Multidisciplinary design and optimization of hybrid-electric high-aspect ratio strut braced wings

PhD Student: João Carvalho

PhD Aerospace Engineering UC3M
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2nd and 3rd June 2026

Motivation

Aircraft climate impact

Policy and sustainability targets

Expand design space

Opportunity

Improvements in terms of efficiency, noise, emissions and environmental impact.

High Aspect Ratio
maximizing aerodynamic efficiency

Distributed Hybrid Electric Propulsion
sustainable propulsion technologies

Strut Braced Wing
enabling higher aspect ratio and lower structural weight

Weight module and structures

$$TOW = OEW + W_{Payload} + W_{Fuel} + W_{battery}$$

Primary structure

Physics - Based GFEM sizing of wing, strut, and central fuselage section

Secondary structure, tails, landing gear, nacelles, furnishings, and systems

Handbook, legacy semi-empirical methods

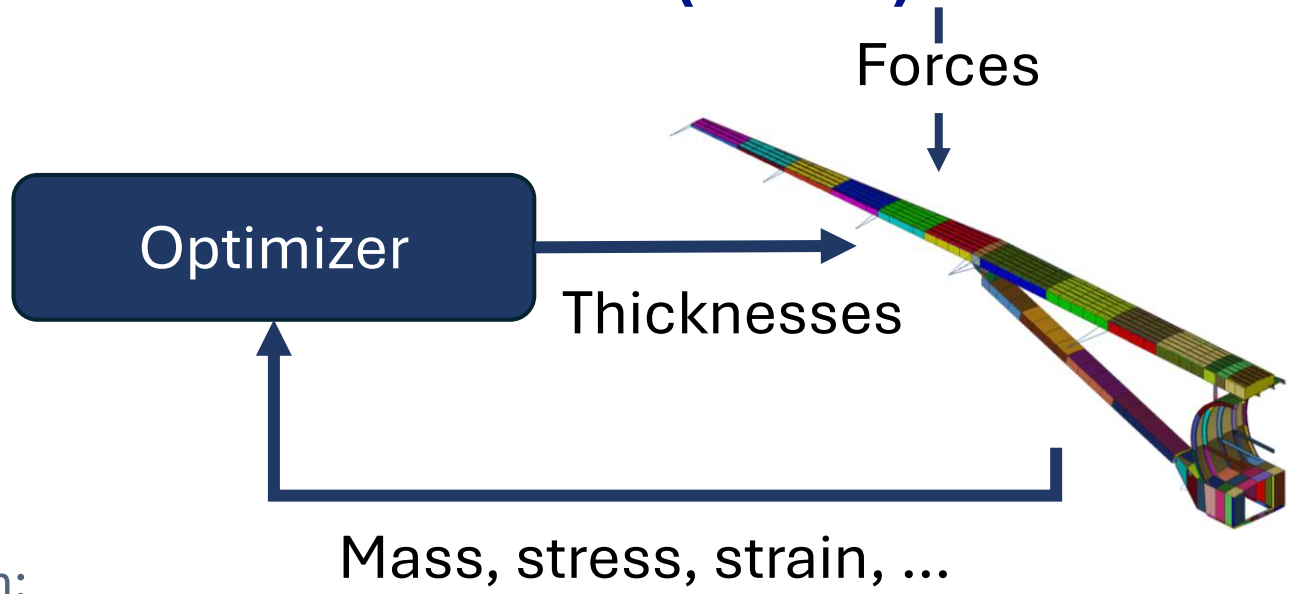
Powerplant & electric masses

Specific power assumptions + Indigo partner surrogate + battery sizing

Primary Structure - Global Finite Element Model (GFEM)

Minimize: Mass

By varying: Thicknesses



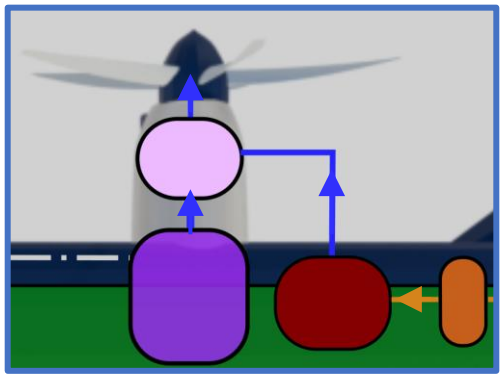
Subject to:

- **Minimum thicknesses**
  - **Composite Sizing Constraints:**
    - Discrete ply thickness;
    - Total Stack Thickness ≤75 mm;
    - Ply share constraints.
- **Strength Constraints:**
  - **Composite**: Maximum allowable strain of 3500 μm in tension and compression @ -1.5g, 3.75g;
  - **Metal:** 70% of the Von Mises Stress for metals: 289.56 MPa @ -1g, 2.5g ;
- **Buckling Constraints:**
  - Buckling factor greater than 1.5 @ -1g, 2.5g ;

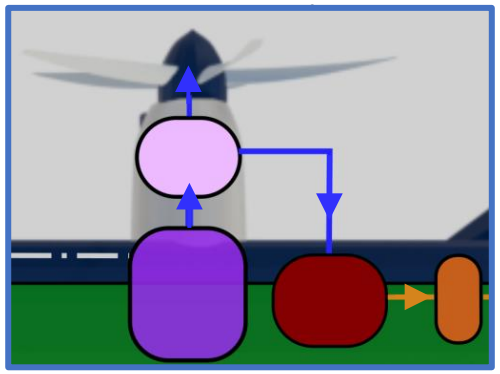
Powerplant

Local hybridization factor: $HF_{local} = \frac{P_{out\ gearbox}}{P_{IB\ propeller}}$

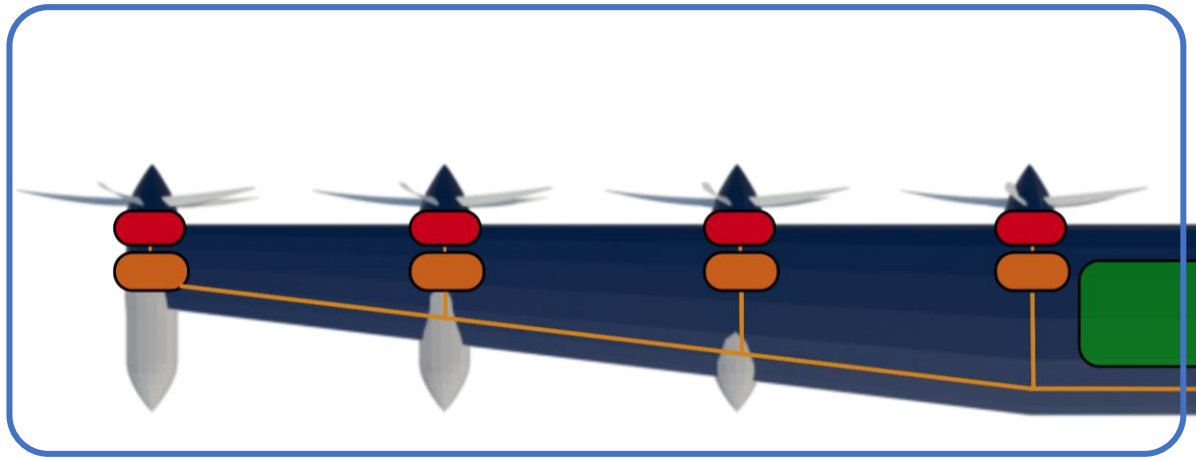
Thrust Split: $\psi = \frac{T_{OB\ total}}{T_{total}}$



$HF_{local} > 0$ - motor

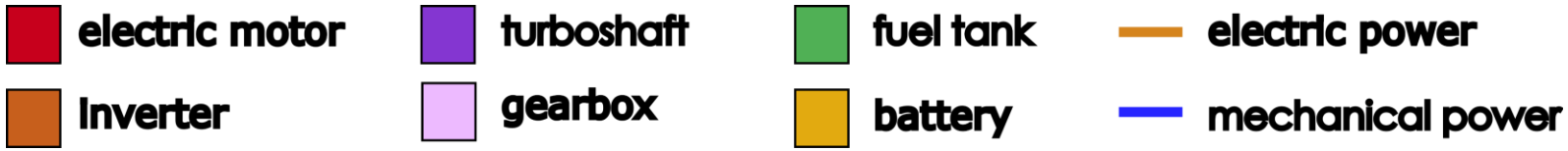


$HF_{local} < 0$ - generator operation



Outboard (OB)

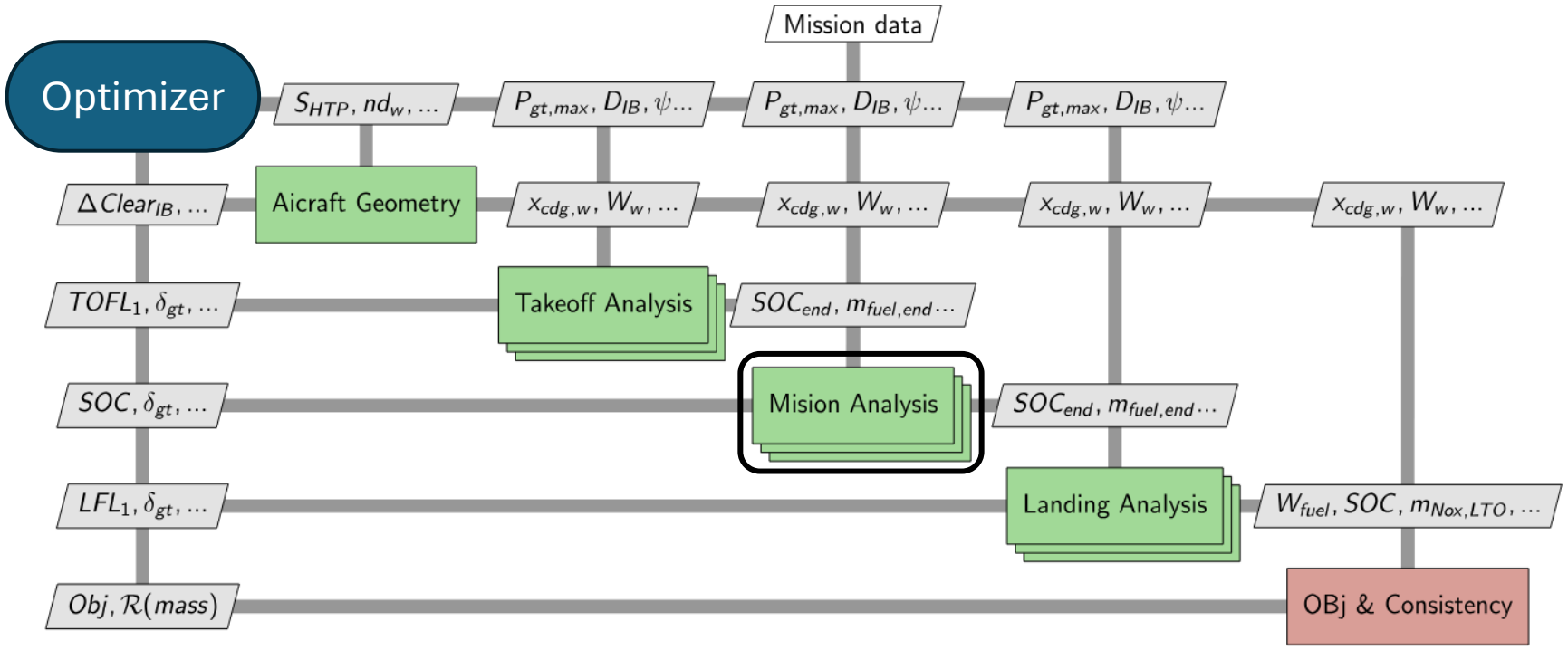
Inboard (IB)



MDAO

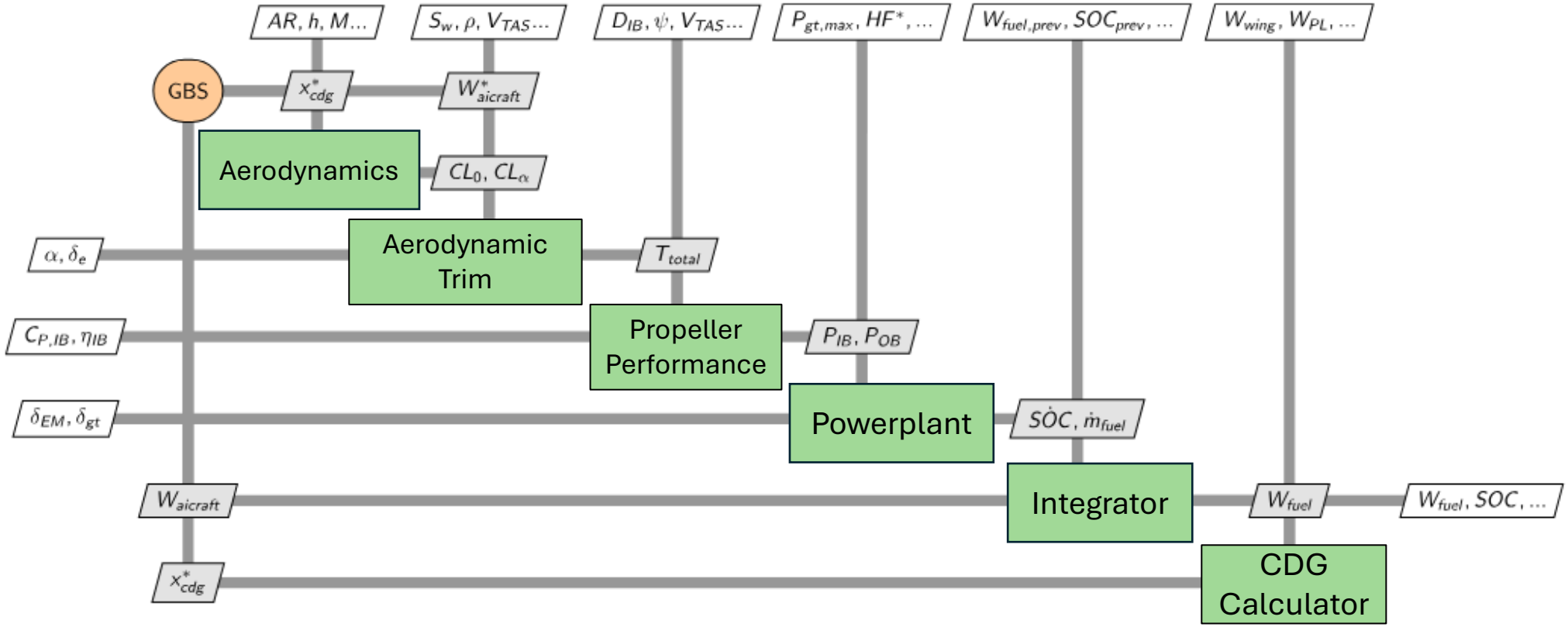
TOPAZ - A Tool for Optimizing Powerplants and Aircraft with Zero-Emissions:

- Open-source implementation based on GEMSEO;
- Supports gradient-based optimization;
- Enables coupled multidisciplinary analysis;
- Uses automatic differentiation through JAX in selected disciplines.



XDSM of the main optimization problem.

MDA - For each steady state flight phase



XDSM of the main optimization problem.

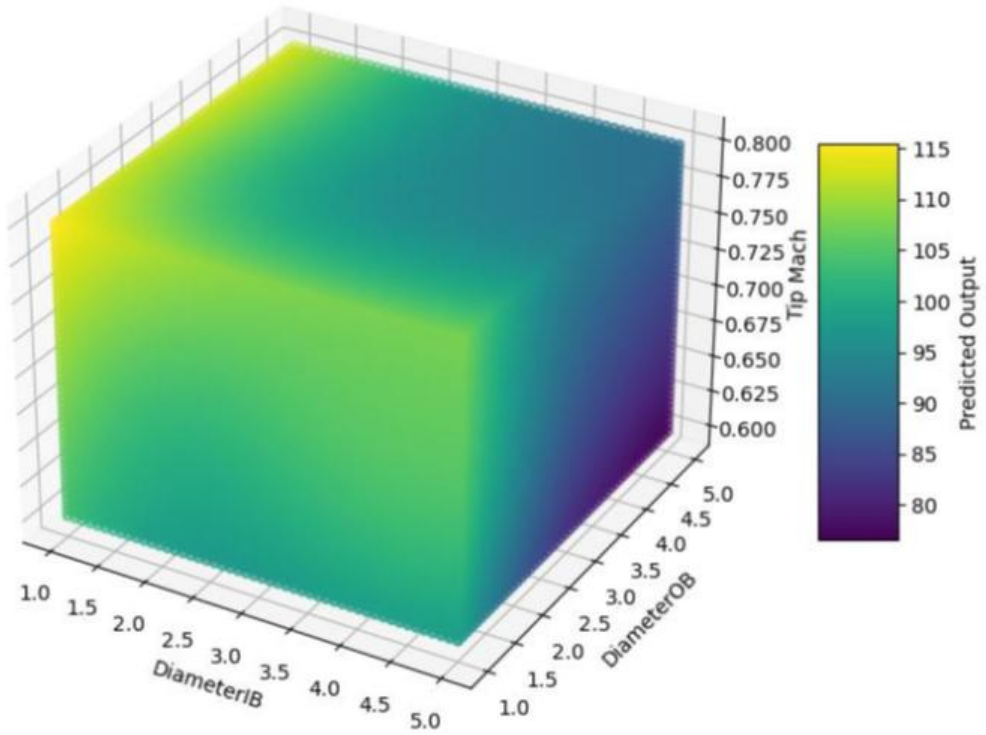
Noise evaluation

1. Use IMMIS+ to build a database of single-propeller noise.
2. Train a surrogate using diameter, power and rotational speed.
3. Evaluate each propeller separately, then combine in decibels.

$$EPNL_{tot} = 10 \log_{10}(\Sigma\, 10^{EPNL_i/10})$$

Then correct for simulated altitude using free-field spreading:

$$EPNL_2 = EPNL_1 - 20 \log_{10}(h_2/h_1)$$



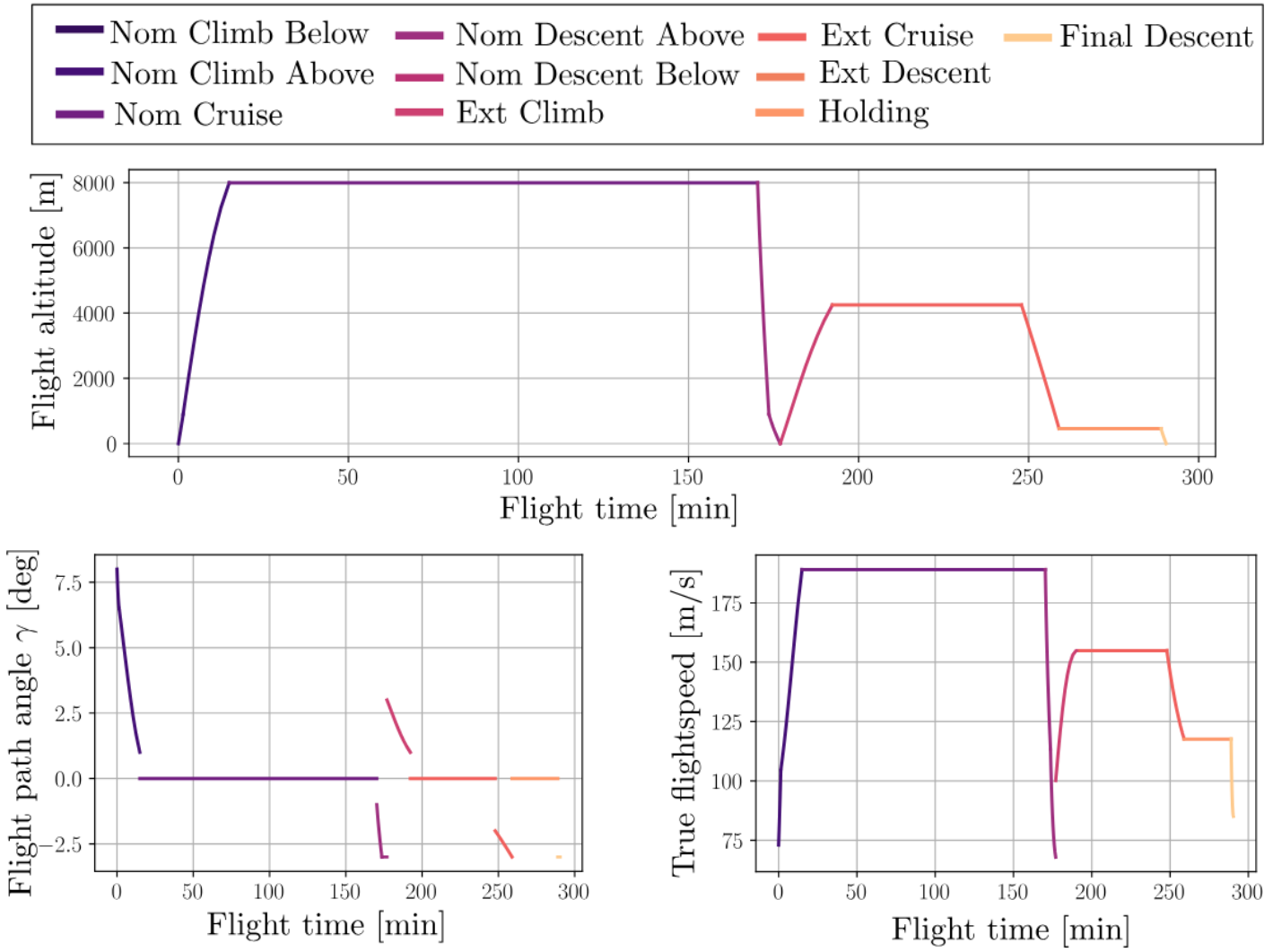
Example surrogate response surface: predicted acoustic output across design and operating variables.

Case Study: Block Fuel / noise tradeoff.

$$\begin{cases} \underset{x}{\text{minimize}} & BF \\ \text{subject to} & c(x) \leq 0 \\ & EPNL = \bar{N} \end{cases}$$

with BF meaning nominal mission fuel and EPNL meaning effective perceived noise level.

- 1000 nm nominal mission + 400nm diversion mission;
- cruise conditions:
  - h_{cr} = 8000 m;
  - M_{cr} = 0.6;
- MTOW =79 tons and payload = 20 tons.



Optimization Design Space

Group	Variable	Units	Meaning	LB	UB
Powerplant	$P_{TS,TOC}$	MW	turboshaft rating TOC	0.06	–
	$P_{gearbox}$	MW	gearbox rating	0.5	–
	$P_{IB,max}$	MW	IB peak design power	0.0	–
	$P_{OB,max}$	MW	OB peak design power	0.0	–
	W_{bat}	tons	battery weight	0.7	20.0
	$\delta_{EPS,TO}$	–	EPS throttle at takeoff	0.1	0.9
Each flight phase	HF^*	–	hybridization factor	−10.0	0.9
	ψ	–	split factor	0.1	0.9

Note: TOC = top of climb; IB = inboard; OB = outboard; EPS = electric propulsion system.

Optimization Design Space

Group	Variable	Units	Meaning	LB	UB
Propellers	$k_{RPM,LA}$	–	low-altitude multiplier	0.85	1.0
	d_{IB}	m	diameter IB	1.0	5.0
	d_{OB}	m	diameter OB	1.0	4.0
	C_{TIB}	–	IB design thrust coefficient	0.2	0.5
	C_{TOB}	–	OB design thrust coefficient	0.2	0.5
	M^*_{tipIB}	–	sea-level tangential tip Mach	0.3	0.5
	M^*_{tipOB}	–	sea-level tangential tip Mach	0.3	0.5
Failure case	$\delta_{EPS,FC}$	–	EPS throttle	0.1	0.9
	$\delta_{TS,FC}$	–	turboshaft throttle	0.1	0.9
	HF^*_{FC}	–	hybridization factor	−10.0	0.9

Note: TOC = top of climb; IB = inboard; OB = outboard; EPS = electric propulsion system.

Optimization Constraints

Variable	Meaning	LB	UB
$\mathcal{R}_{TOW}\,[kg]$	TOW consistency	-	0.0
TOFL [m]	TO Field Length	-	2000.0
LFL[m]	Landing Field length	-	1500.0
$\mathcal{R}_{\mathcal{M}_z}\,[N \cdot m]$	Yawing-moment trim in FC2	-	0.0
SM	Static-margin constraint	0.2	-
$\mathcal{R}_{cl}\,[-]$	Propeller-propeller clearance	-	0.0
δ	Tthrottles (all powertrain components)	0.0	0.9/1.0
SOC_{bat}	Battery SoC	0.2	1.0

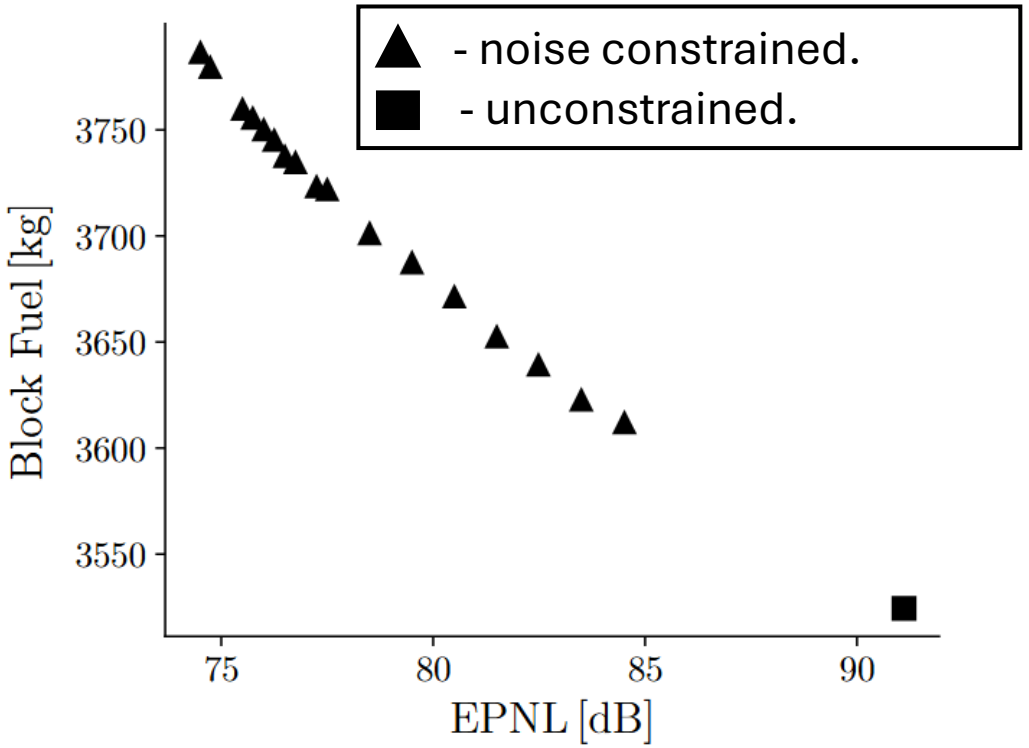
Propeller-to-propeller clearance enforces a minimum separation equal to 10% of the propeller diameter

$$\mathcal{R}_{cl} = 0.1\,\max(D_i, D_j) - \mathrm{dist}(\mathrm{Prop}_i, \mathrm{Prop}_j) \leq 0$$

Blue variables have a limit of 90% during nominal operation and 100% in failure scenarios.

Note: SoC = State of Charge; Sm = Static Margin.

Results



Pareto front between nominal mission block fuel and flyover noise EPNL in dB.

Quieter may be feasible, but not free…

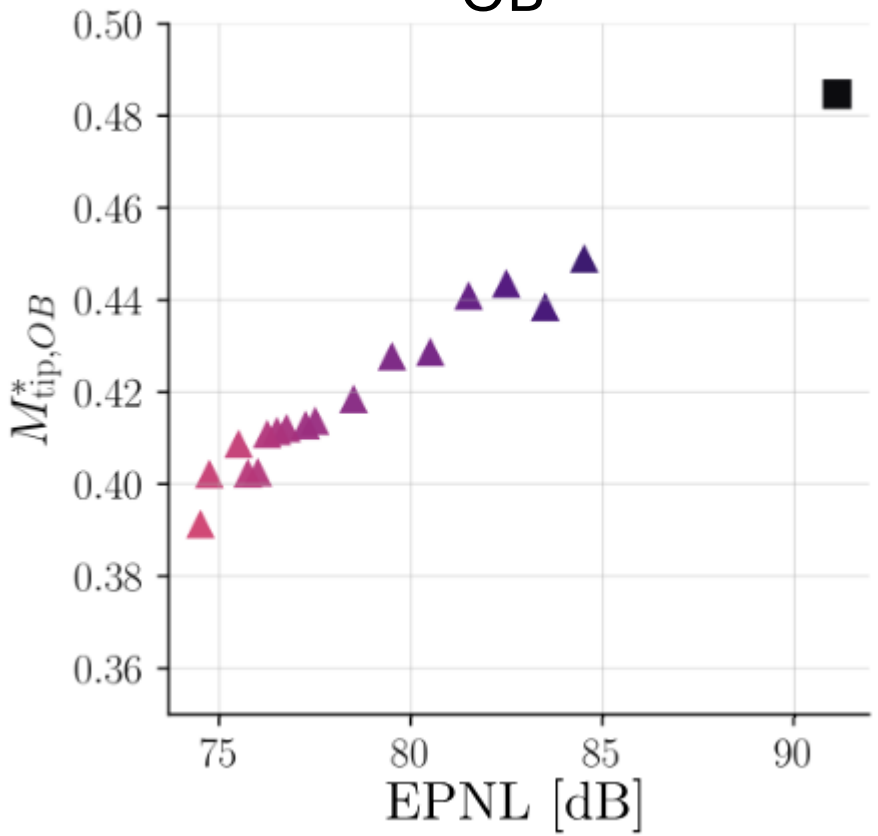
91.1 dB
MinBF point
3.52 tons BF

+7.7% (+0.27 t)
Fuel increase

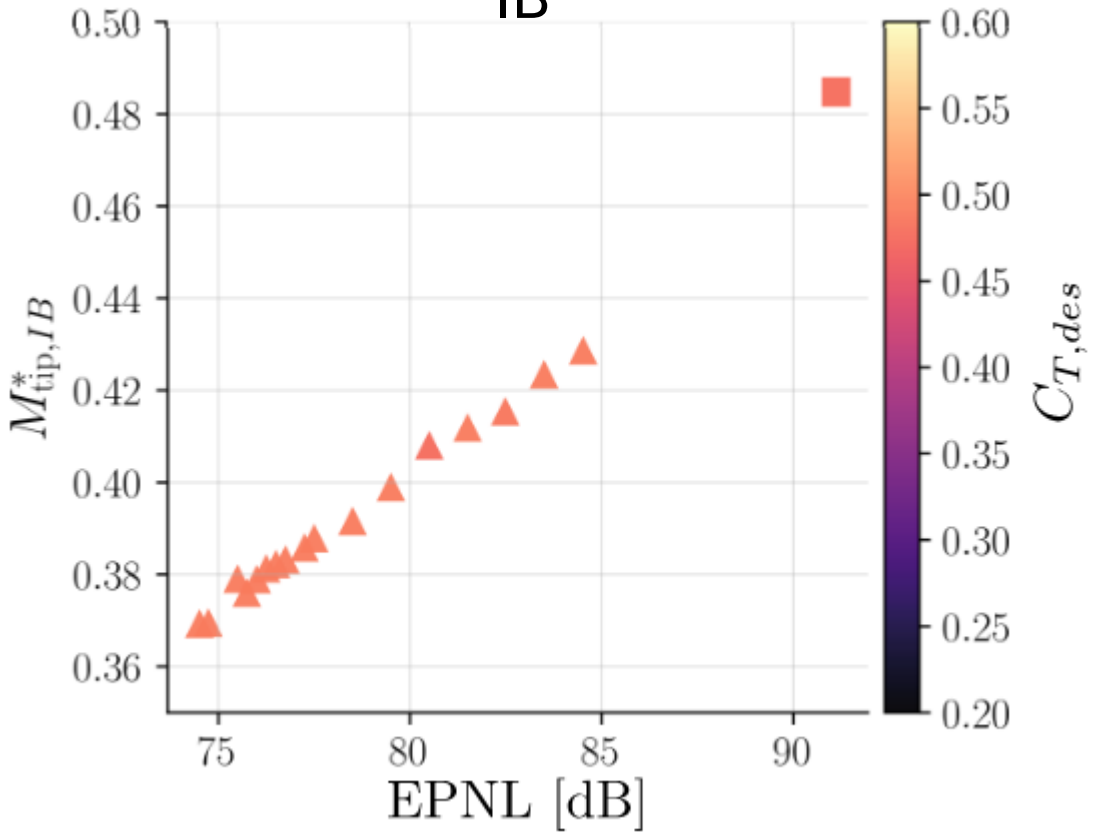
74.5 dB
Min Noise point
3.79 tons BF

Results

OB

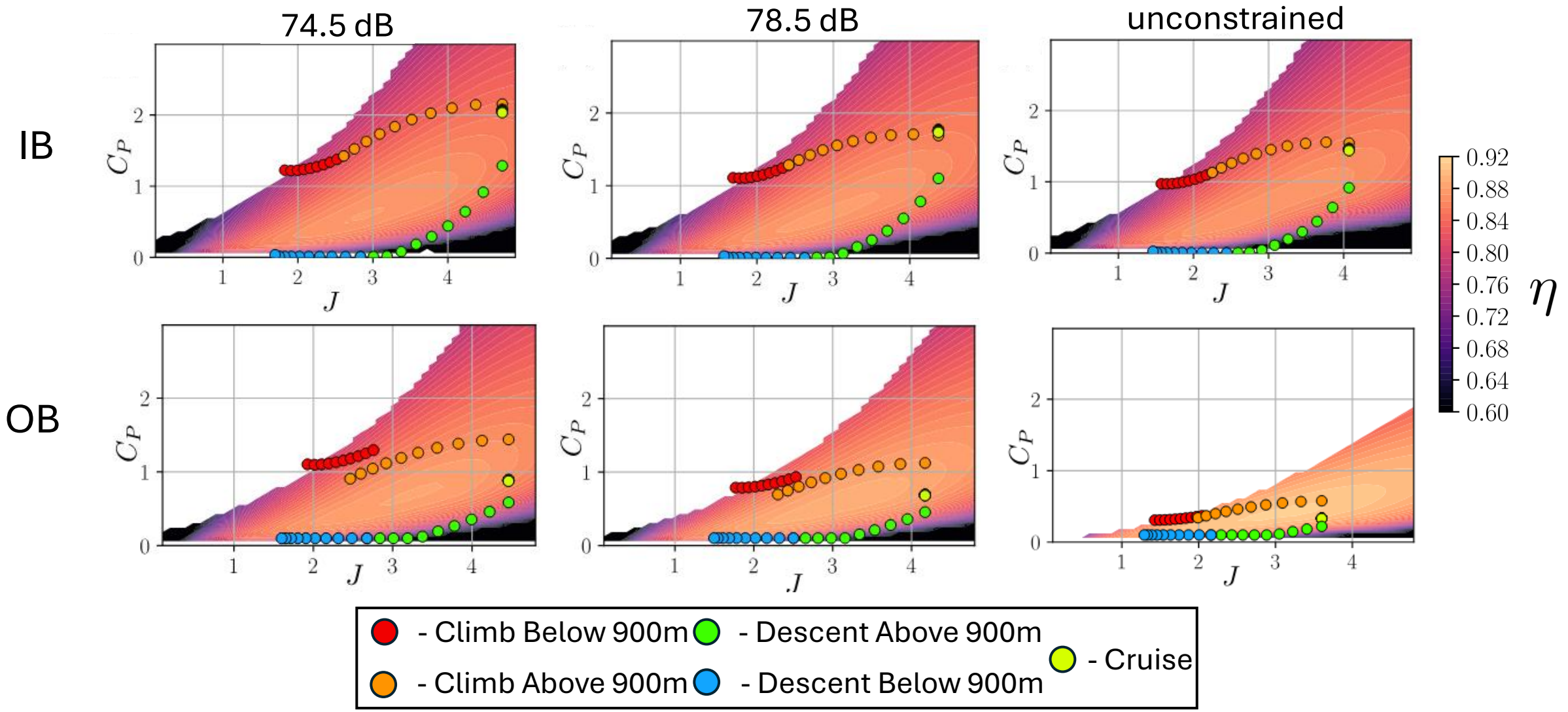


IB



- Lower noise solutions are obtained mainly by reducing propeller rotational speed, i.e. designing for lower tangential tip Mach number, M^*_{tip}.
- Reduced rotational speed at fixed diameter decreases thrust capability, so the optimizer compensate by operating at higher thrust coefficients.

Results

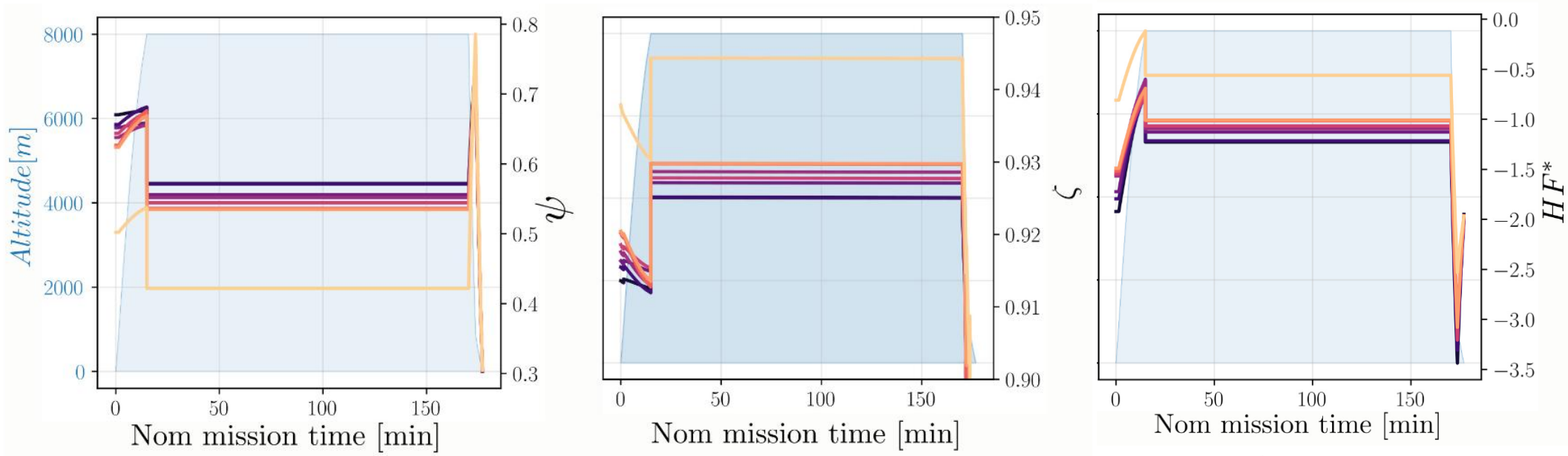


Propeller efficiency maps and mission operating points. (a) 74.5 dB, (b) 78.5 dB, (c) unconstrained.

Results

- **Thrust shifts toward the outboard propellers** as noise constraints become stricter ($\psi \uparrow$).
- **Overall efficiency decreases** due to higher electrical conversion and transmission losses ($\zeta \downarrow$).
- **Local hybridization factor becomes more negative**, indicating increased generator operation to power the outboard propulsors.

$$\zeta = \frac{P_{\text{developed}}}{P_{\text{provided}}} = \frac{8\,P_{\,in\ OB\ propeller} + 2\,P_{in\ IB\ propeller}}{P_{\,out\ battery} + 2\,P_{\,out\ \text{turboshaft}}}$$



Achievements

Scientific Publications & Conferences

- Carvalho, J.; Cavallaro, R.; Cini, A. *Structural Optimisation for Mass Estimation of Large-Aspect-Ratio Wings with Distributed Hybrid Propulsion*. Eng. Proc. 2025, 90, 85. DOI: 10.3390/engproc2025090085
- Carvalho, J.; Norczyk, P.; Cavallaro, R. *Multidisciplinary Optimization of Large-Aspect-Ratio Wings with Distributed Hybrid-Electric Propulsion for Enhanced Local Air Quality and Noise Reduction*. Accepted for publication, Proceedings of Vienna Aviation Days 2025.

Indigo Project Workshops and technical meetings:

- INDIGO 1st Project Workshop — University of Strathclyde, Glasgow, Scotland, 10 June 2024 (in person)
- INDIGO 2nd Project Workshop — CIRA, Capua, Italy, 26–27 June 2025 (online)
- INDIGO Final Project Workshop — Barcelona Supercomputing Center, Barcelona, Spain, 7–8 July 2026 (in person)

Thank you for your attention

João Carvalho

fcarvalh@ing.uc3m.es

joao-f-carvalho

indigo-sustainableaviation.eu

company/indigo-he-project/

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Back-up slides

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Propeller Module

Propeller design parameters:

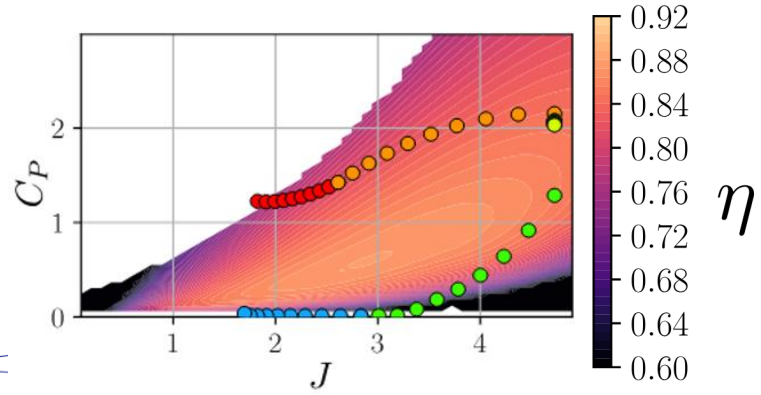
- Propeller diameter, D
- Mach number, M^*_{tip}
- Design thrust coefficient, $C_{T,des}$

Operating conditions:

- Flight speed, V
- Air density, ρ
- Required thrust, T

Model predicts:

- Propeller efficiency, η_{prop}
- Required shaft power, P



Gas Turbine Module

Engine design parameters:

- Overall pressure ratio, OPR,
- Turbine inlet temperature, $T4_t$.

Operating conditions:

- altitude,
- Mach number
- power settings;

Model predicts:

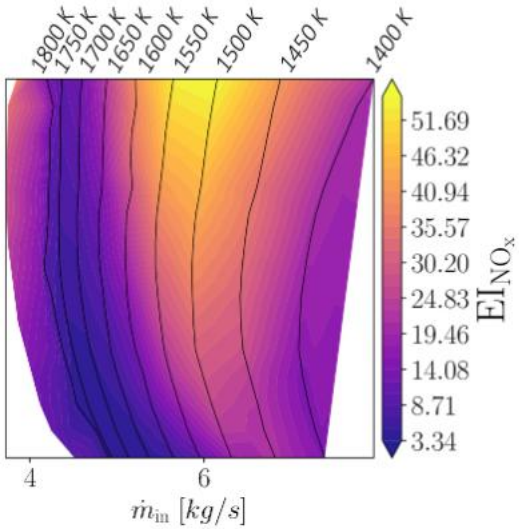
- Power specific fuel consumption (PSFC)
- Pollutant emission indices, Ei_i.

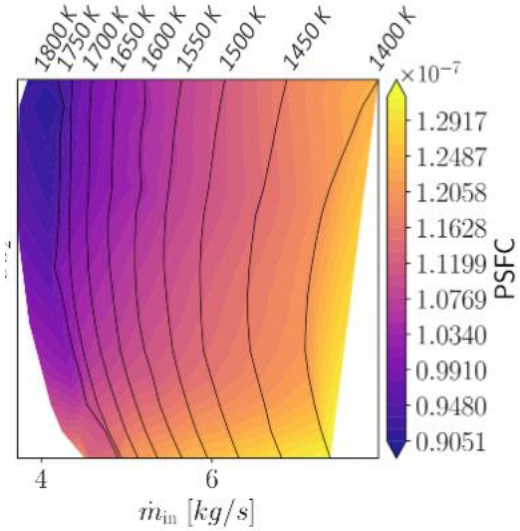
- fuel flow rate is calculated from:

$$\dot{m}_{fuel} = PSFC \cdot Pout$$

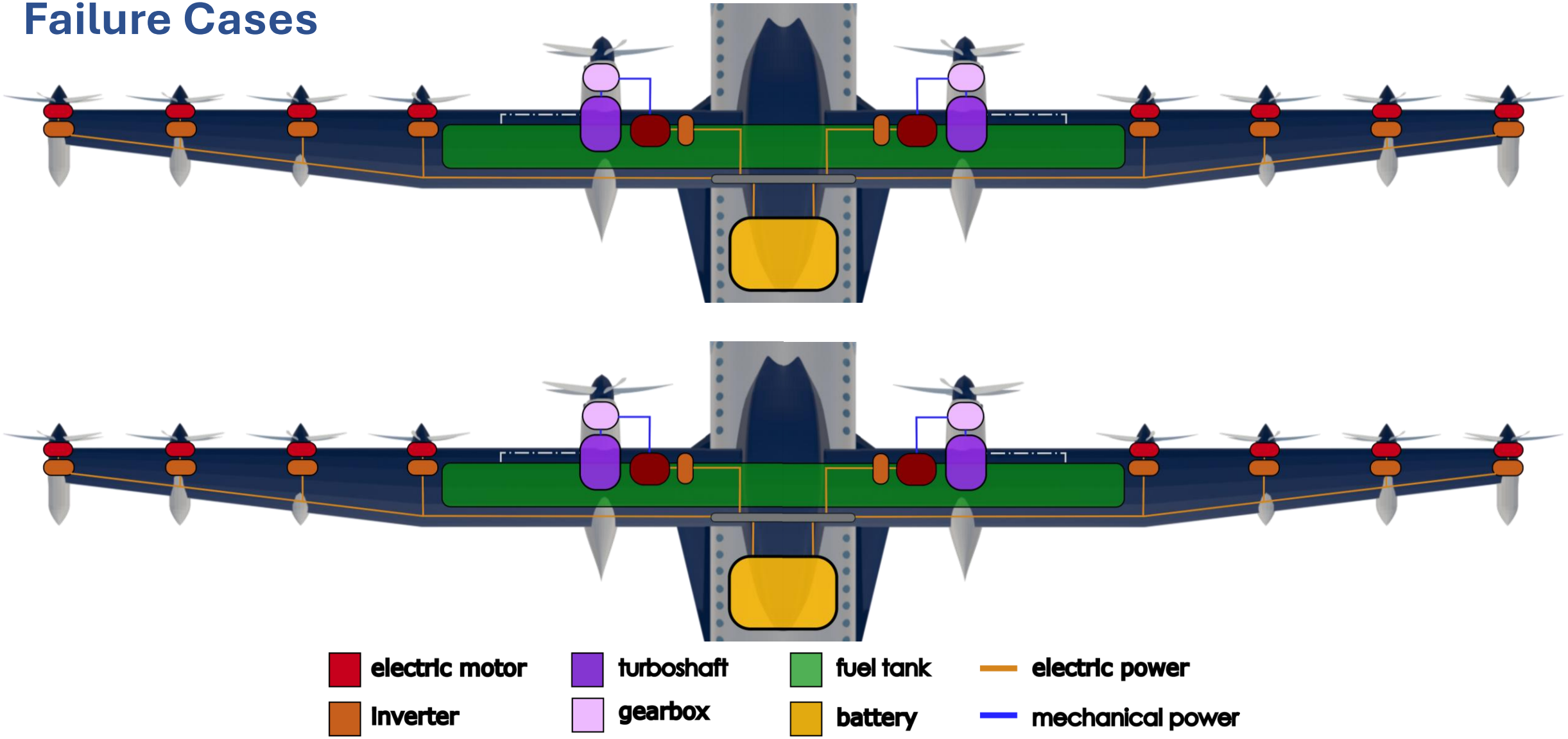
- pollutant flow rate is calculated from:

$$\dot{m}_i = EI_i \cdot \dot{m}_{fuel}$$



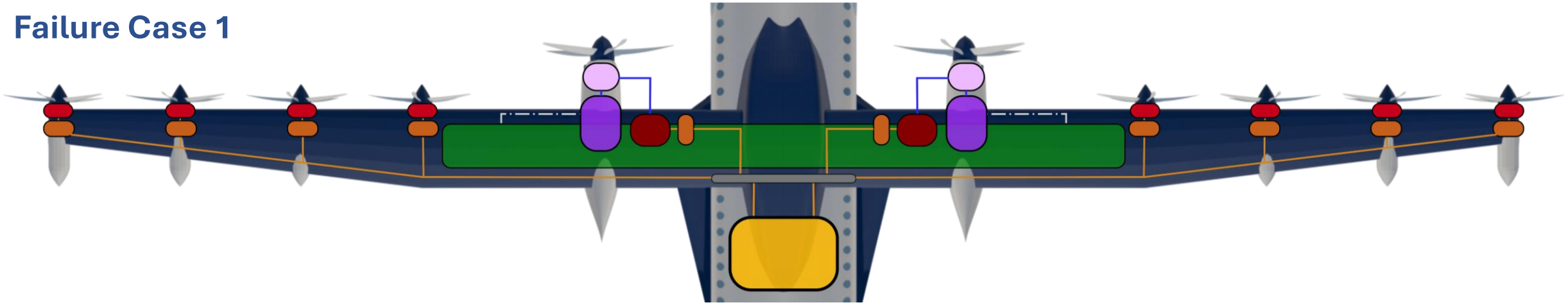


Failure Cases

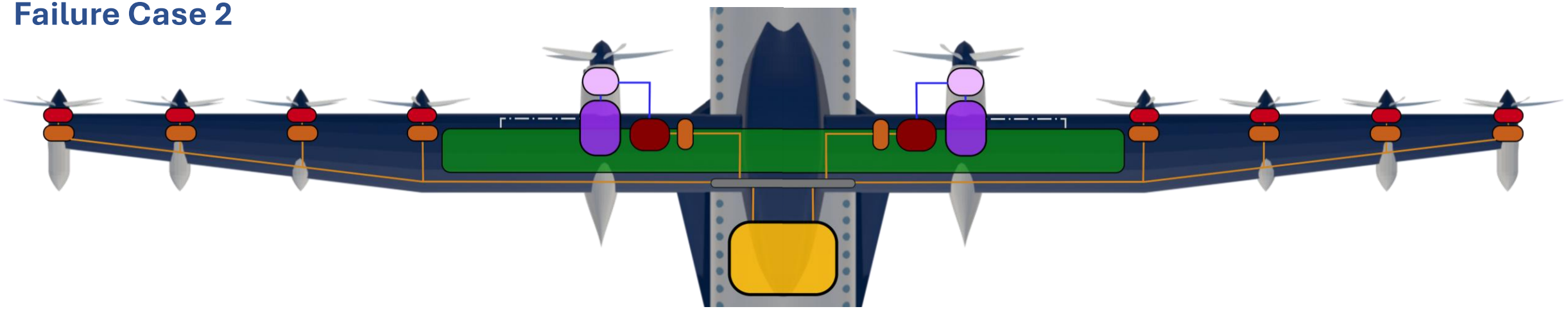


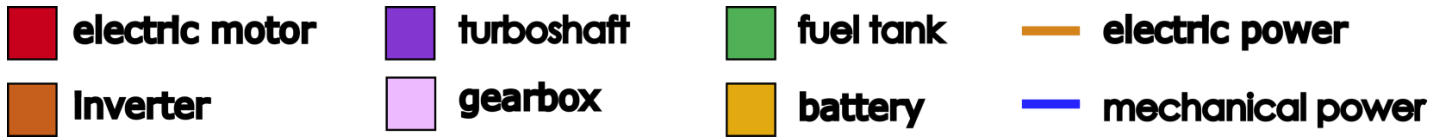
Methodology

Failure Case 1



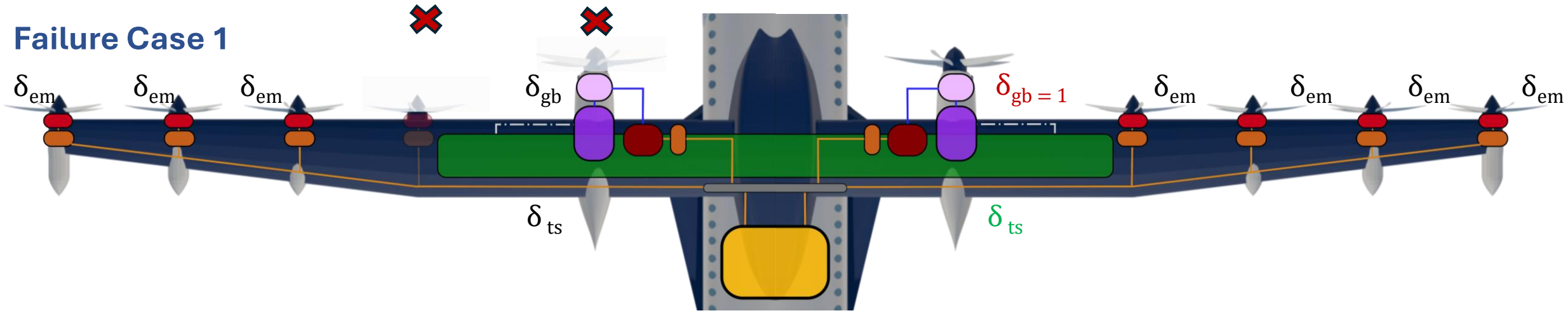
Failure Case 2



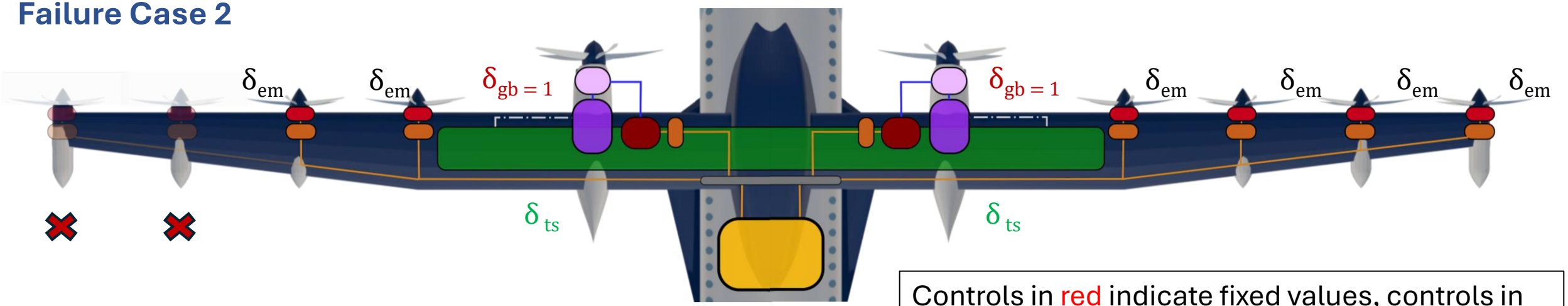


Methodology

Failure Case 1



Failure Case 2



electric motor
turboshaft
fuel tank
electric power
Inverter
gearbox
battery
mechanical power

Controls in red indicate fixed values, controls in **black** indicate optimization design variables, and controls in green indicate state variables