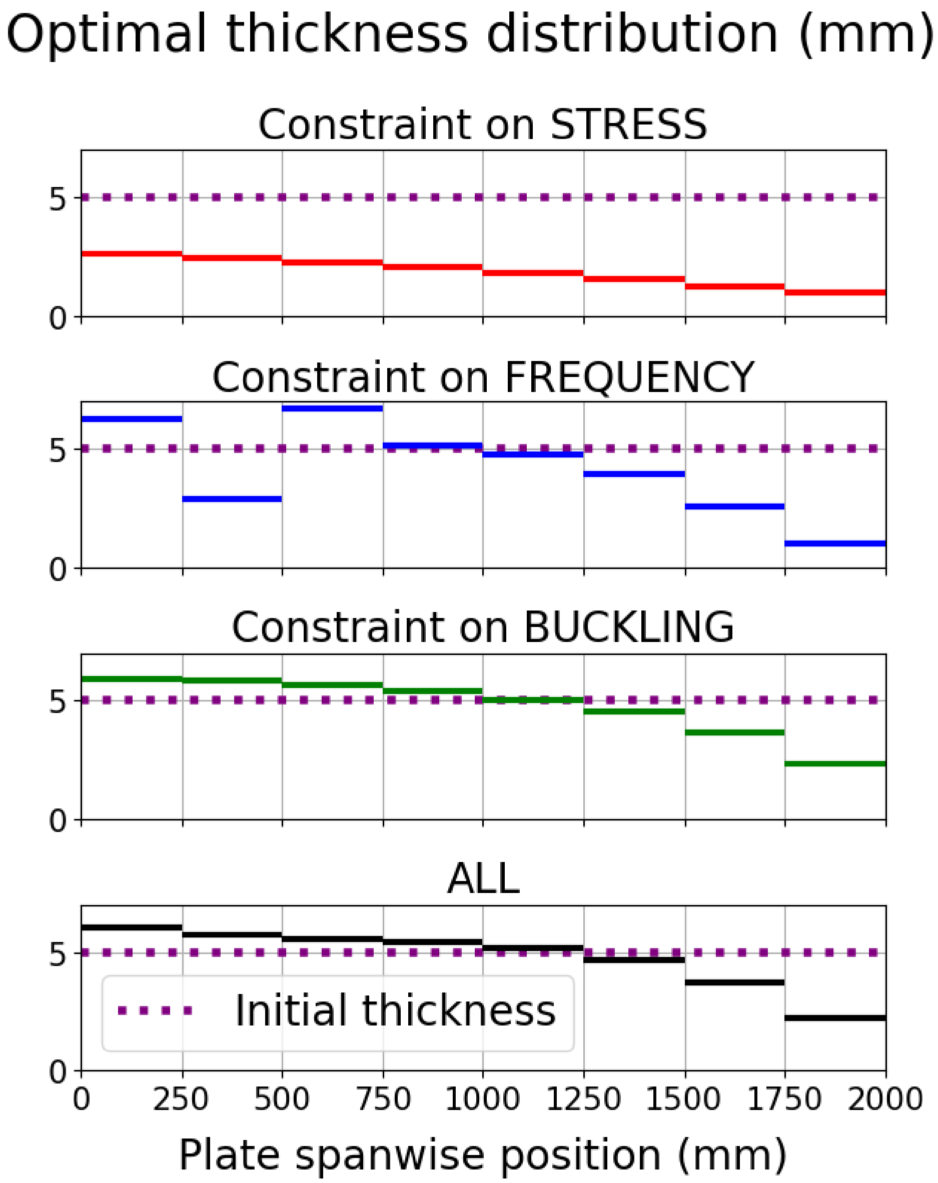


- **8 DVs:** $\alpha_{s,0} = 5.0 \text{ mm}; \quad 1.0 \text{ mm} \leq \alpha_{s,i} \leq 10.0 \text{ mm}$
- **4 optimisation runs** for **4 constraint sets:**
  1. **Stress:** σ_{VM} aggregated on all elements; $\sigma_{ADM} = 270\ MPa$
  2. **Frequency:** $(\omega_2 - \omega_1) \geq 1.2 * (\omega_2 - \omega_1)_{init}$
  3. **Buckling:** $\lambda_1^{cr} \geq 1.2 * (\lambda_1^{cr})_{init}$
  4. **All:** stress + frequency + buckling together

Structural optimisation - testcase 1 - results

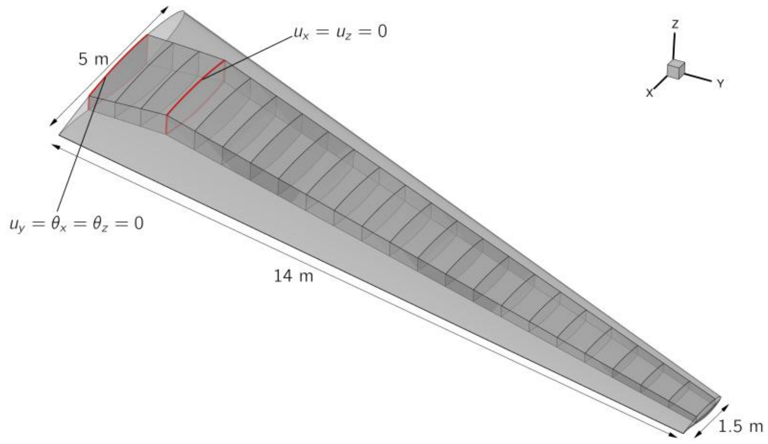


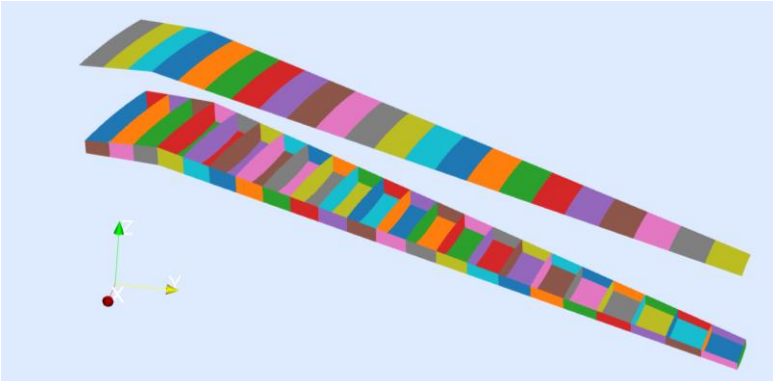
Constraint	Stress	Frequency	Buckling	all
M (Kg)	7.12	15.76	18.17	18.19
Δm (%)	-62.33	-16.61	-3.86	-3.76



Structural optimisation - testcase 2

High-Fidelity Aeroelastic Optimisation Benchmark





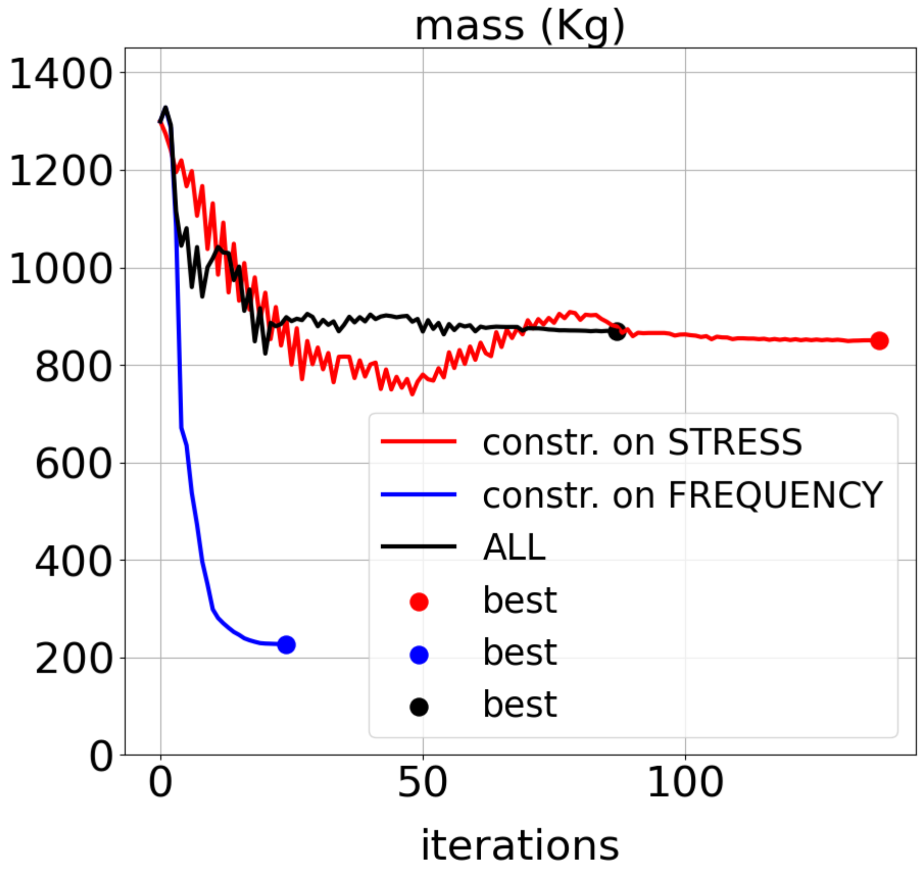
Gray A. C., Martins J.R.. A proposed Benchmark Model for Practical Aeroelastic Optimization of Aircraft Wings, AIAA SciTech 2024 Forum, https://doi.org/10.2514/6.2024-2775.

- rib nodes loaded along the z direction; root & fus. intersection constr.
- **111 DVs** : $\alpha_{s,ini} = 7.0 \text{ mm}; \;\; 1.0 \text{ mm} \leq \alpha_{s,i} \leq 20.0 \text{ mm}$
- **3 optimisation runs** for **3 constraint sets:**

1. Stress constraint set: 5 aggregation areas		
RIBS		
FRONT SPAR		
REAR SPAR	σ_{ADM} = 320 Mpa	Imposed simultaneously (5 constraints)
TOP SKIN		
BOTTOM SKIN		
2. Frequency constraint		
$(\omega_2 - \omega_1) \geq \rho_\omega(\omega_2 - \omega_1)_{ini}$	ρ_ω= 1	Imposed simultaneously (3 constraints)
$(\omega_3 - \omega_2) \geq \rho_\omega(\omega_3 - \omega_2)_{ini}$	ρ_ω= 1	
$\omega_1 \geq \rho_\omega(\omega_1)_{ini}$	ρ_ω= 1.15	
3. Mixed (“All”) constraint set: stress + frequency constraint sets together (8 in total)		

Structural optimisation - testcase 2 - results

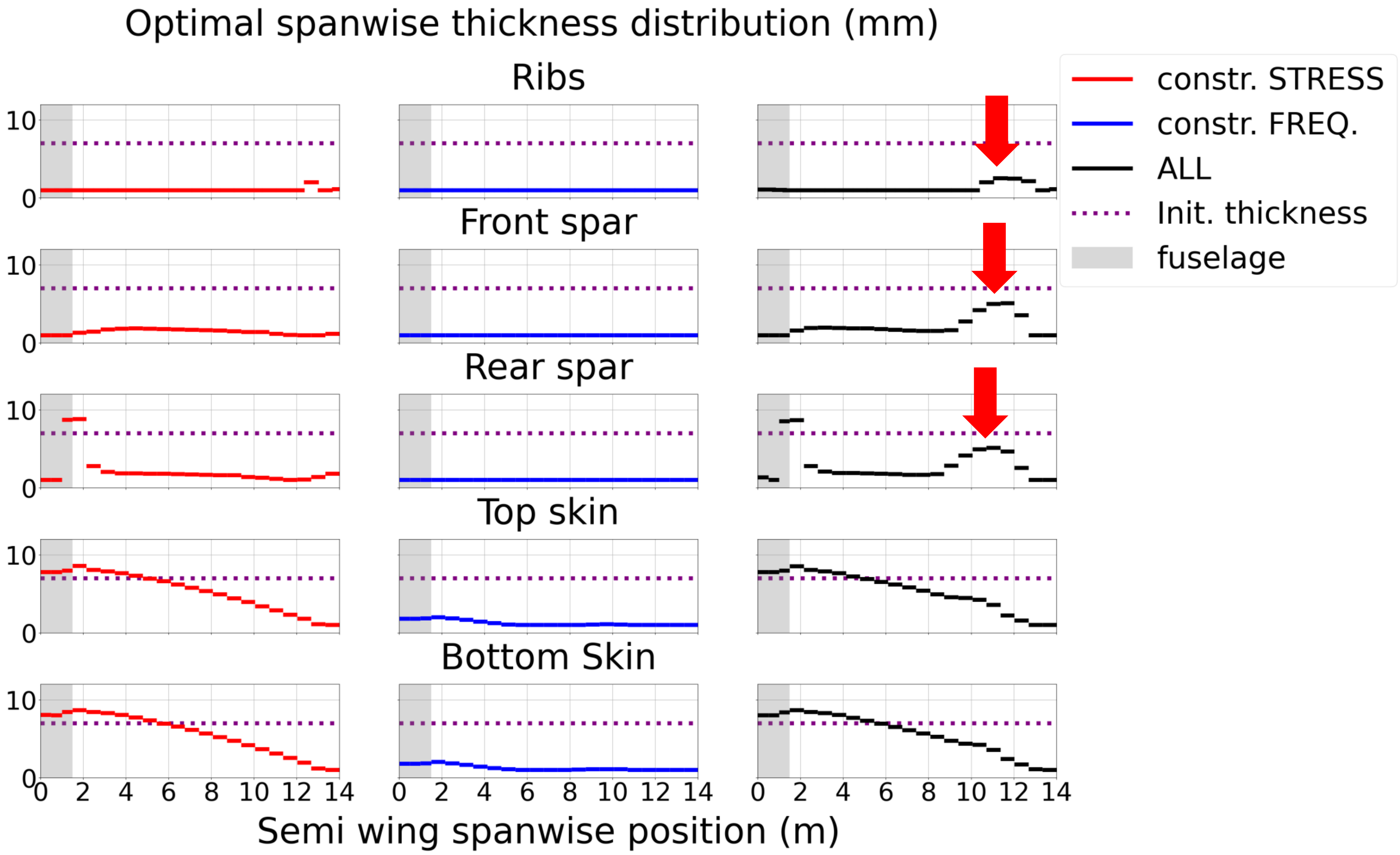
uc3m



Constraint	Stress	Frequency	all
M (Kg)	850.17	227.58	869.91
Δm (%)	-34.58	-82.49	-33.06

Active constraints			
	Constr. on STRESS	Constr. on FREQUENCY	ALL
J_σ^{RIBS}			
J_σ^{FSPAR}			
J_σ^{RSPAR}			
J_σ^{TSKIN}			
J_σ^{BSKIN}			
$J_\omega^{(\omega_1)}$			
$J_\omega^{(\omega_2-\omega_1)}$			
$J_\omega^{(\omega_3-\omega_2)}$			

Structural optimisation - testcase 2 - results



17 July 2025
University of Kaiserslautern-Landau

Multidisciplinary Design Optimization for Next-Generation Sustainable Aircraft

Rauno Cavallaro, PhD

Associate Professor,
Department of Aerospace Engineering,
Universidad Carlos III de Madrid

Scientific Computing
University of Kaiserslautern-Landau