uc3m PHD

Aerospace

ADVANCING ROAD VEHICLE DESIGN:

MACHINE LEARNING-BASED AERODYNAMIC SHAPE OPTIMIZATION

ALBERTO VILARIÑO TARRÍO

PHD DIRECTORS: CARLOS SANMIGUEL VILA AND RODRIGO CASTELLANOS

INTA

Support by: ALTAIR

PHD DOCTORAL MEETINGS 2025. PHD PROGRAM IN AEROSPACE ENGINEERING UC3M

TABLE OF CONTENTS

INTRODUCTION

The aim of this thesis is developing new methodologies to based on AI for vehicle aerodynamics shape optimization.

Aerodynamics is a crucial discipline in modern automotive development:

- **Fuel Efficiency:** Reducing drag minimizes fuel consumption, crucial for combustion and electric vehicles.
- **Stability and Handling:** Managing airflow ensures predictable behaviour at high speeds.
- **Noise Reduction:** Aerodynamically optimized designs reduce wind noise, improving passenger comfort.

Constrains:

- **Aesthetics and design**.
- **Engineering requirements:** cooling, off road capabilities, cabin space, etc.
- **Package**

THE OPPORTUNITY

In recent times the development cycles had shortened, with a need for faster solutions the integration of AI is being promoted.

WE ARE NOT DOING ANYTHING NEW...

References:

Volkswagen Golf Mk8: c_D ~ 0.29

BMW 3 Series G20: c_D ~ 0.26

Audi Q5 : c_D ~ 0.34

Mercedes GLS: c_D ~ 0.37

Range Rover: c_D ~ 0.30

1930 1970 2020

1934 - Tetra T77: c_D ~ 0.36

1955 - Citroën DS: c_D ~ 0.36

1981 – Audi 100: c_D = 0.30

1989 - Opel Calibra: c_D = 0.26

1996 – GM EV1: c_D = 0.195

1999 – Audi A2: c_D = 0.25

2013 – Volkswagen XL1 XL1: c_D = 0.189

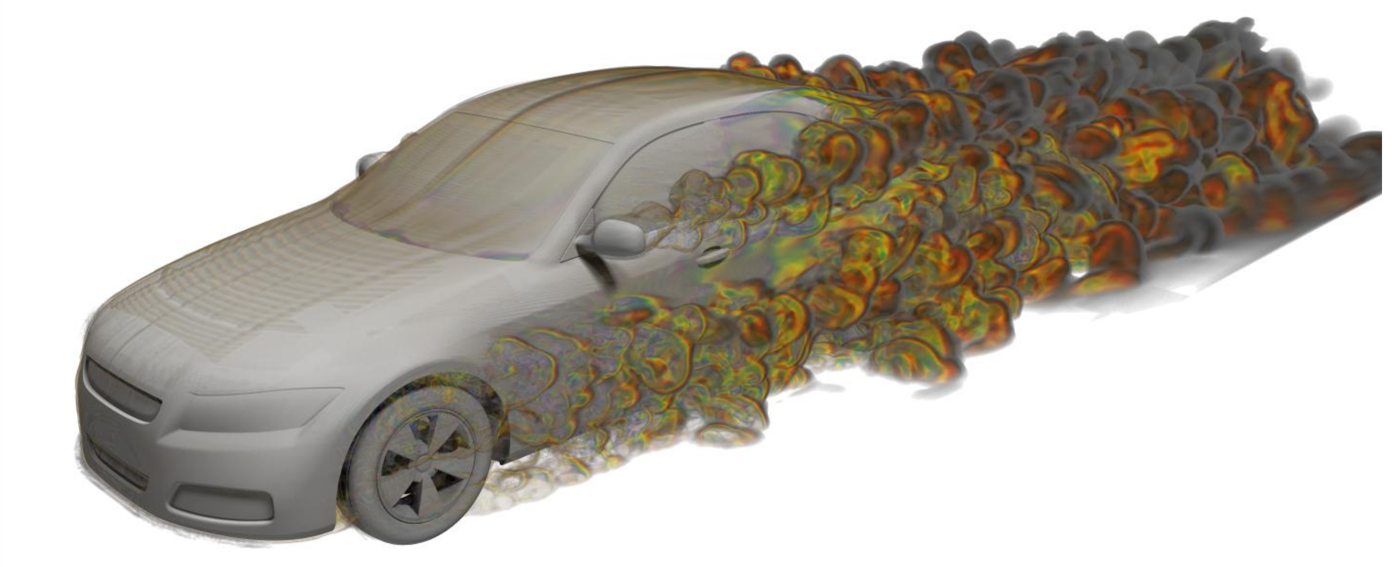
2020 – Mercedes EQS: c_D = 0.20

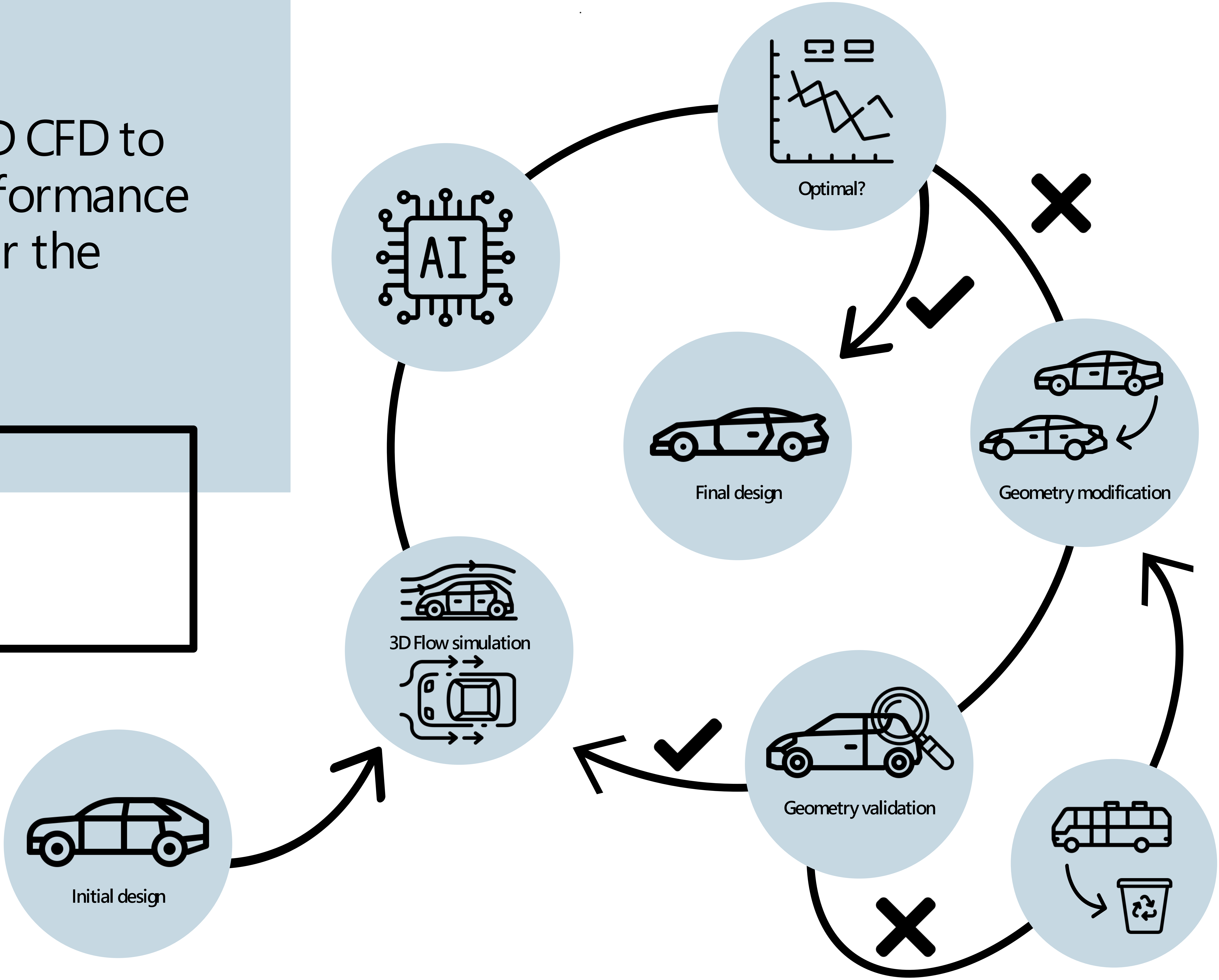
...BUT WE WILL ACCELERATE THE PROCESS

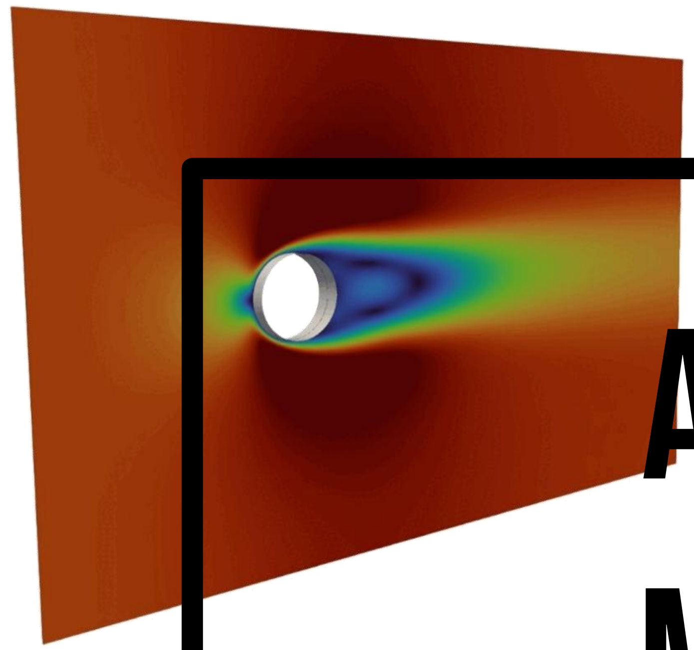
Goal: Integrate ML with 3D CFD to optimize aerodynamic performance in road vehicles and deliver the **global optimal solution.**

WORKFLOW

Vehicle to be used: DrivAer model.







ADJOINT METHOD

- ✓ Scalable: gradient calculation independent of number parameters.
- ✓ Accurate sensitivity analysis.
- ✓ Suitable for constrained optimization.
- ✗ Requires gradient.
- ✗ Local optimization.
- ✗ Solver dependent: need implement with CFD solver.
- ✗ High complexity.
- ✗ Only works with continuous, differentiable design spaces.

GENETIC ALGORITHM

- ✗ Computationally expensive (requires many evaluations).
- ✗ Slow convergence
- ✓ No gradient required.
- ✓ Global optimization.
- ✓ Solver independent (black box).
- ✓ Handles any type of variable (discrete choices, non-differentiable geometries, and topological changes).
- ✓ Medium complexity.
- ✗ Hard to impose constrains.

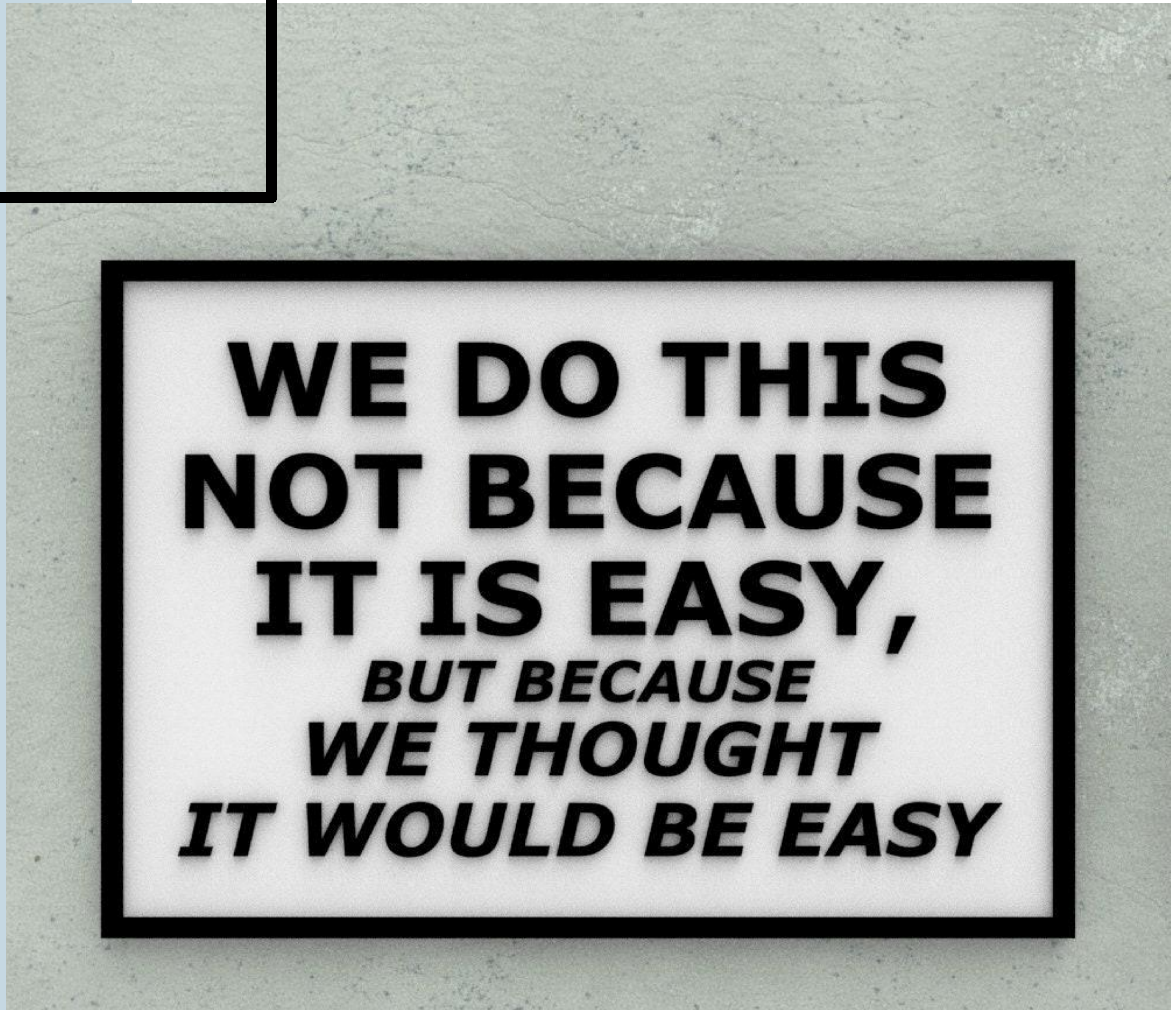
REINFORCEMENT LEARNING

- ✗ Sample inefficiency (requires lots of data to learn).
- ✗ Reward design is hard.
- ✓ Gradient is optional.
- ✓ Global optimization.
- ✓ Solver independent (black box).
- ✓ Adaptive optimization.
- ✓ Handles sequential decision problems.
- ✓ No need for explicit models (can operate on simulation or experimental data alone).
- ✗ Very high complexity.
- ✗ Hard to impose constrains.

RUN BEFORE WALK…

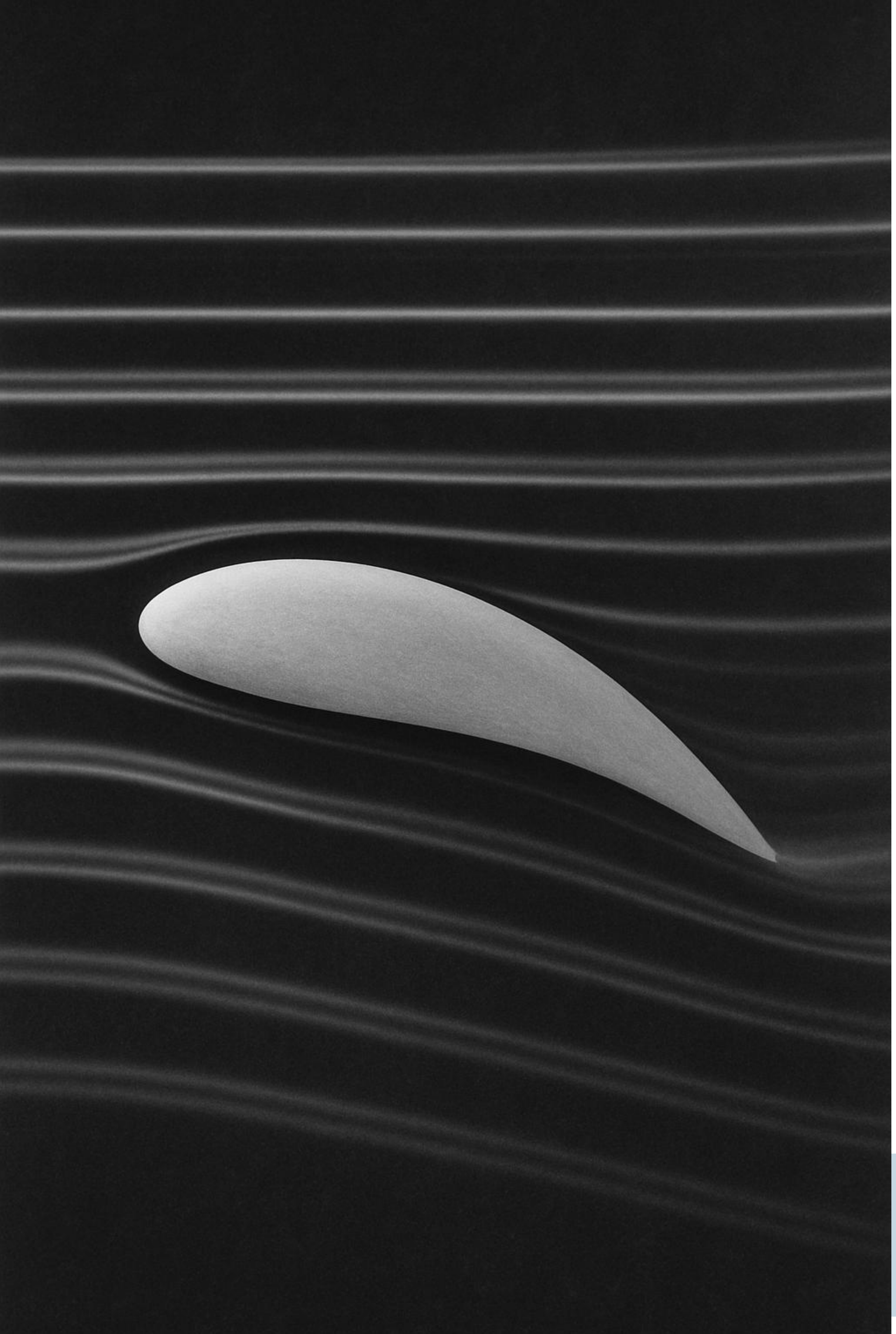
Initial Challenges

- CFD:
  - Simulation convergence issues (Auto CFD, cL)
  - Mesh generation
- Parametrization and geometry modification:
  - Difficulties in geometry manipulaion.
  - Lack of clarity on constraints
  - Implementation details: need to understand how parametrizes the geometry (morph? Bezier curves?)
- Overall, time-consuming evaluations that lead to slow development.
- In summary:
  - High complexity problem.
  - Plus, integrate ML agent (GA).



Small steps… Proposed solution:

- Start with a simplified 2D model
- Use a basic airfoil geometry
- Run simulations with a faster, more accessible tool: XFOIL



XFOIL

Open-source program for analyzing and designing subsonic subsonic airfoils, based on a panel method for inviscid flow flow coupled with a boundary layer formulation for viscous viscous effects.

CST

Method for airfoil parametrization that uses class and shape shape functions to smoothly and efficiently define airfoil geometry.

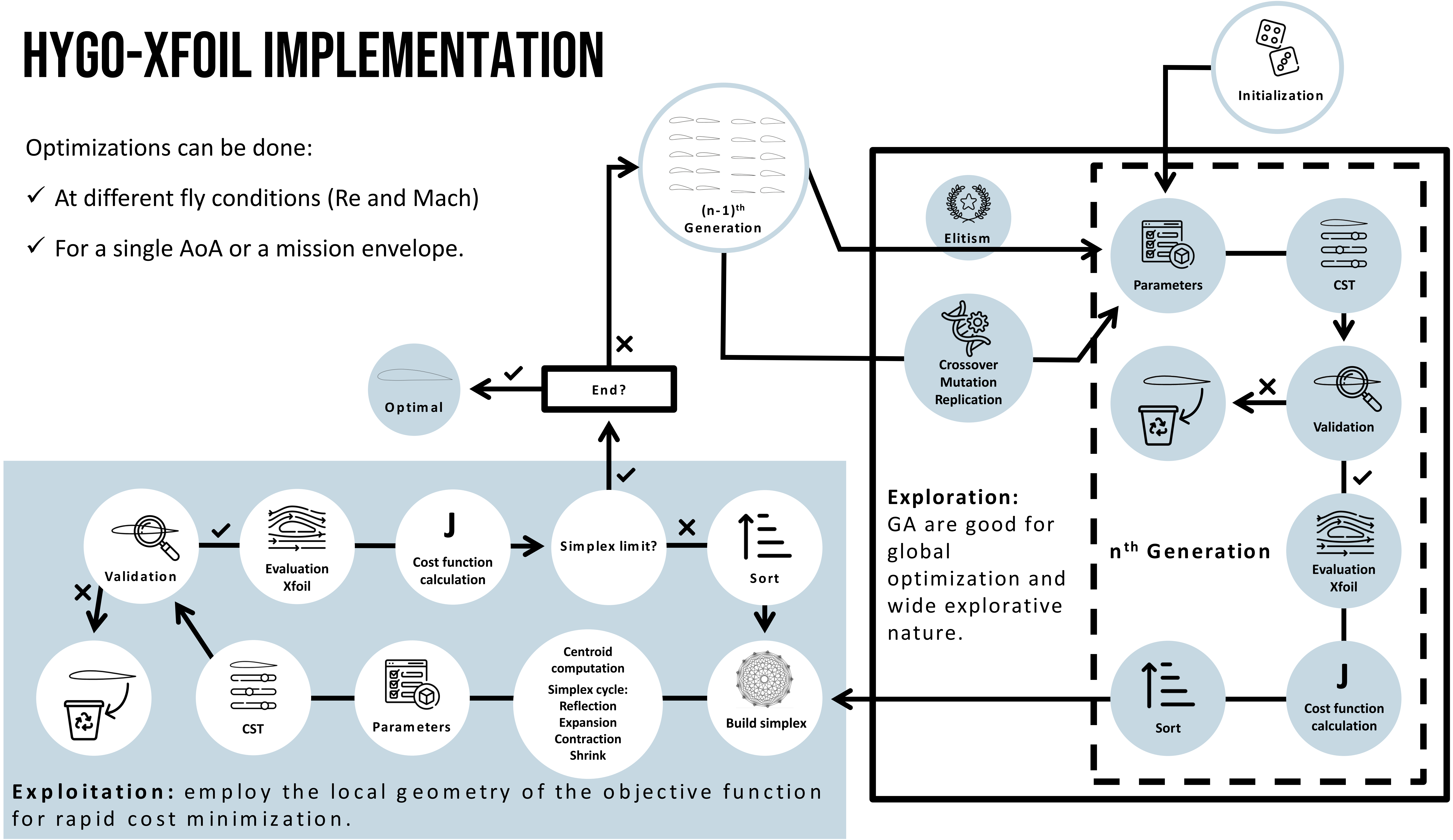
HYGO

Hybrid optimization algorithm that combines a linear genetic genetic algorithm with the Downhill Simplex method to balance to balance global exploration and local exploitation

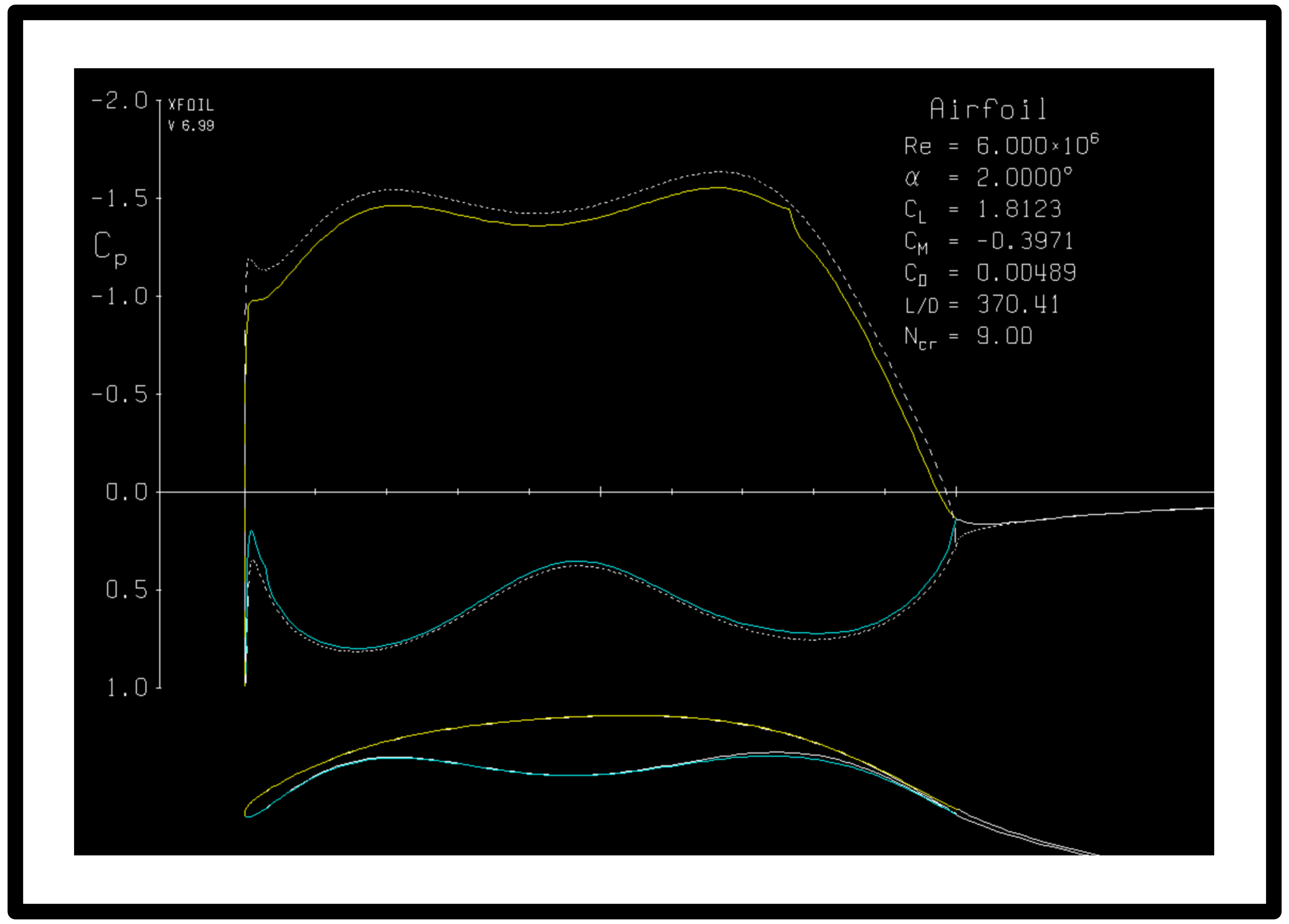
HYGO-XFOIL IMPLEMENTATION

Optimizations can be done:

- ✓ At different fly conditions (Re and Mach)
- ✓ For a single AoA or a mission envelope.



HYGO-XFOIL CHALLENGES



ENSURE VALID AIRFOILS

Airfoil upper and lower surfaces do not intersect intersect

Limit maximum thickness

Constrain maximum thickness x position

Avoid sharp edges: smooth continuous surface

CONSTRAIN THE PROBLEM

Limit CST parameters to boundary the design space.

Also, improve the output data control overall shape.

Separate study with all NACA 4 and 5 airfoils to understand limits.

EVALUATE THE COST FUNCTION

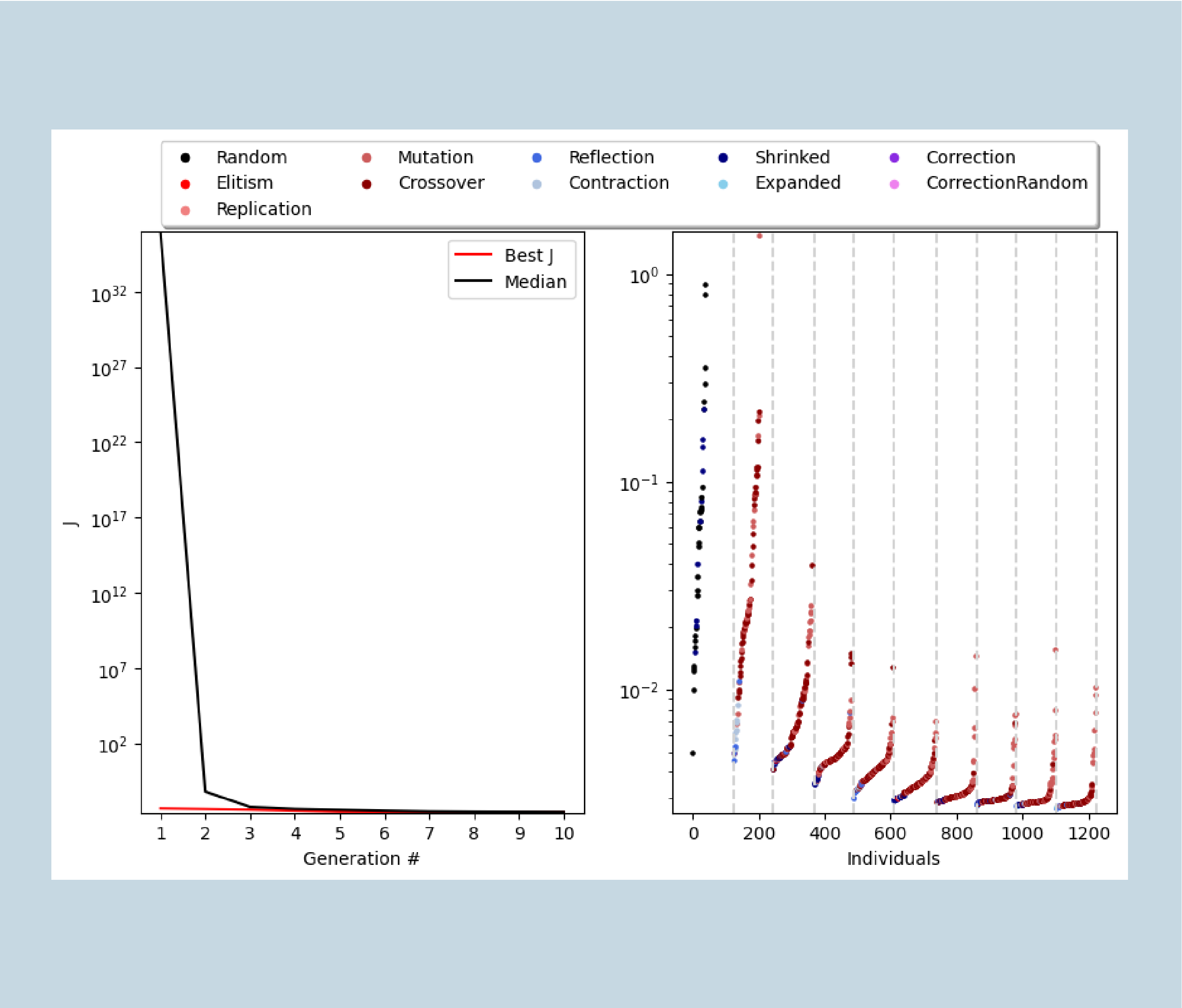
Xfoil run until convergency: fail safe implemented.

Extract data from Xfoil.

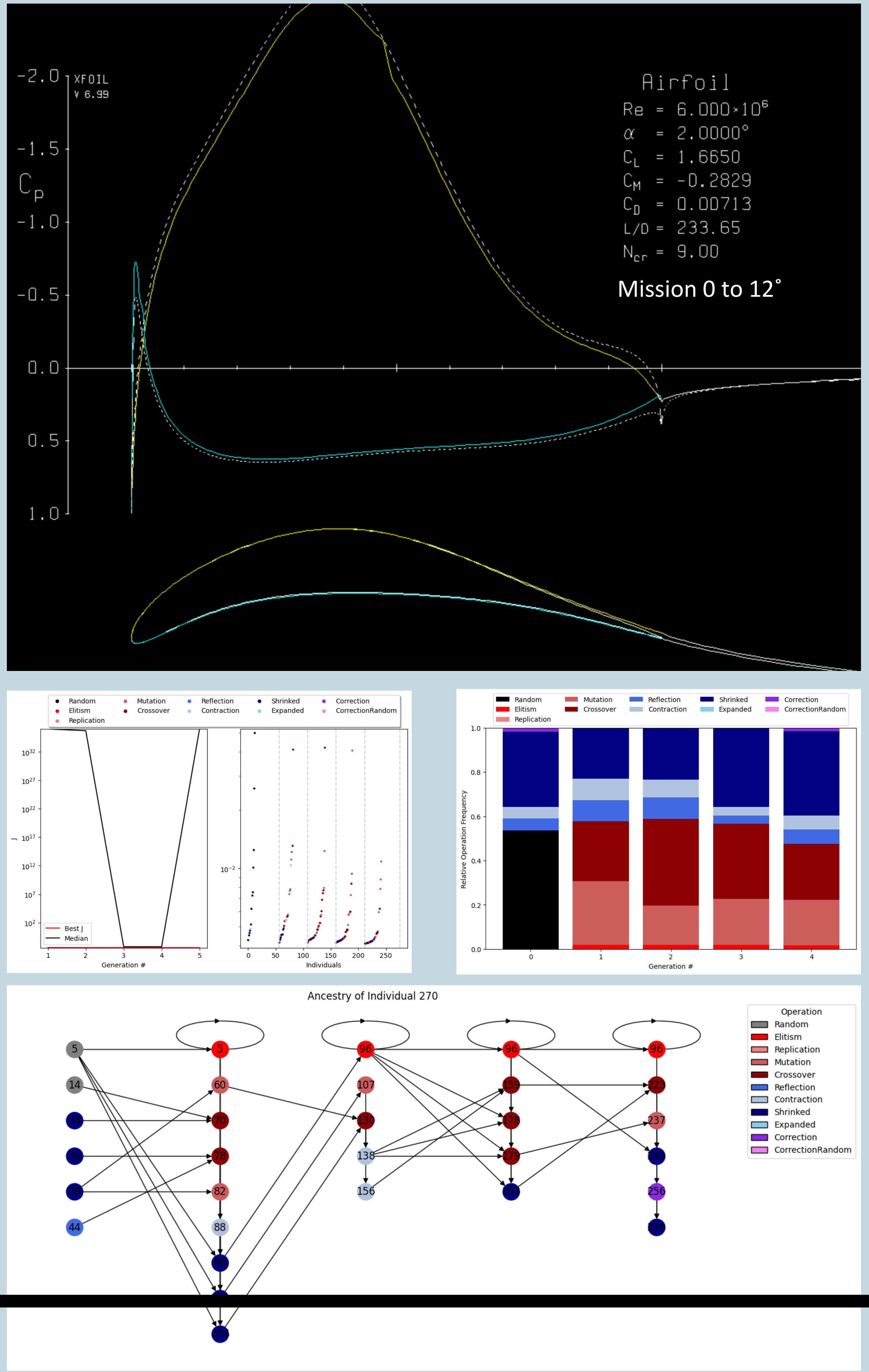
Ensure coefficients are valid: c_D and c_L always positive.

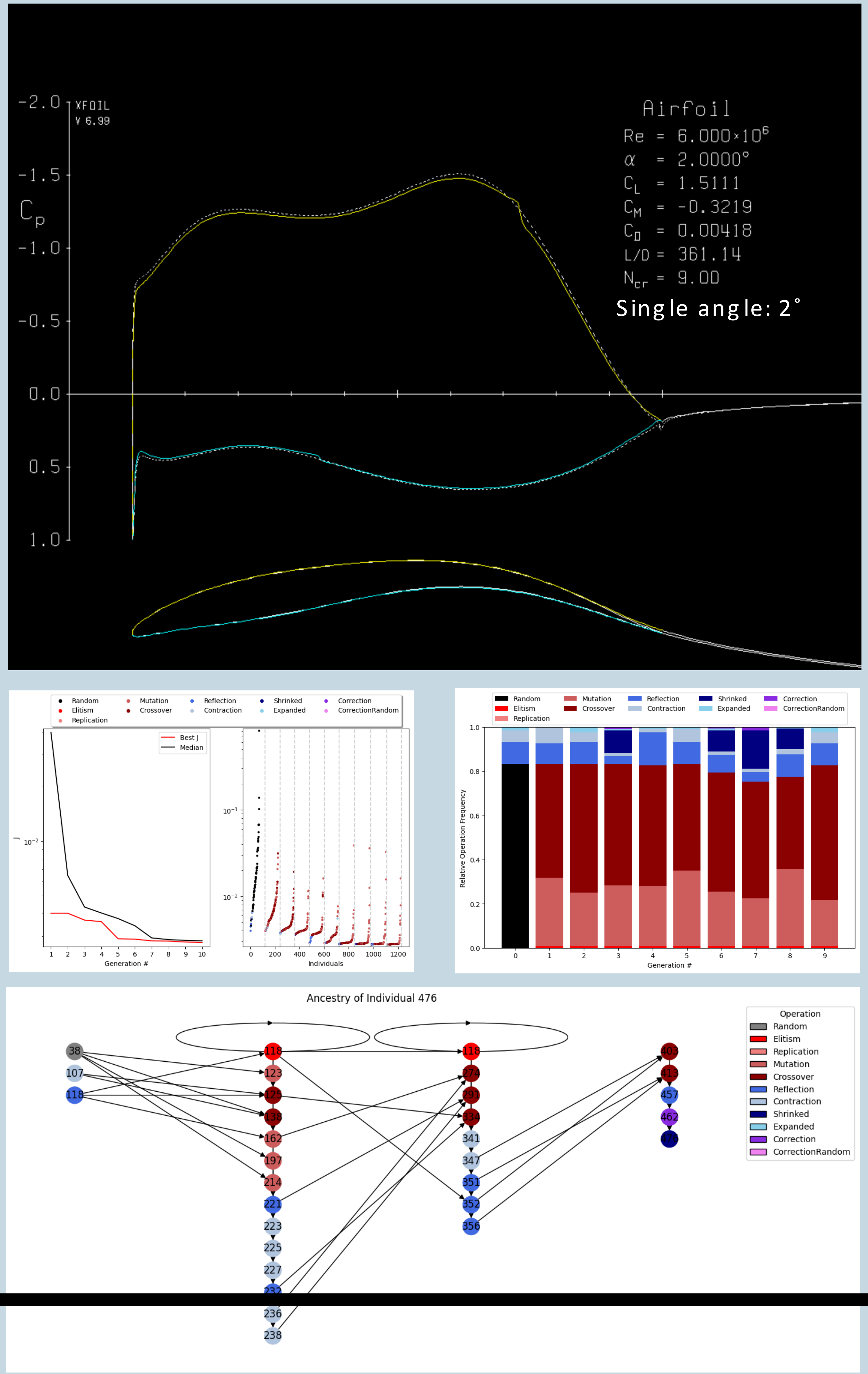
Define cost function:

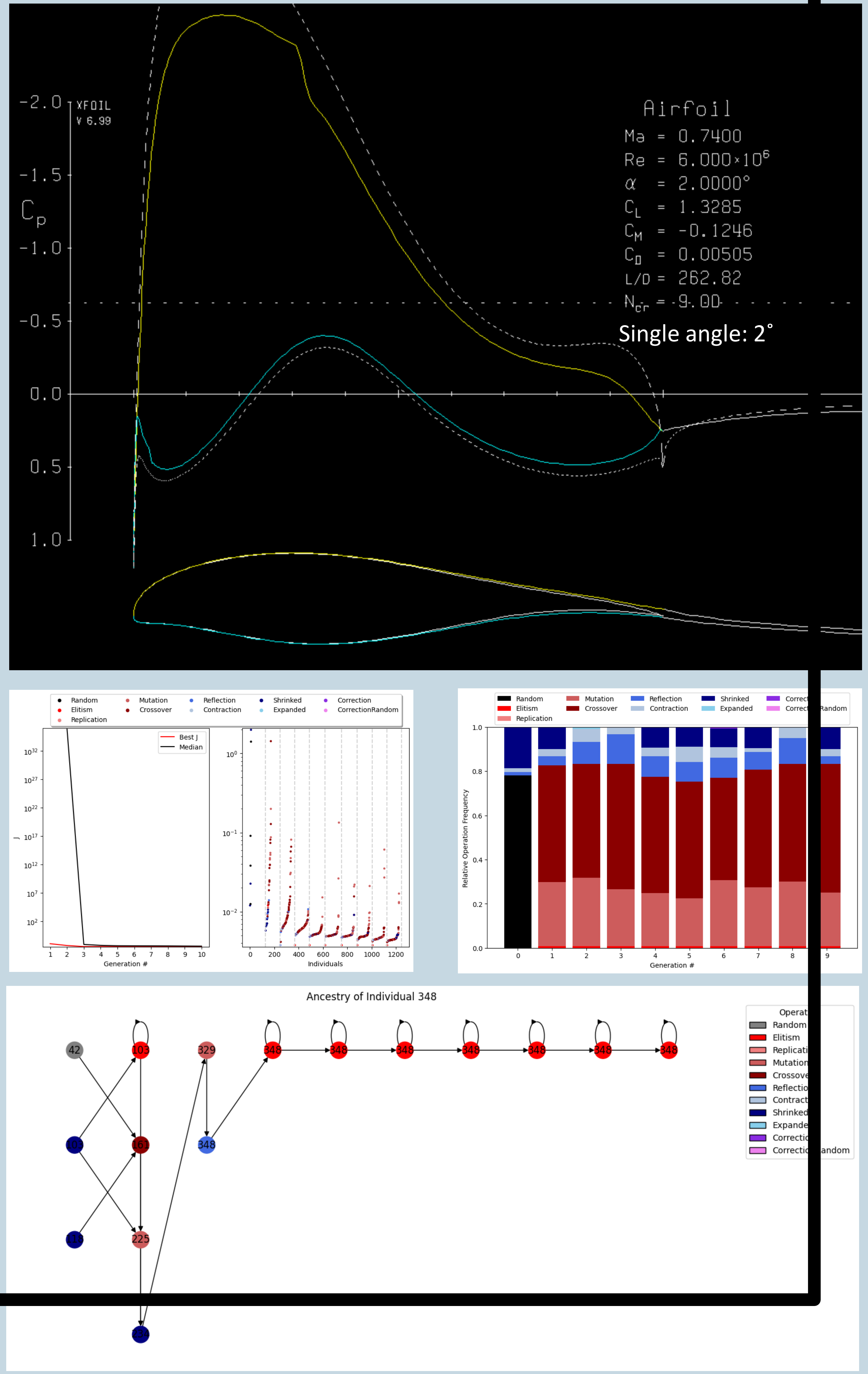
$$J = \frac{c_D}{c_L} \text{ or } J = \frac{\sum_{i=1}^{n} FT_i \frac{c_{D_i}}{c_{L_i}}}{\sum_{i=1}^{n} FT_i}$$



RESULTS: EXAMPLE OF USAGE







LESSONS LEARNT

Good overview of the whole process.

How genetic algorithms work.

Implementation of different software together.

Efficient geometry parametrization.

Define geometrical constrains and limit the design space.

Importance of geometrical validation.

Validate results.

Define cost functions.

Data and file management.

ONGOING

Implementation of MSES (Multi- (Multi-element Surface Euler Euler Solver)

RANS validation.

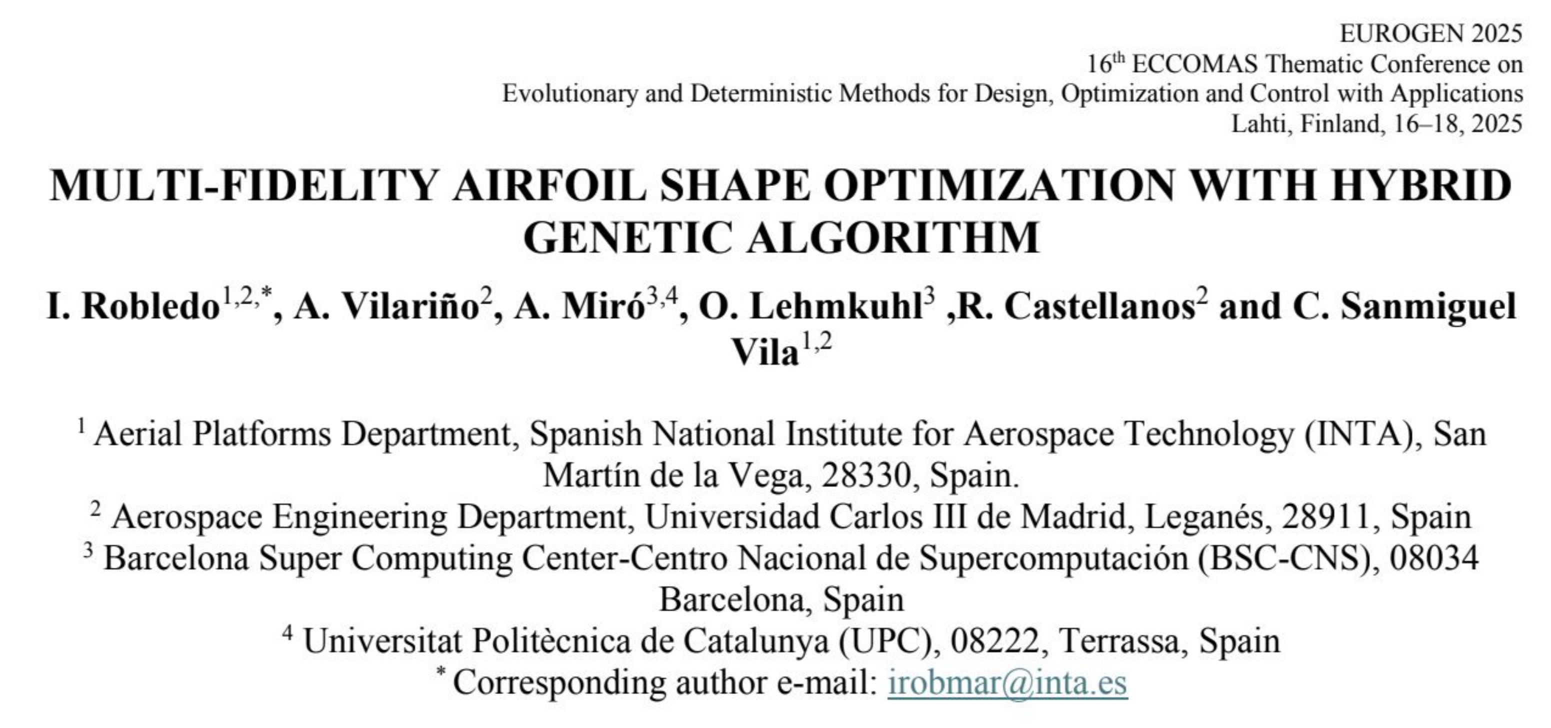
Public current work in EuroGen EuroGen 2025

FUTURE WORK

Progress my investigation towards road vehicle optimization:

- Integrate vehicle parametrization using DrivAerNet++

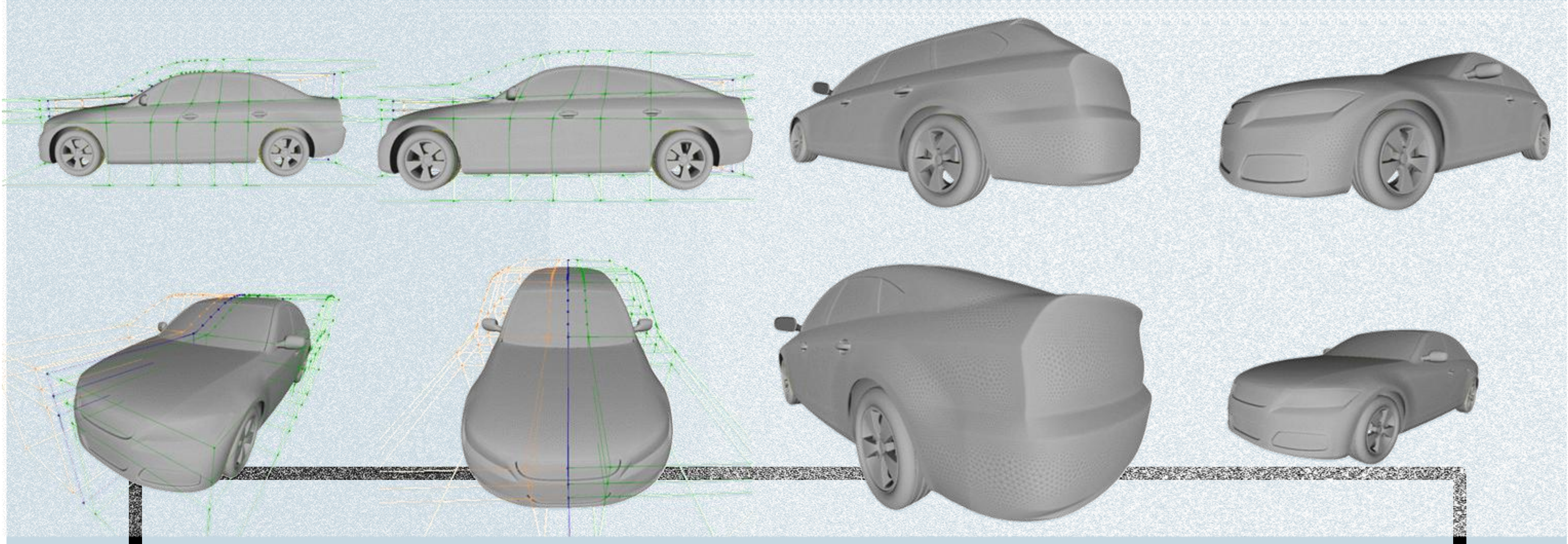
Investigate other ML approaches (reinforcement learning)

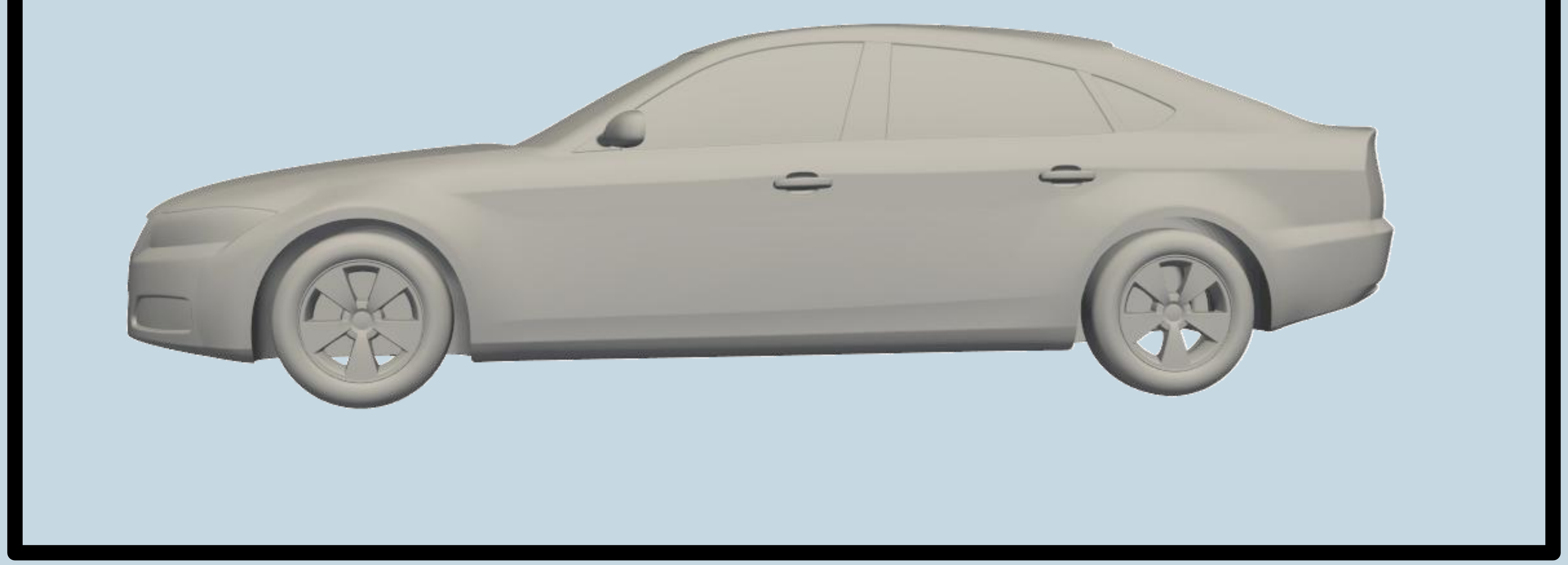

EUROGEN 2025
16th ECCOMAS Thematic Conference on
Evolutionary and Deterministic Methods for Design, Optimization and Control with Applications
Lahti, Finland, 16–18, 2025

MULTI-FIDELITY AIRFOIL SHAPE OPTIMIZATION WITH HYBRID GENETIC ALGORITHM

I. Robledo[1,2,*], A. Vilariño[2], A. Miró[3,4], O. Lehmkuhl[3], R. Castellanos[2] and C. Sanmiguel Vila[1,2]

[1] Aerial Platforms Department, Spanish National Institute for Aerospace Technology (INTA), San Martín de la Vega, 28330, Spain.
[2] Aerospace Engineering Department, Universidad Carlos III de Madrid, Leganés, 28911, Spain
[3] Barcelona Super Computing Center-Centro Nacional de Supercomputación (BSC-CNS), 08034 Barcelona, Spain
[4] Universitat Politècnica de Catalunya (UPC), 08222, Terrassa, Spain
* Corresponding author e-mail: irobmar@inta.es





PLEASE FEEL FREE TO ASK ANY QUESTION OR GETTING IN TOUCH

I want to thank Isaac Robledo for all his support with Python and the development of HyGO, and Javier Nieto for his help in getting me up to speed with CST and Xfoil.

And a special mention to Arnau from BSC for all his patient and support provided.

ALBERTO VILARIÑO TARRÍO

ALBERTO.VILARINO@ALUMNOS.UC3M.ES