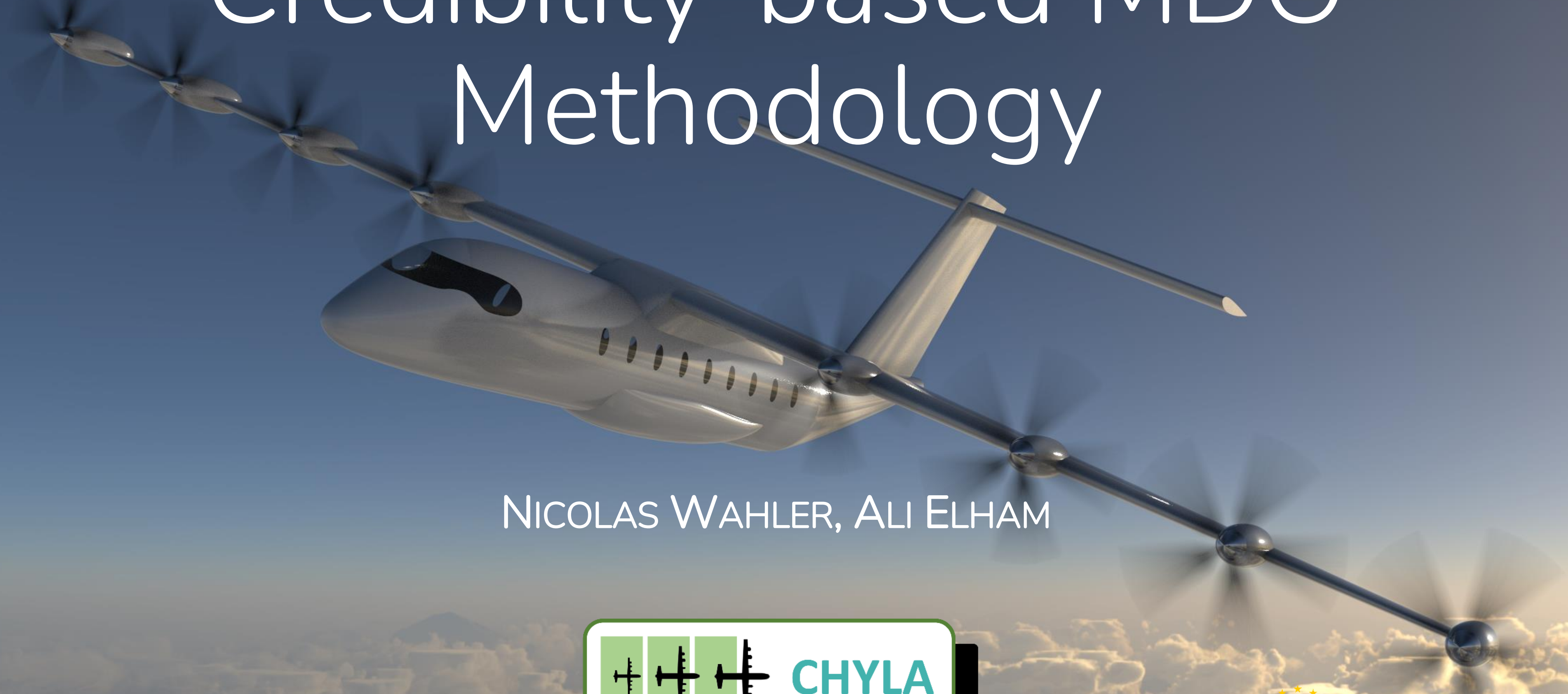
Credibility-based MDO Methodology



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CHYLA
CREDIBLE HYBRID ELECTRIC AIRCRAFT

TU Delft
University of Southampton
Technische Universität Braunschweig
Clean Sky 2

Motivation

Introduction

- (Hybrid-) electric aircraft major focus of research and development
- Concepts usually based on expected technology levels in future
  - Assumed values can vary widely (without proper scientific basis)
  - Vast improvements in state of the art required

➢ *Quantify uncertainty of integral parameters for electric aircraft designs*

➢ *Optimise aircraft designs under credibility constraints*

What is Credibility-based MDO?

- Current status:
  - MDO in research focuses on optimising aircraft for certain performance metric
  - Constraints limit design space in a physical manner

- Credibility-based approach:
  - Add a layer of ‚chance-of-realisation‘ to the design variables
  - Final results are twofold:
    - Optimised aircraft for performance
    - Credibility (feasibility) of this design to exist in X years
  - Requires additional estimations

Credibility

Credibility

- *For a given design parameter, what is the credibility of a given target value by 2035?*
  - Future predictions always uncertain
  - Estimation of mean and standard deviation

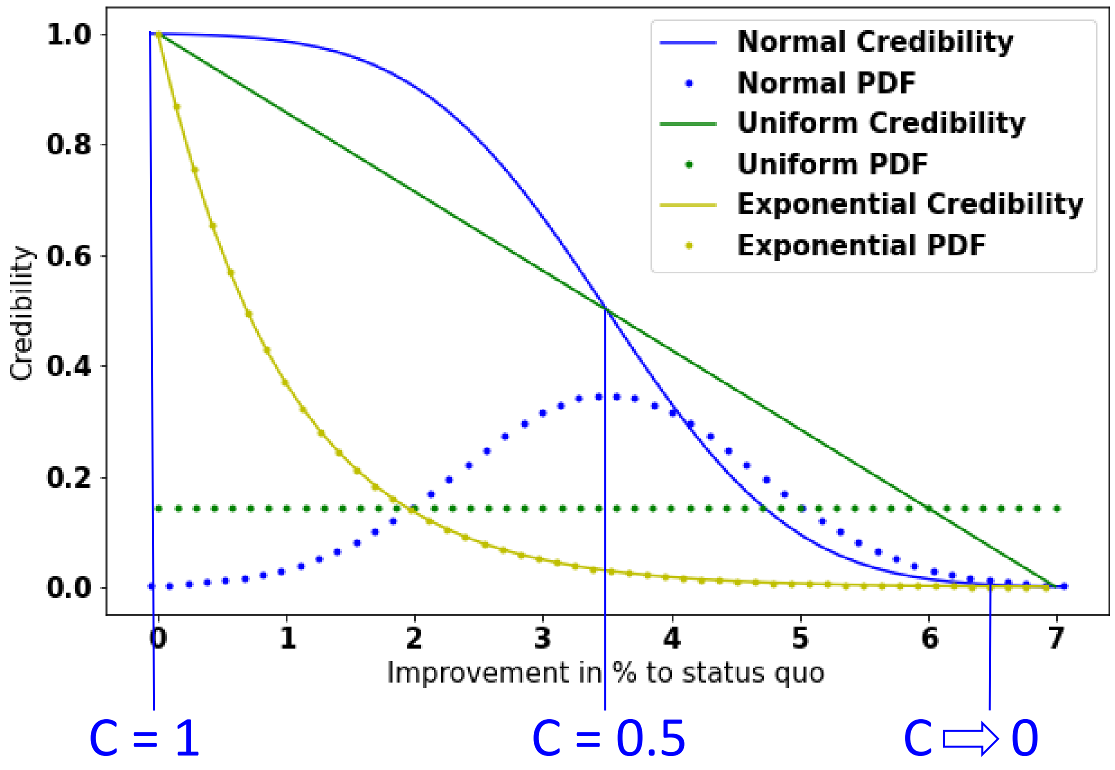
➢ Prediction of a future probability distribution function for a design parameter

Credibility

- Probability that at time X technology Y has reached at least maturity Z

- *Credibility is large when probability that technology can exceed the value is large*

- C = P(X>x) = 1 - P(x≤X) = 1 - CDF



Uncertain variables

- Aircraft design always integration of many systems and innovations
- Range of possible variables where performance is not known a-priori
- Selection must be made
    - Level of uncertainty
    - Impact on overall aircraft design

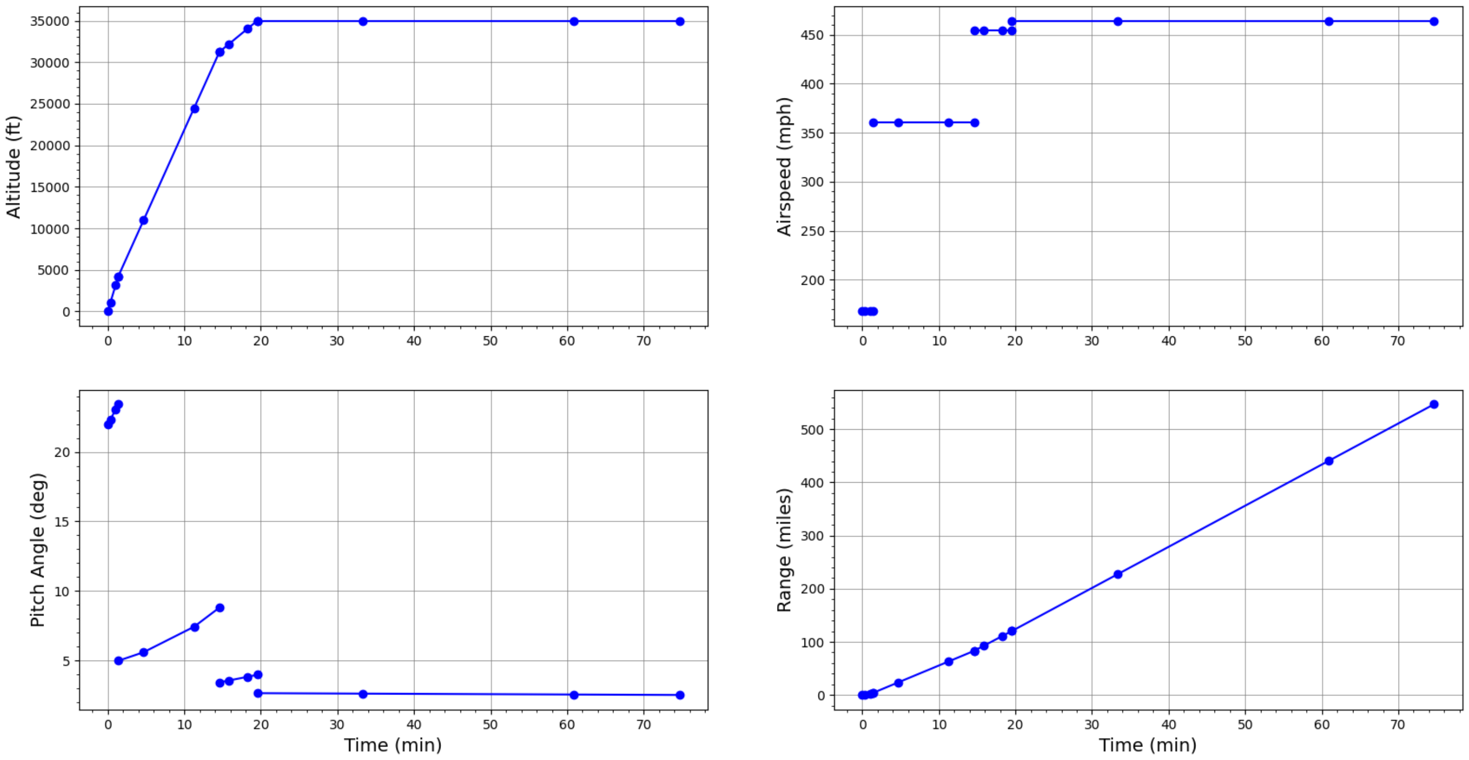
Uncertain variables

- Energy storage
  - Gravimetric energy density of batteries
  - Gravimetric power density of fuel cells
- Electric motors
  - Gravimetric power density of electrical machines
  - Volumetric power density of electrical machines
- Airframe parameters
  - Structural wing weight reductions
  - Area of laminar flow over the wing

Mission simulation tool: SUAVE

- Open source mission simulation programme
- Stanford University
- Aircraft defined by geometric parameters
  - Propulsion sized for TLARs
- Mission specified in segments
- Performance evaluation

SUAVE sample mission



Need for an improved network model

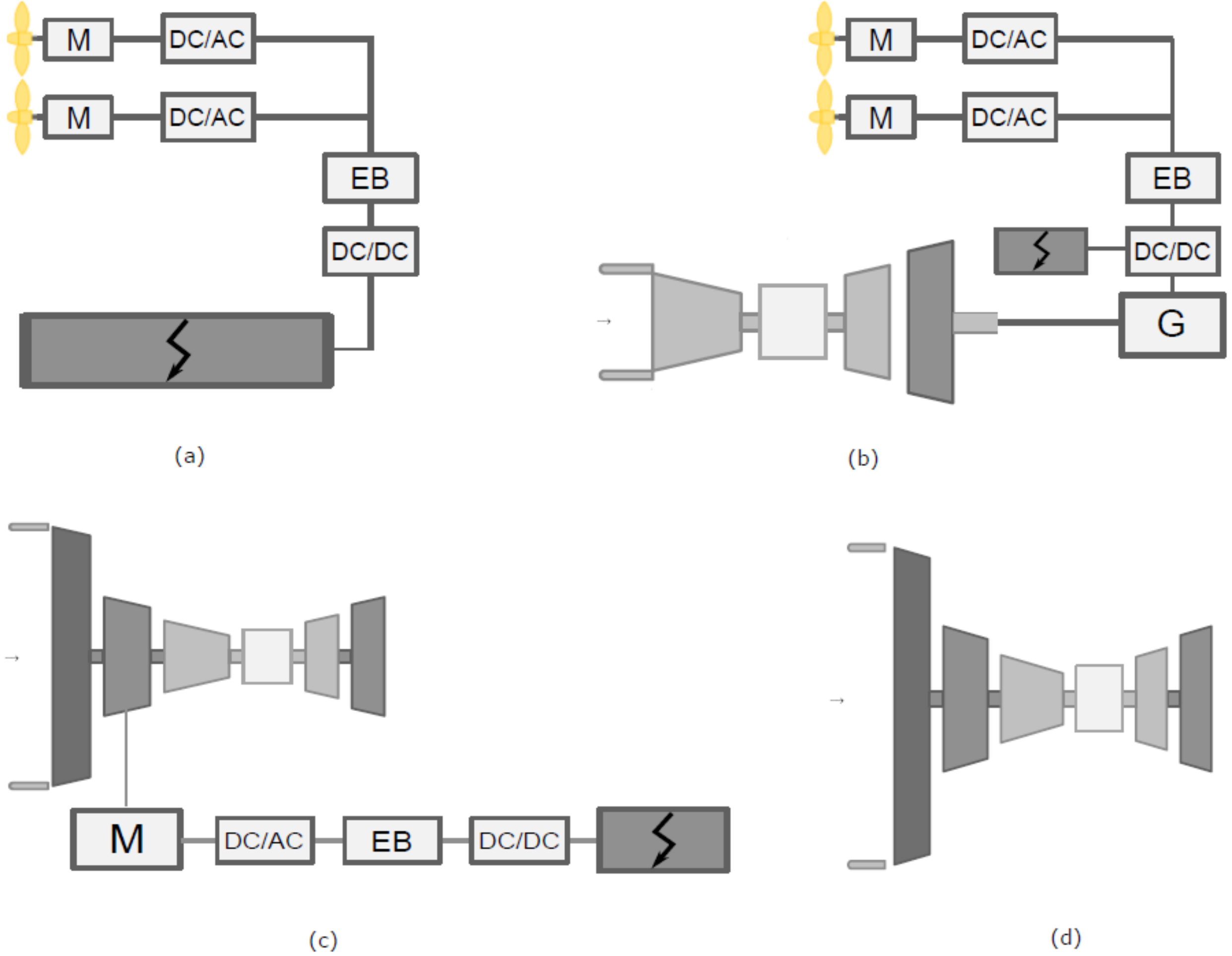
- Conceptual design uses simple network models
  - Simple efficiency values for components
  - Masses implemented by energy/power density

- Simulation of individual components of propulsive network
  - Different design choices per component
  - Investigations in individual component performance
  - Effect of components on overall aircraft design

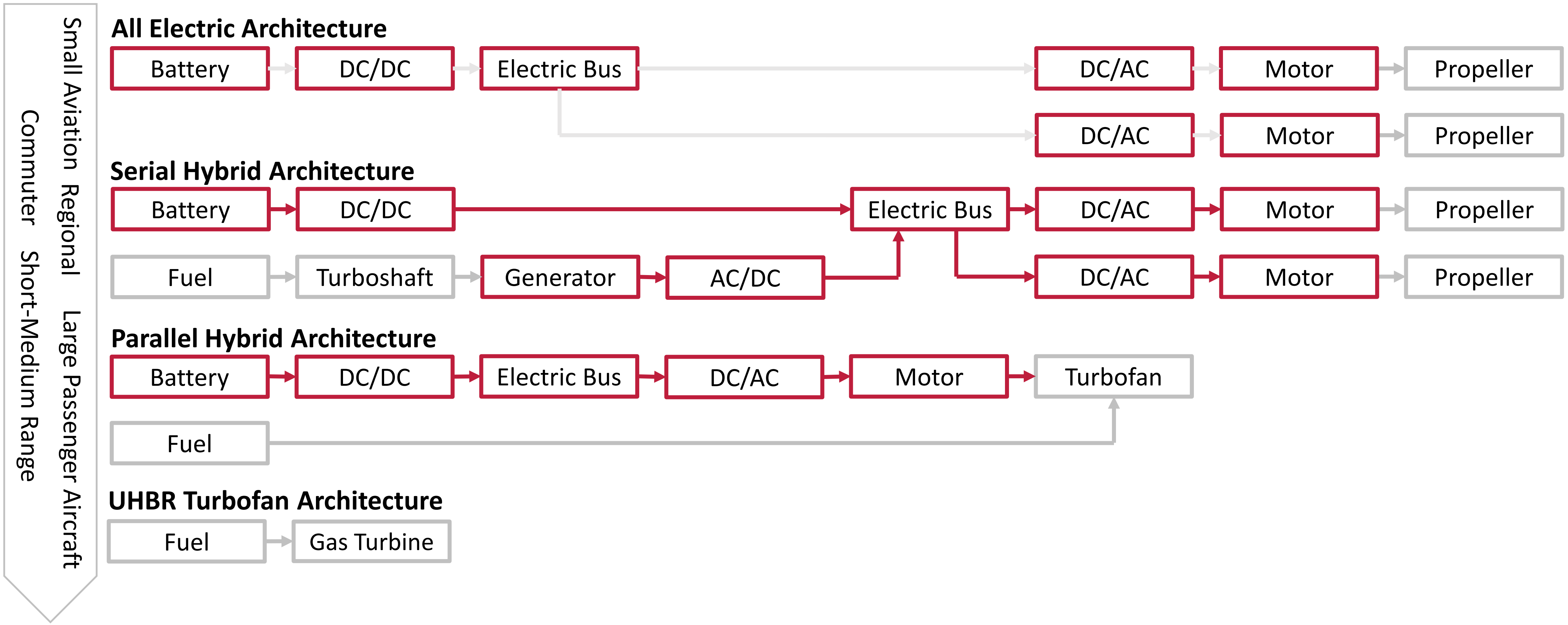
Energy Network Model

Network models

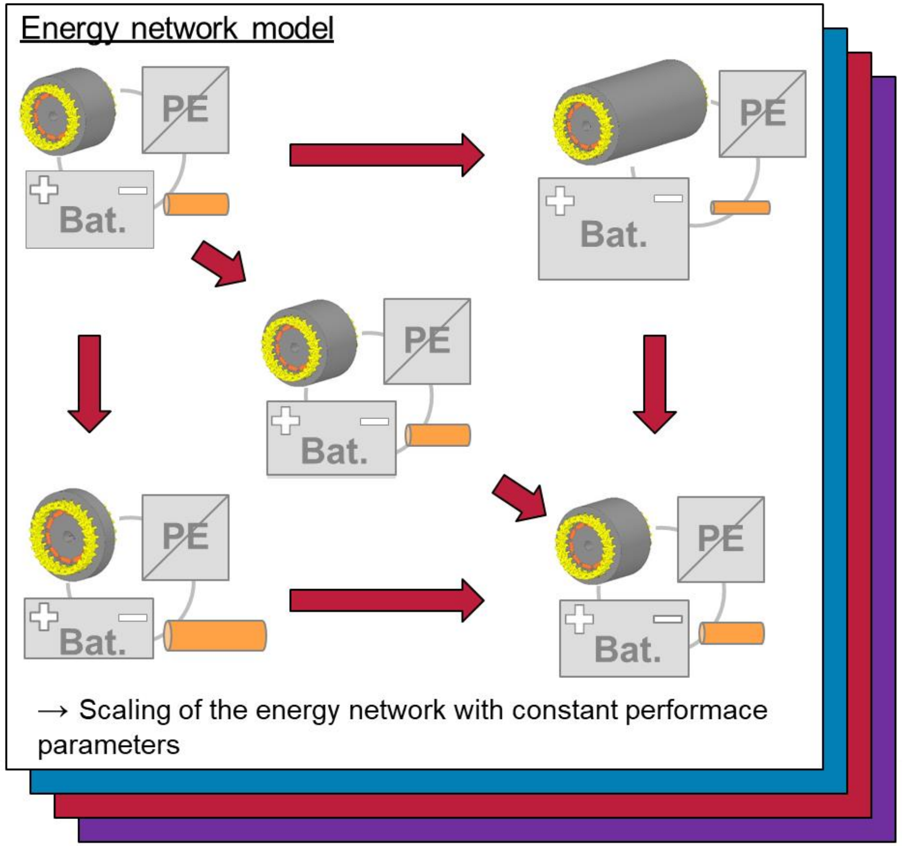
- Full-electric
- Serial-electric
- Parallel-electric
- Turbofan



Energy network architectures



Energy network modelling

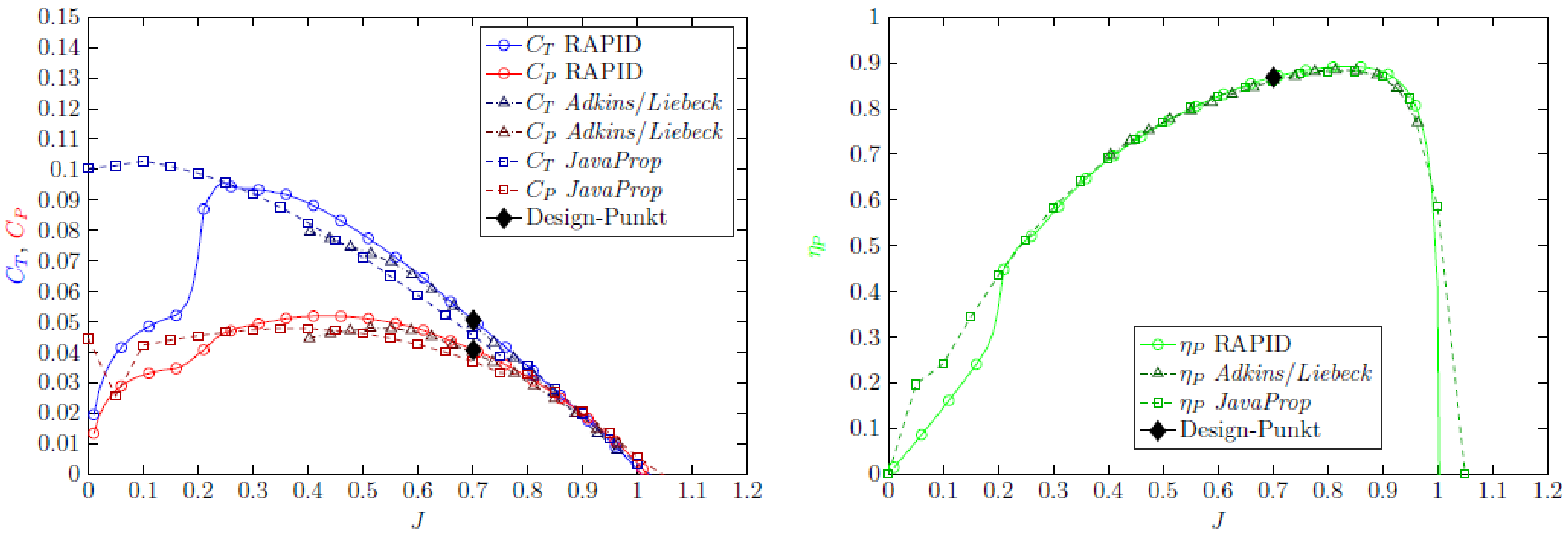


- Every component has multiple 'design choices' that can be selected
- Different energy networks with different technologies/ technology combinations:
  - energy network 2
  - energy network 3
  - energy network 4
- This creates a "catalog" of different energy networks that can be used as inputs for SUAVE optimization.
- No further optimization takes place within the network.

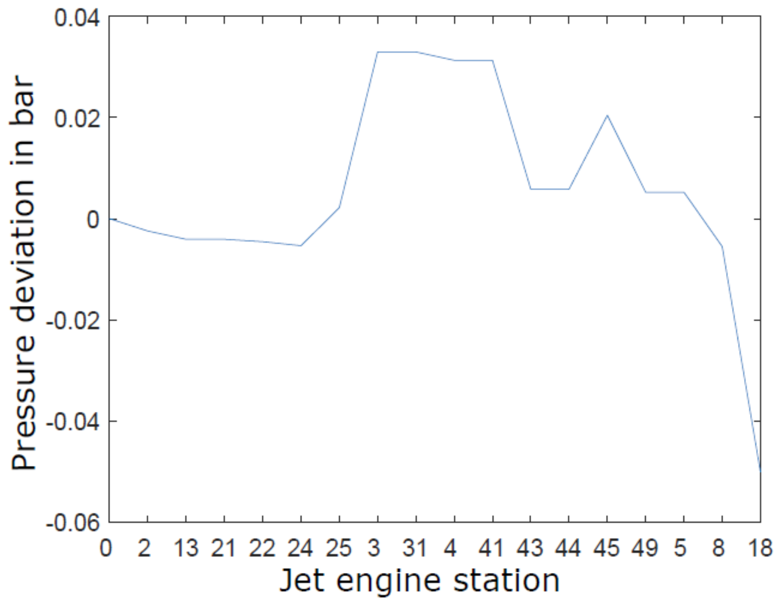
Network design options

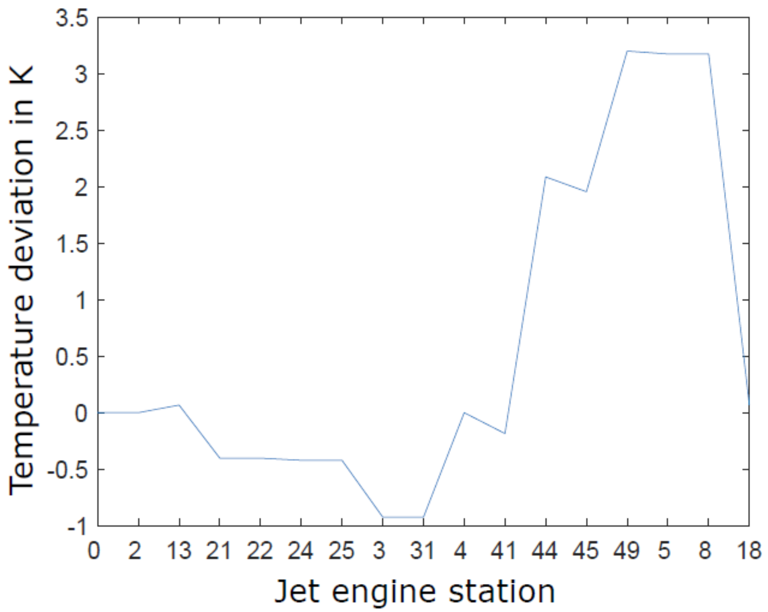
- HVDC
  - Voltage, wiring length, material
- Converter (AC/DC, DC/AC, DC/DC)
  - topology, semiconductor type, switching frequency
- Electrical machine
  - Type (10 different), shape, power
- Propulsor
  - propeller efficiency
  - gas turbine component performance

Verification: Propeller



Verification: Gas turbine





Verification: Electrical machine model

Parameter	HTS machine model	Verification reference data
Power [kW]	3031	3031
Speed [rpm]	4547	4400
Magnetic field [T]	1.5	1.5
Diameter [mm]	350	350
Axial length [mm]	270	269.23
Line current [A/cm]	2083	2000
Gear ratio	1	1

Verification: Network

- DCDC converter
  - 100kW power
  - 100 kHz switching frequency
  - EN-Model: 25 kW/kg
  - Literature: 23 kW/kg

- DCAC inverter
  - 40 kW power
  - SiC 2LC topology
  - EN-Model: 9.5 kW/kg
  - Literature: 10 kW/kg

Energy network model integration

- Replacement of SUAVE internal models
- Significantly higher computational time
  - Turbofan network: 3s vs. 0.015s per evaluation
- Evaluation time significantly varies with concept

➢ Improvements in runtime implemented

Optimisation

Optimisation requirements

- Global optimiser

- Expensive objective function
  - Low number of evaluations

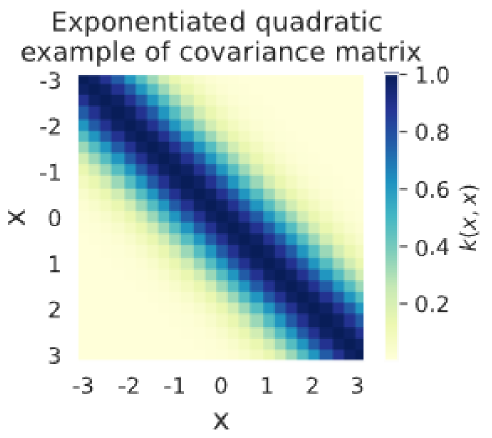
- SUAVE optimisation options limited
  - Gradient based / local optimiser
  - Very limited global optimisation

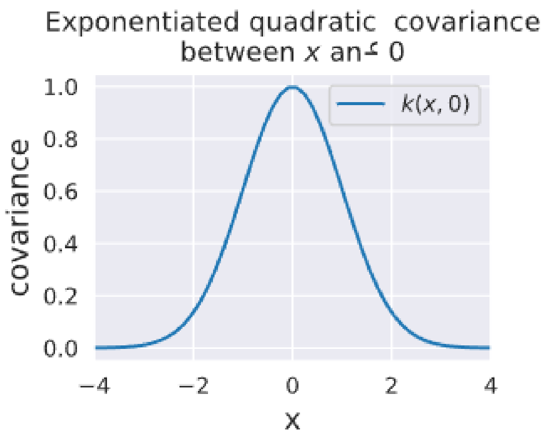
➢ Efficient exploration of the design space
  - ➢ Surrogate modeling approach
  - ➢ Gaussian Processes

The optimisation approach

- Surrogate modeling of the mission analysis tool and constraint functions
  - Machine learning approach: Gaussian process
  - Can be initialised with few sample points (reducing computational time)

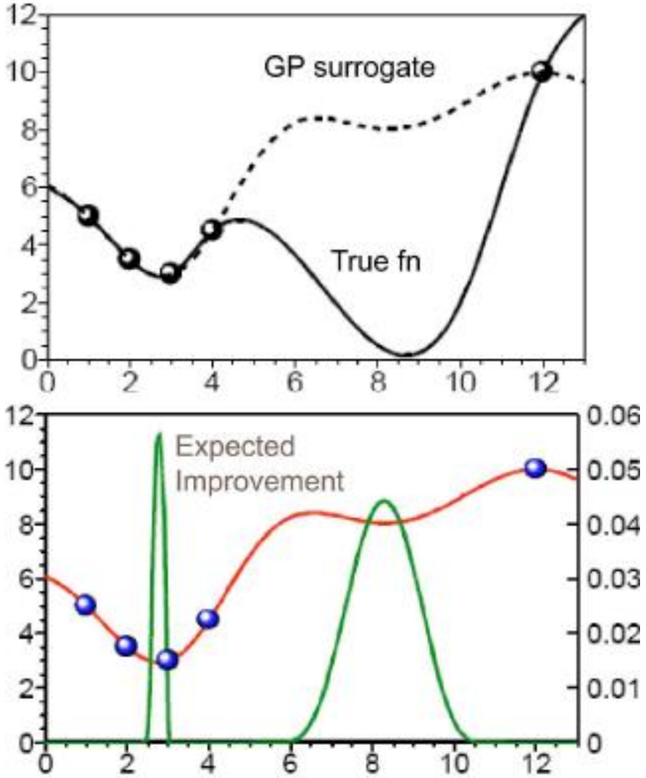
- Gaussian Process
  - Distribution over functions
  - Defined by mean and covariance matrix
  - Analytical model of the design space





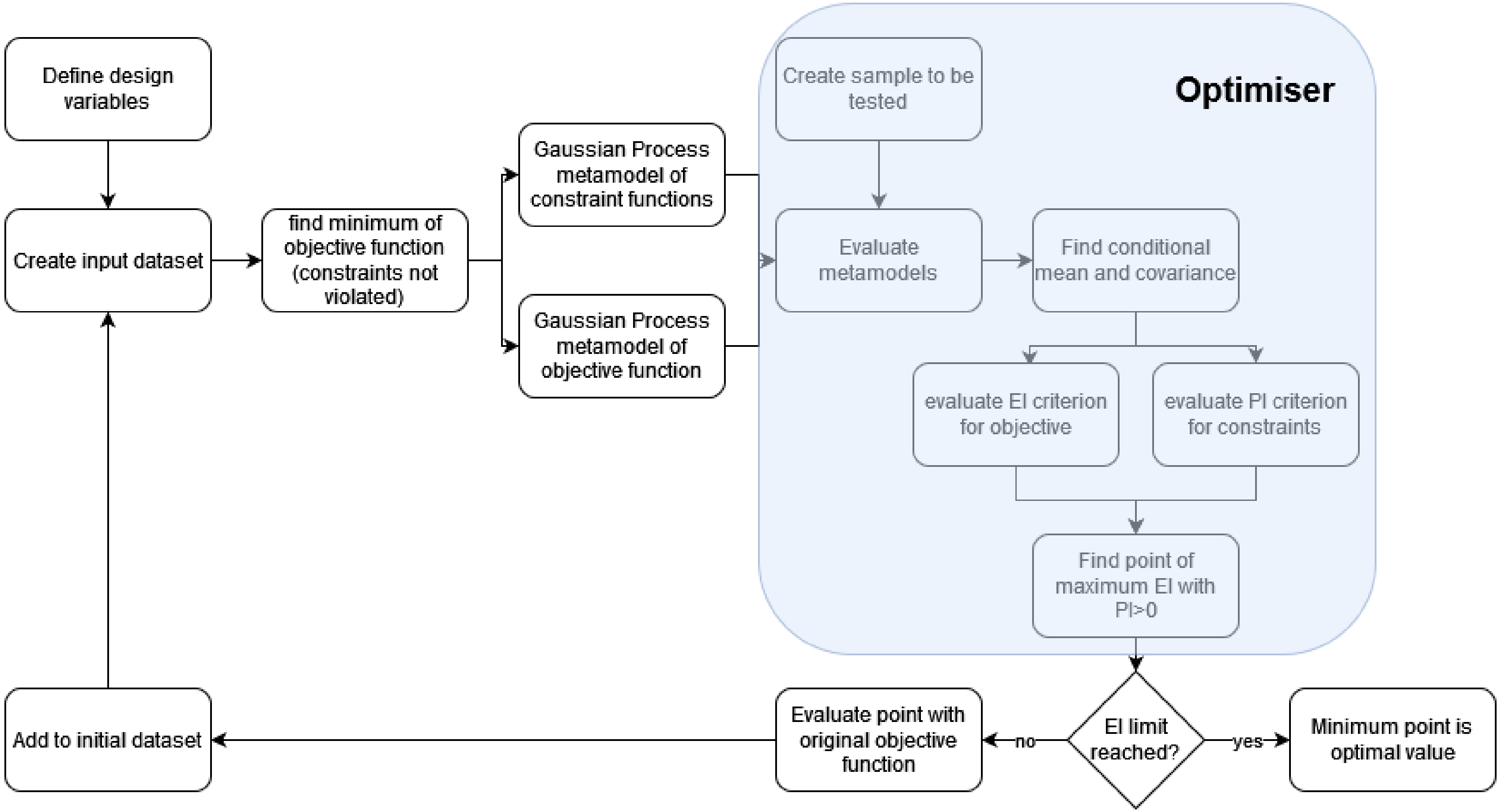
Efficient Global Optimisation

- Infill criterion to refine metamodel
- Expected Improvement (EI)
  - Utilisation of both variance and mean
  - Expected new value to be lowest
- Similar implementation of constraints
  - Expected violation (PI) of true constraint boundary
- New point maximum of EI*PI

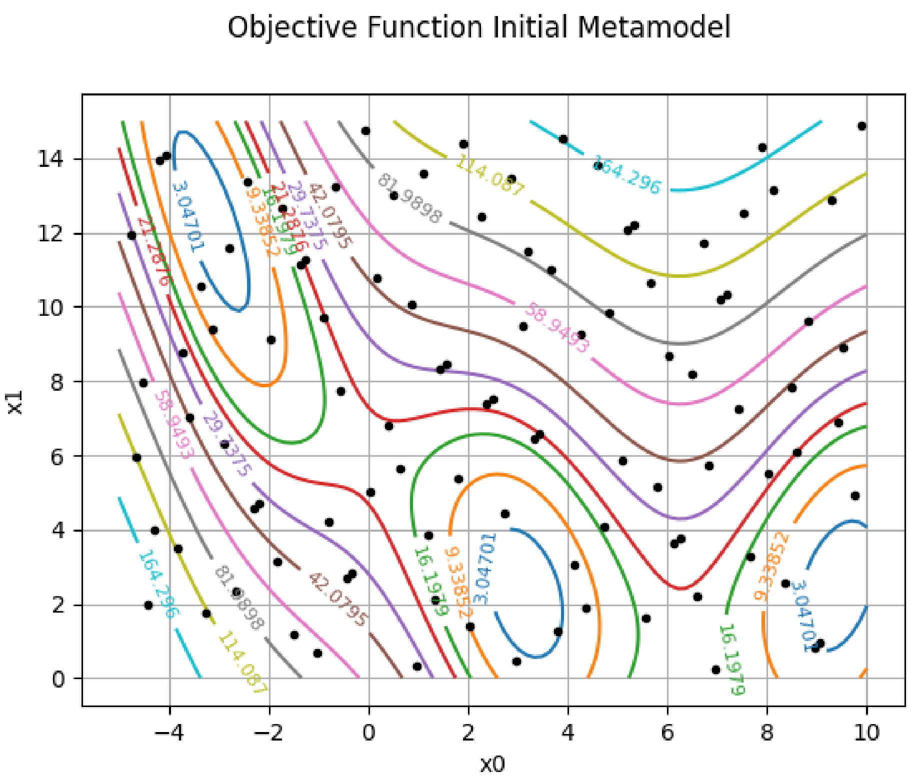


From Jones, Schonlau, Welch, 1998

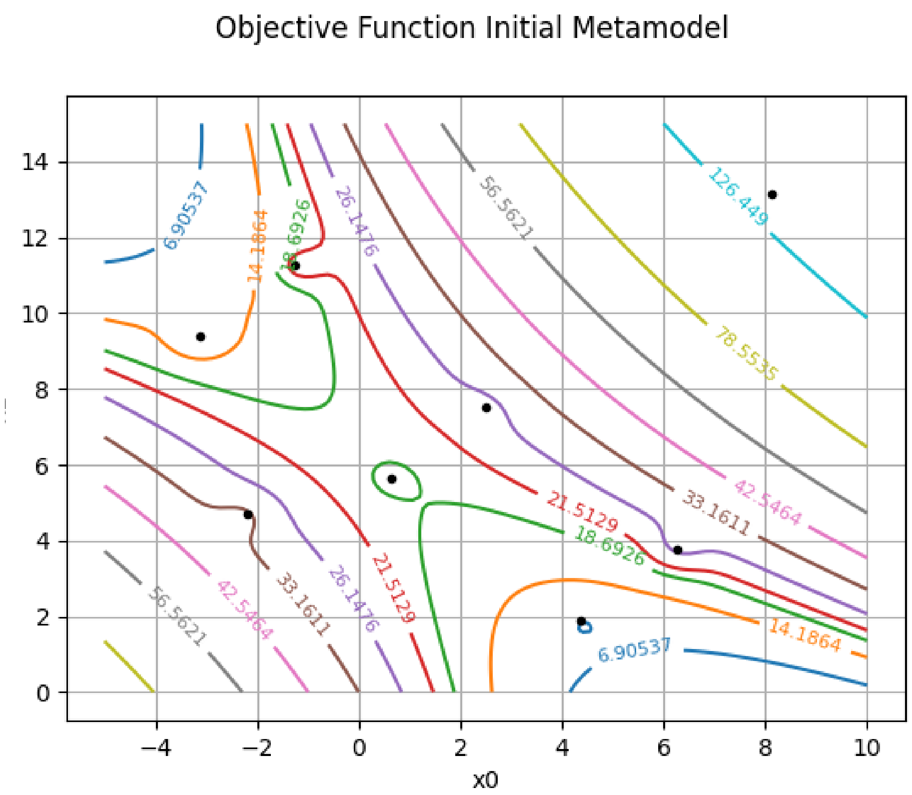
EGO optimisation process



Example: Branin-Hoo – Initial model



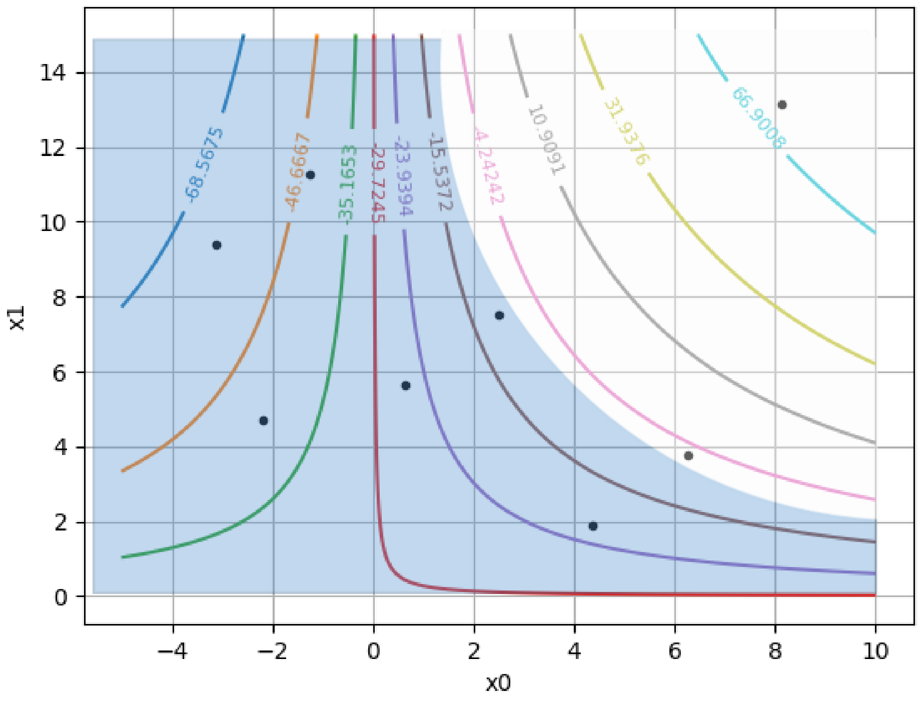
200 initial points



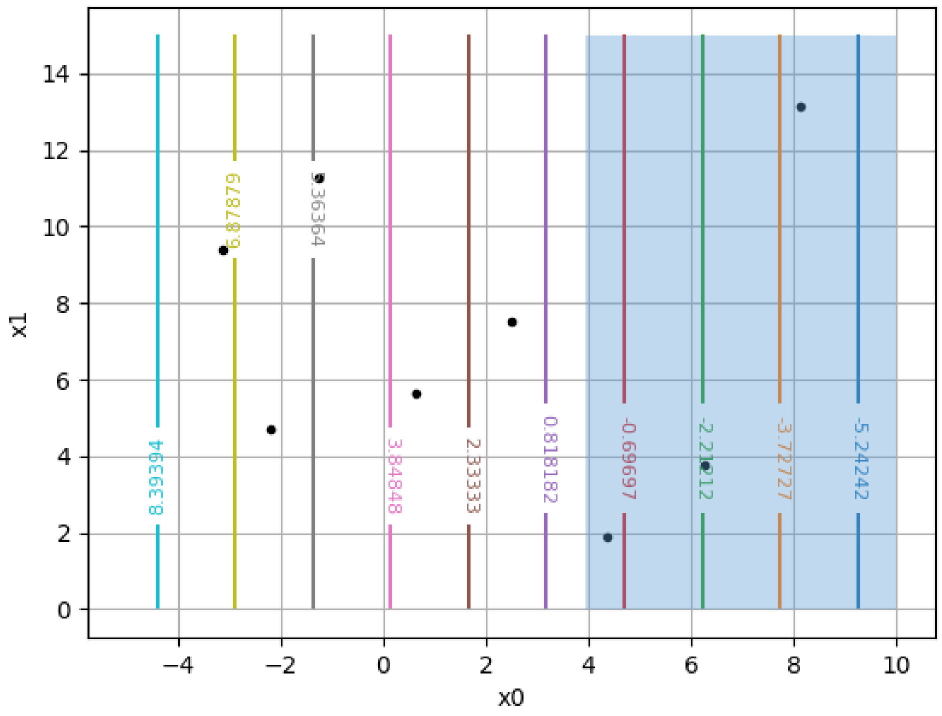
8 initial points

Example: Branin-Hoo – Constraints

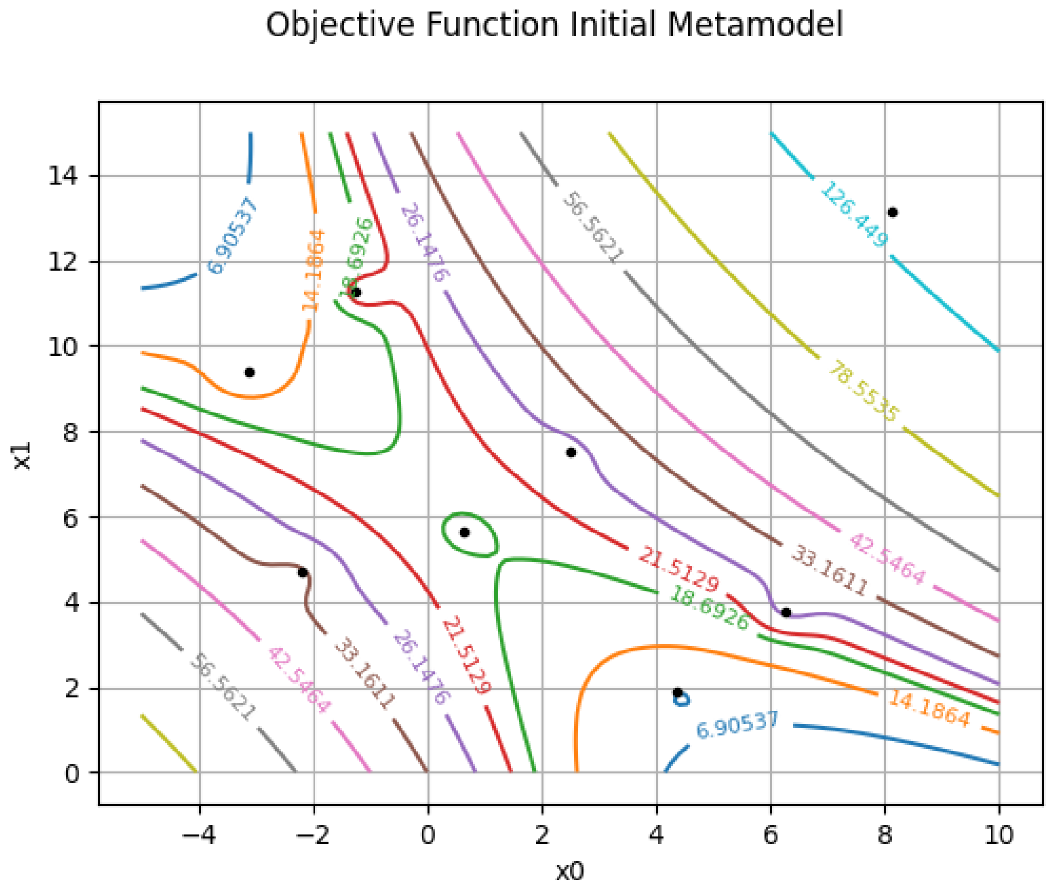
Constraint 1 Initial Metamodel



Constraint 4 Initial Metamodel

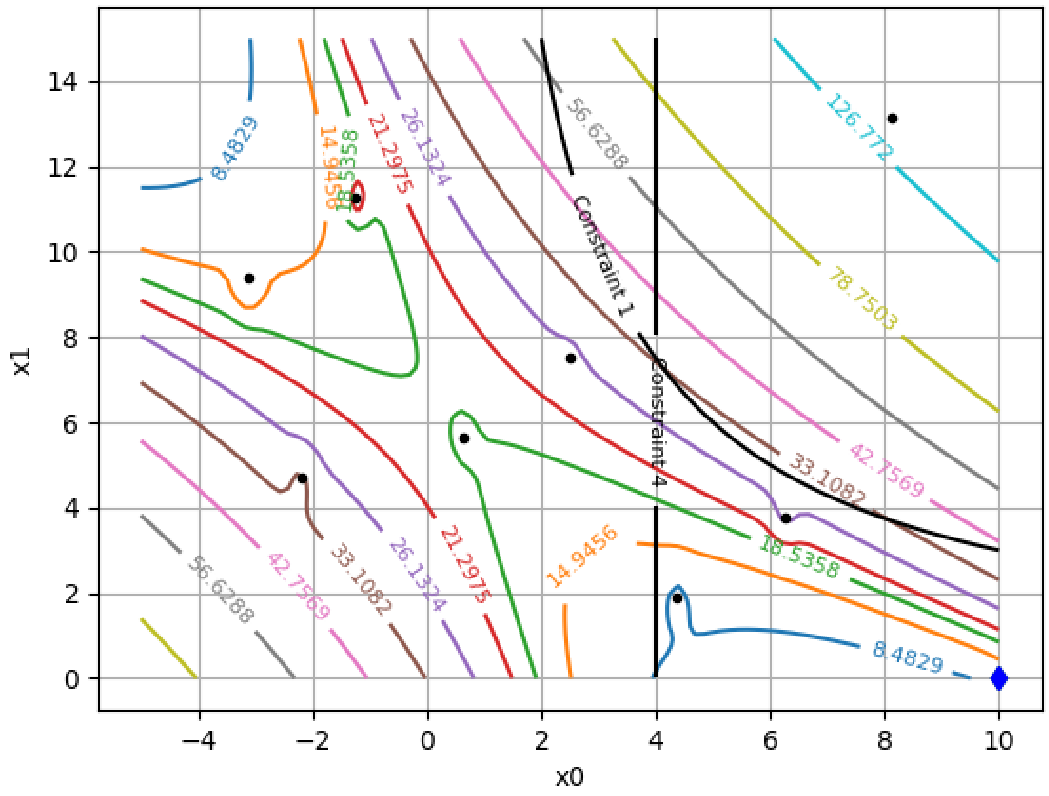


EGO optimisation – 8 point initial

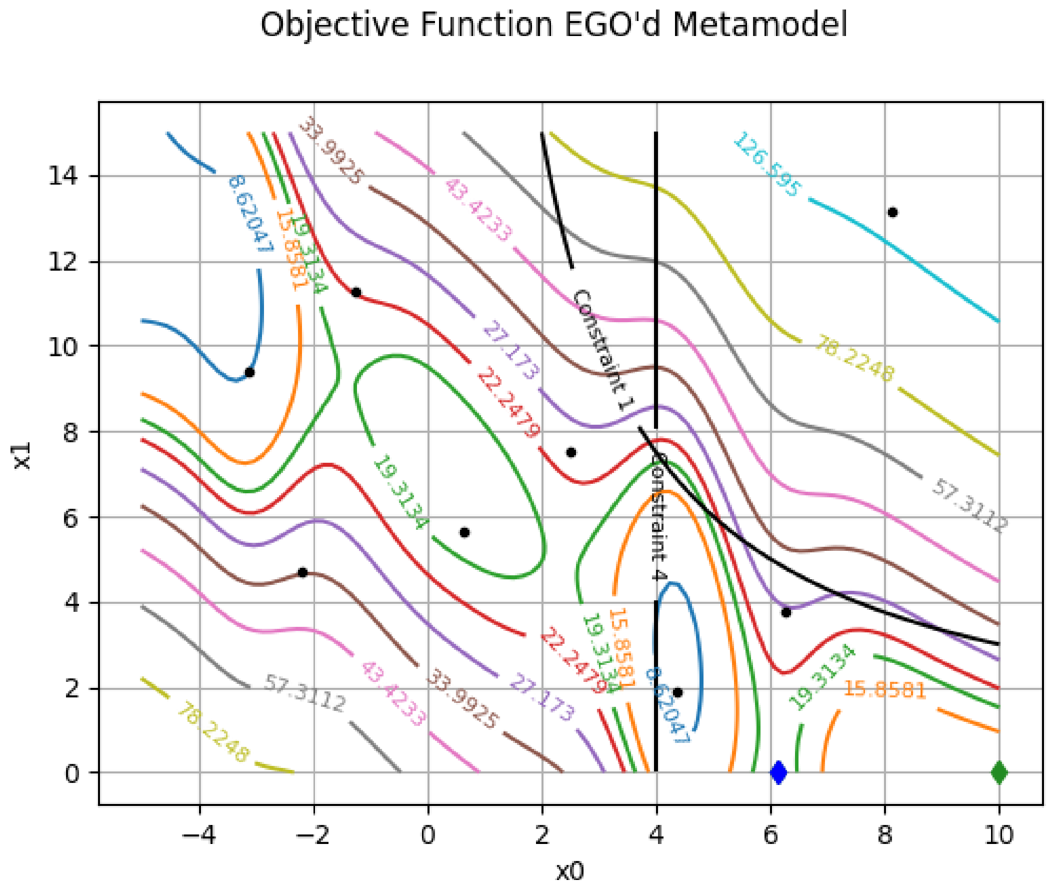


EGO optimisation – 1 additional point

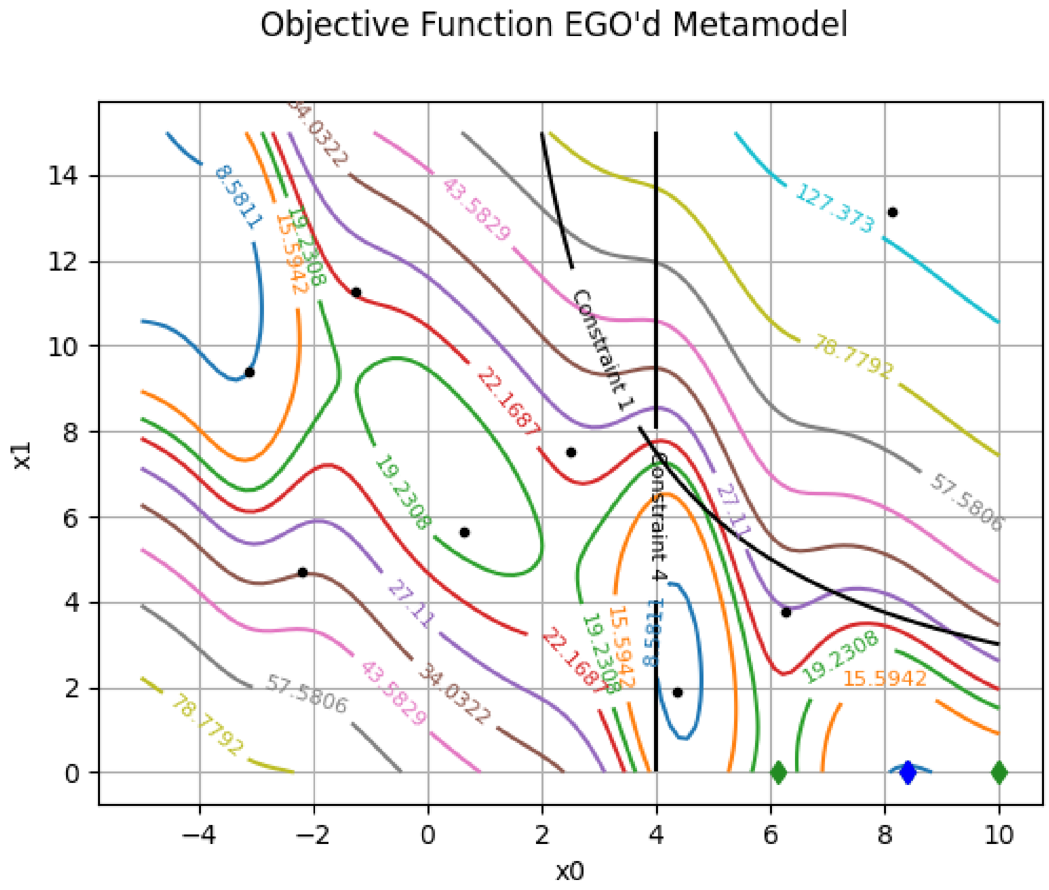
Objective Function EGO'd Metamodel



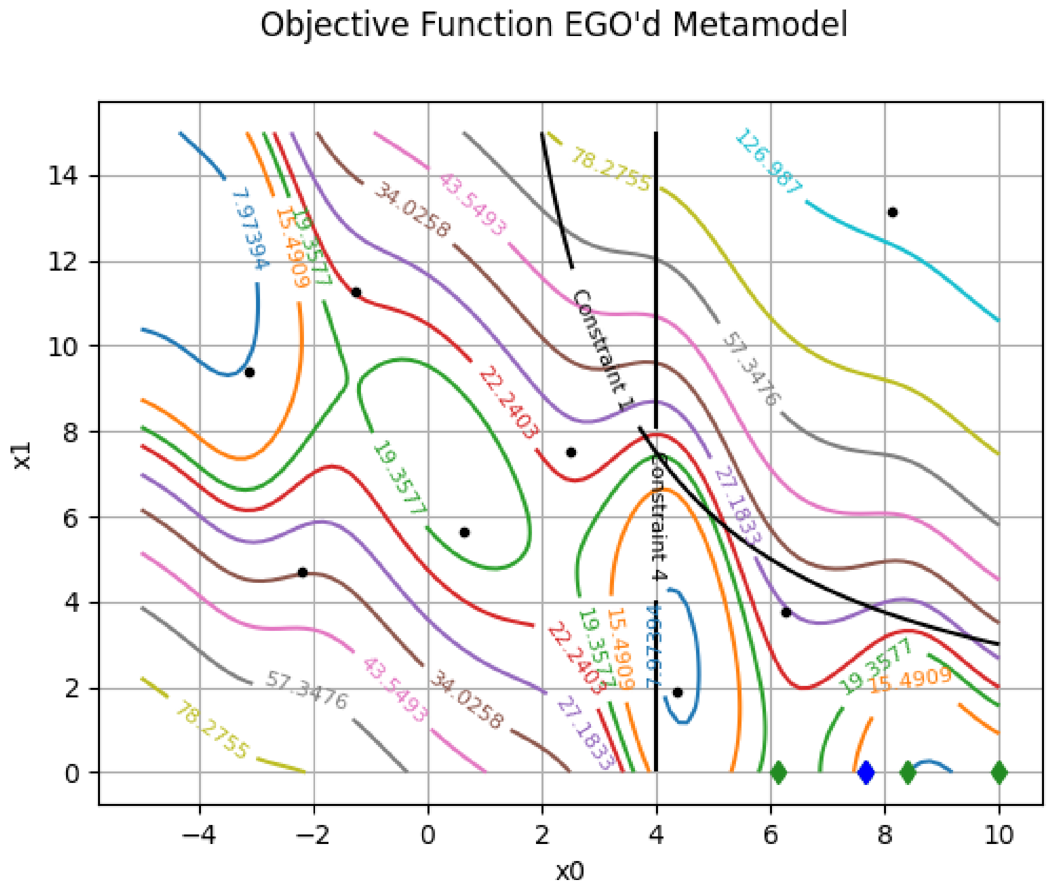
EGO optimisation – 2 additional points



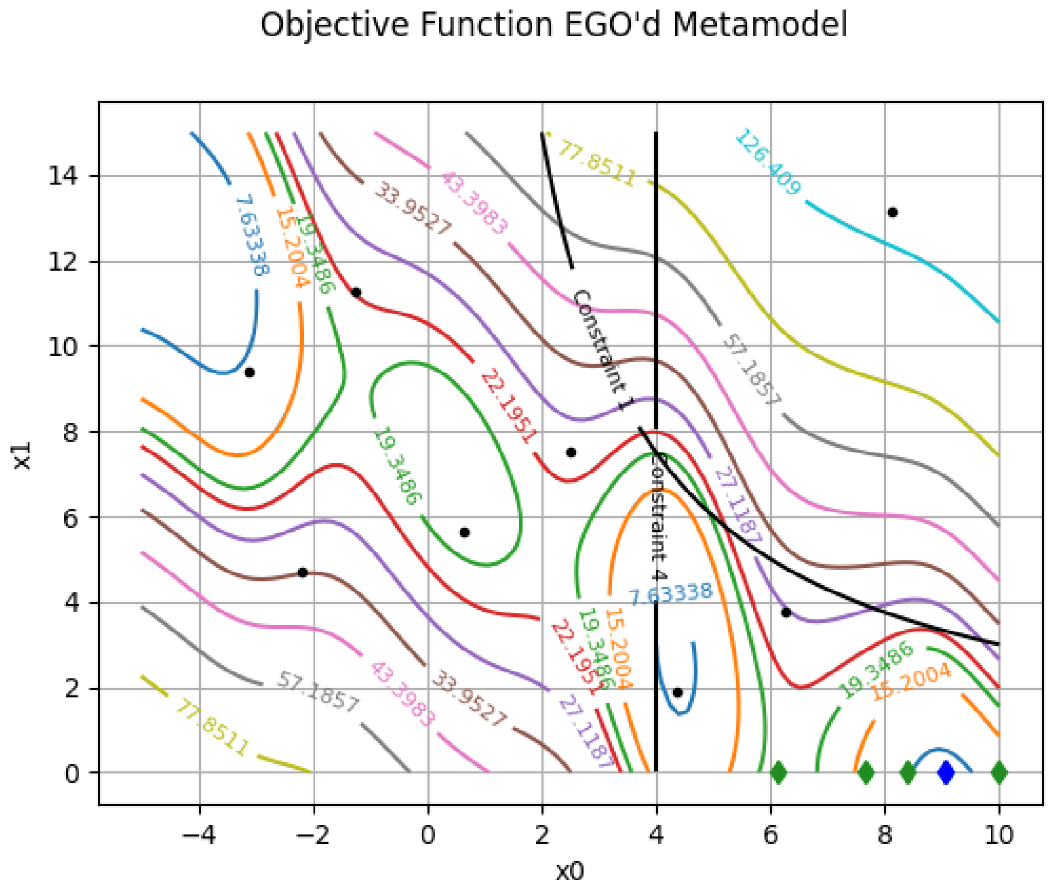
EGO optimisation – 3 additional points



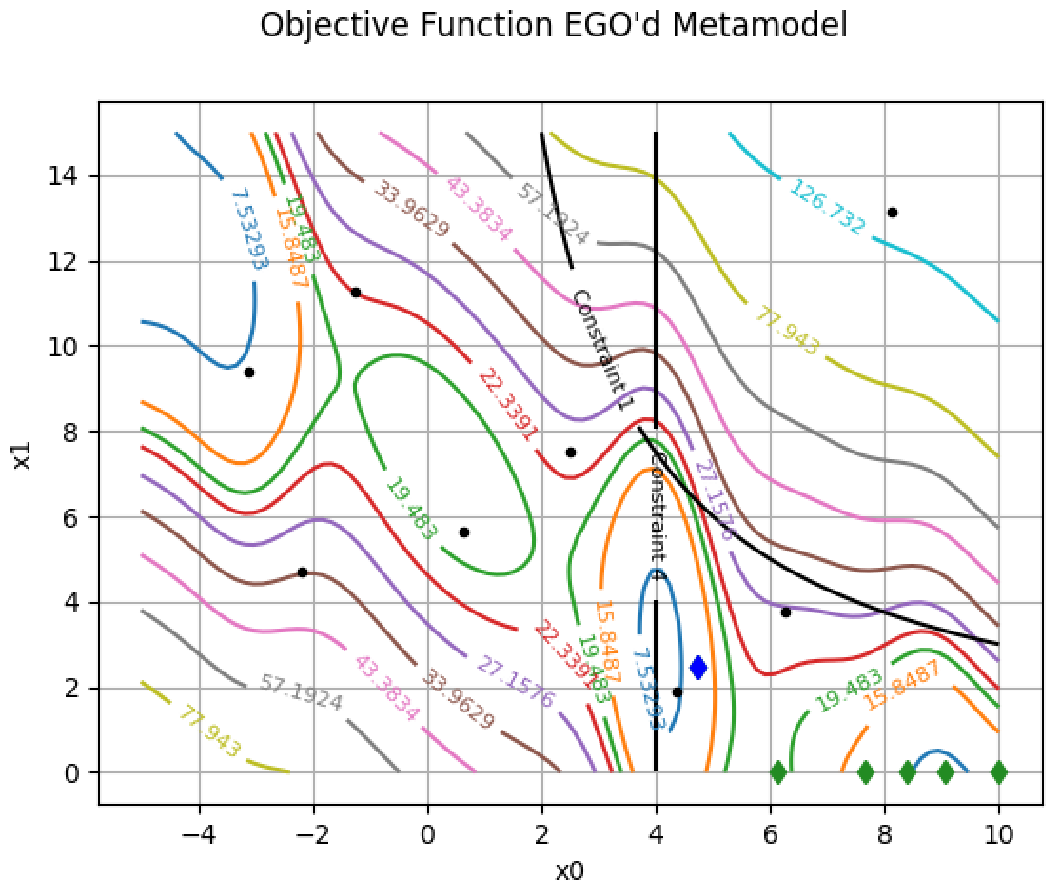
EGO optimisation – 4 additional points



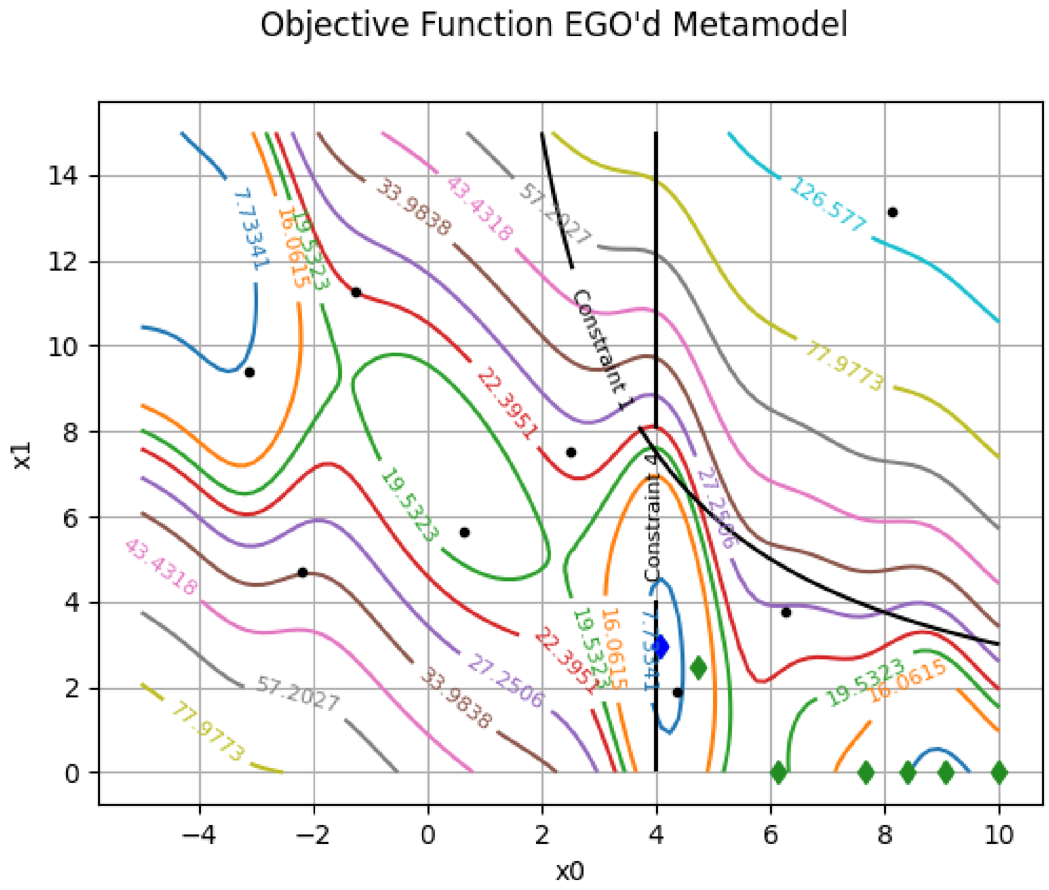
EGO optimisation – 5 additional points



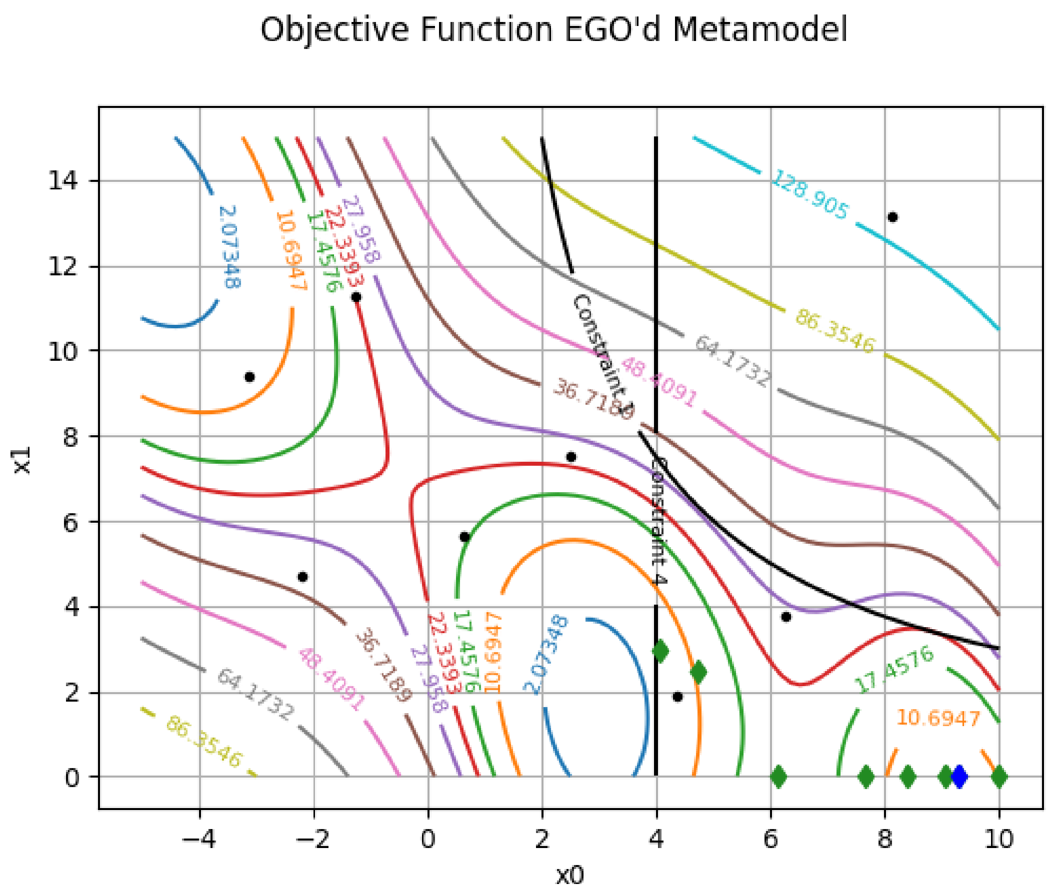
EGO optimisation – 6 additional points



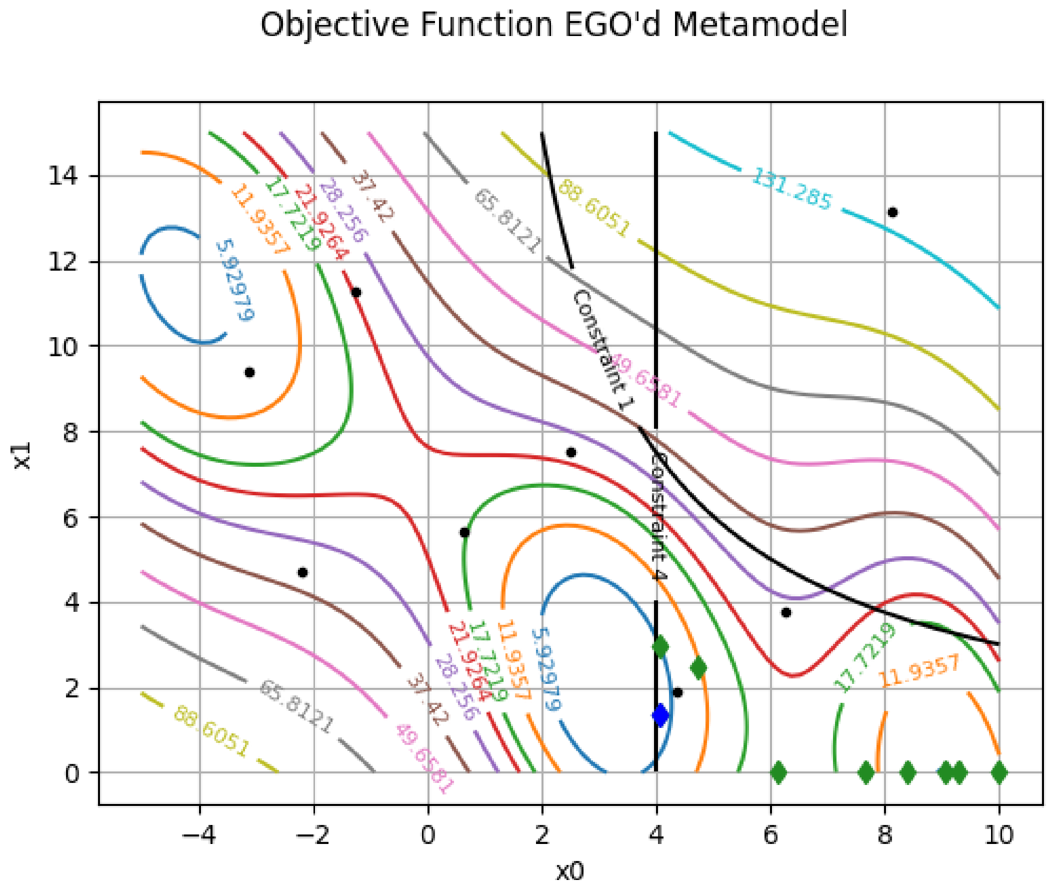
EGO optimisation – 7 additional points



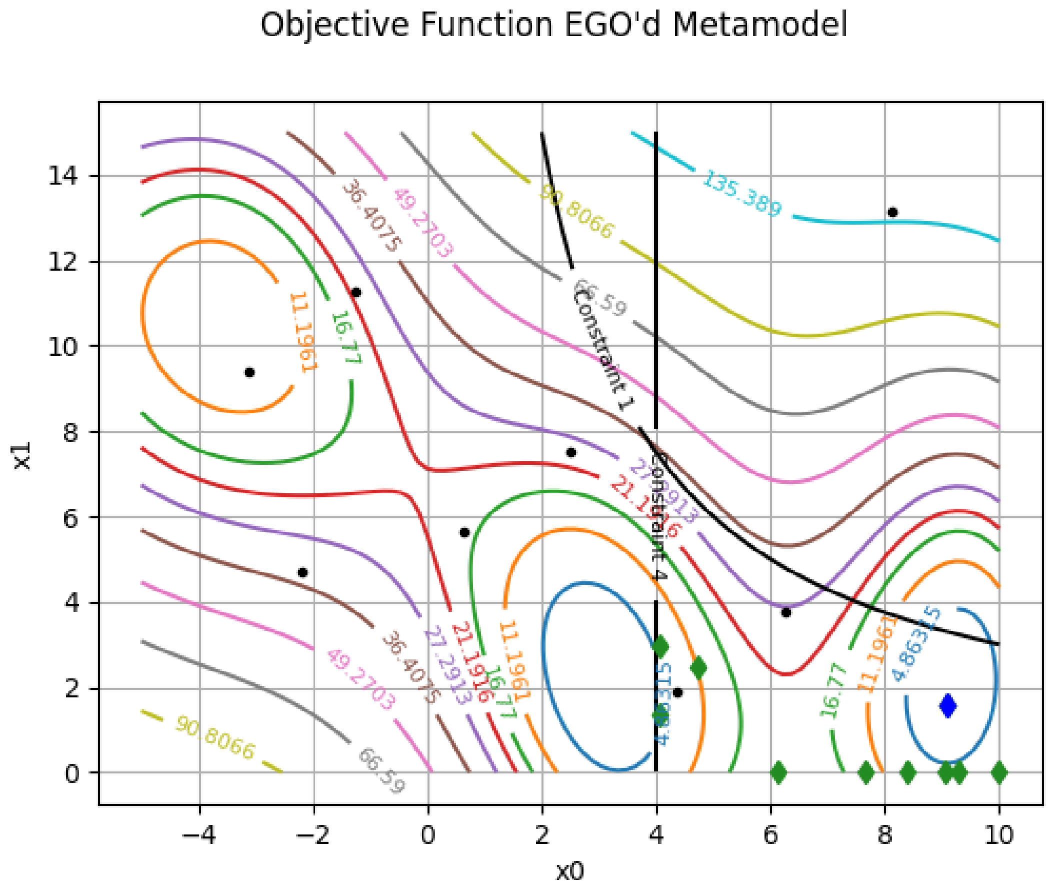
EGO optimisation – 8 additional points



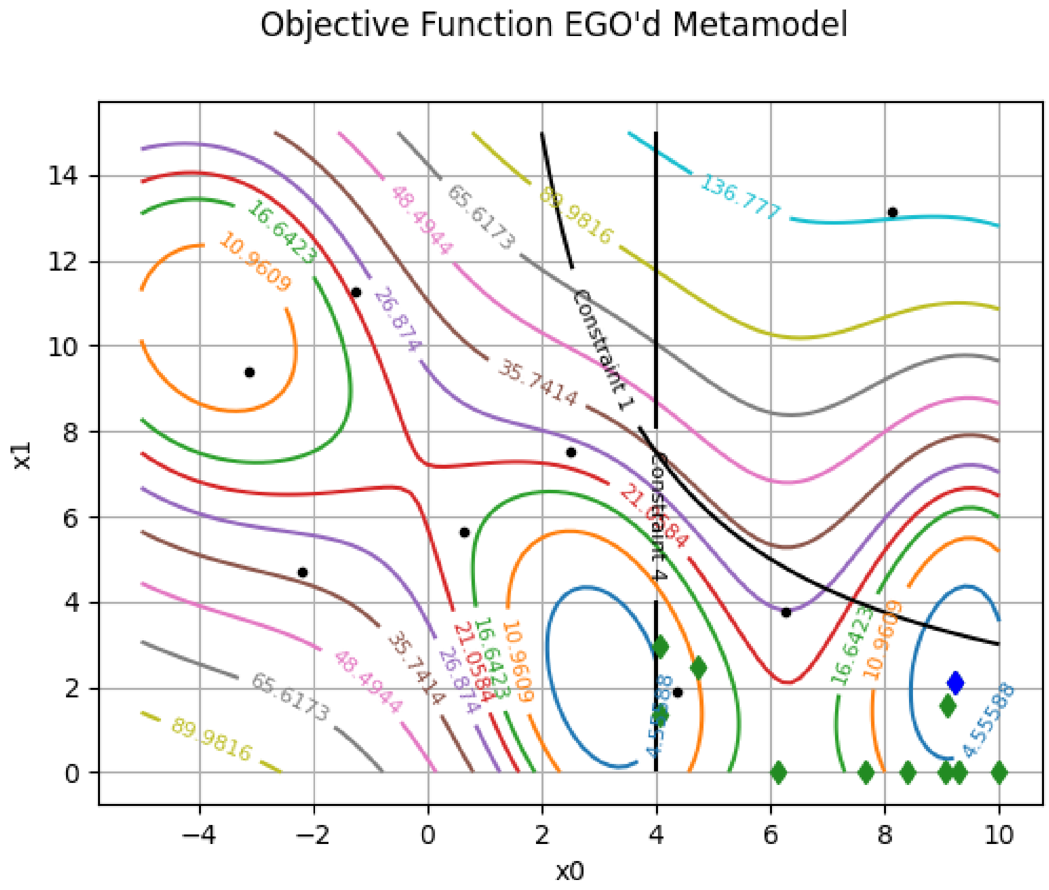
EGO optimisation – 9 additional points



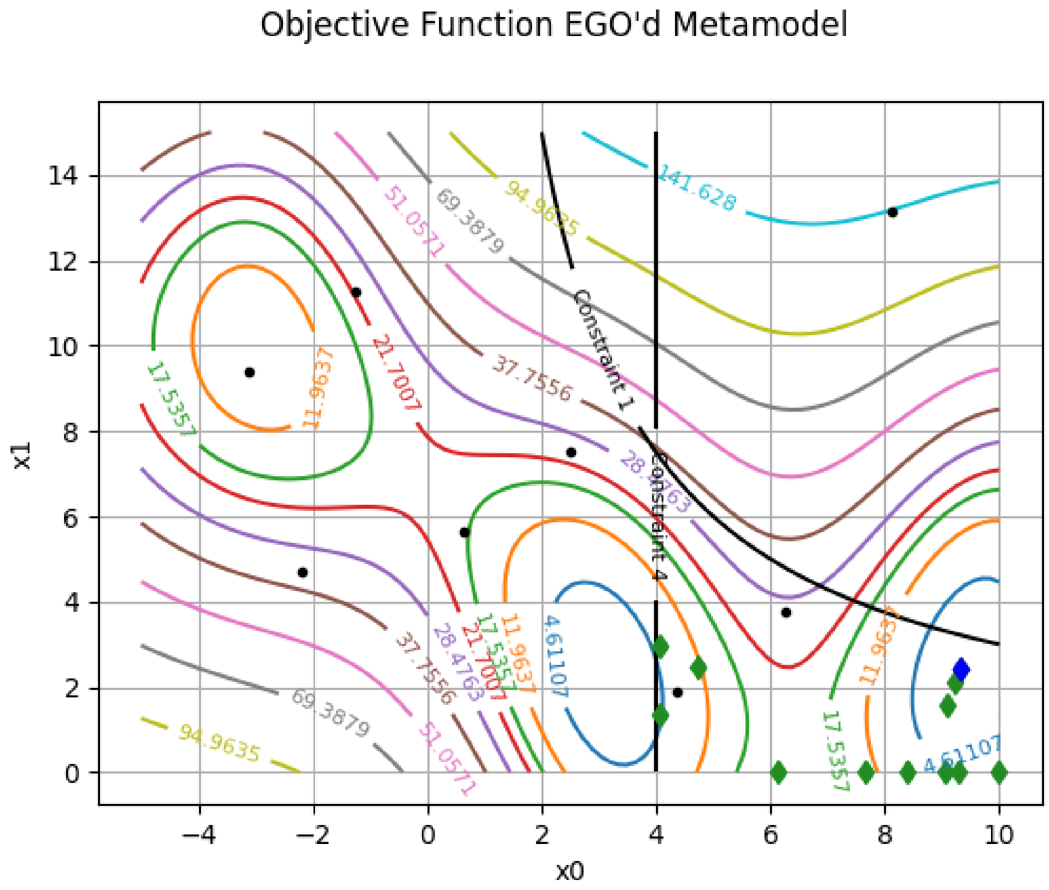
EGO optimisation – 10 additional points



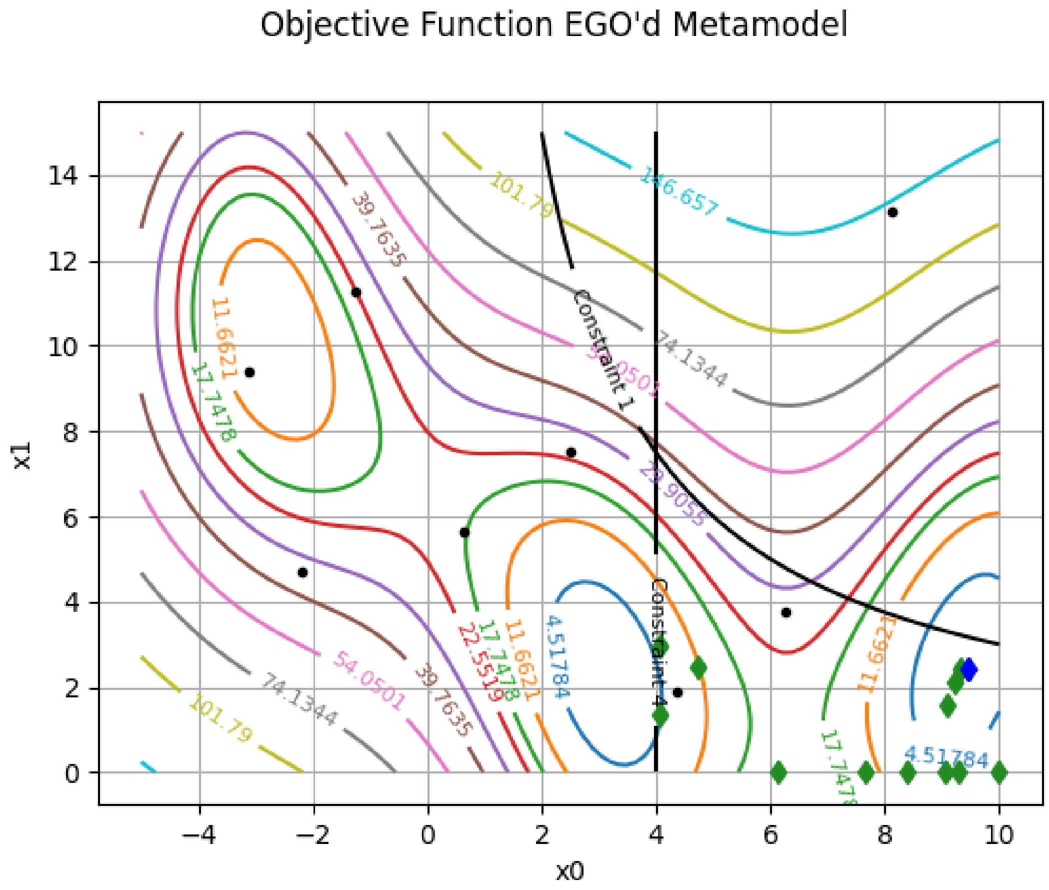
EGO optimisation – 11 additional points



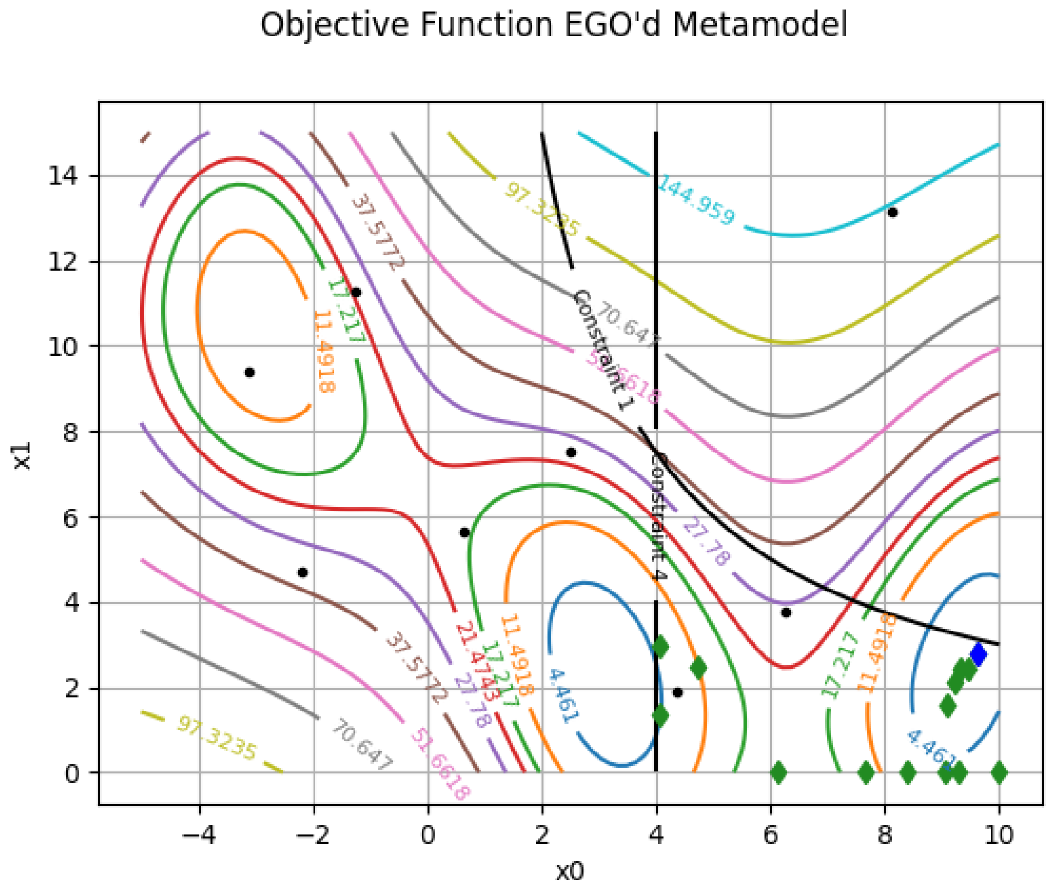
EGO optimisation – 12 additional points



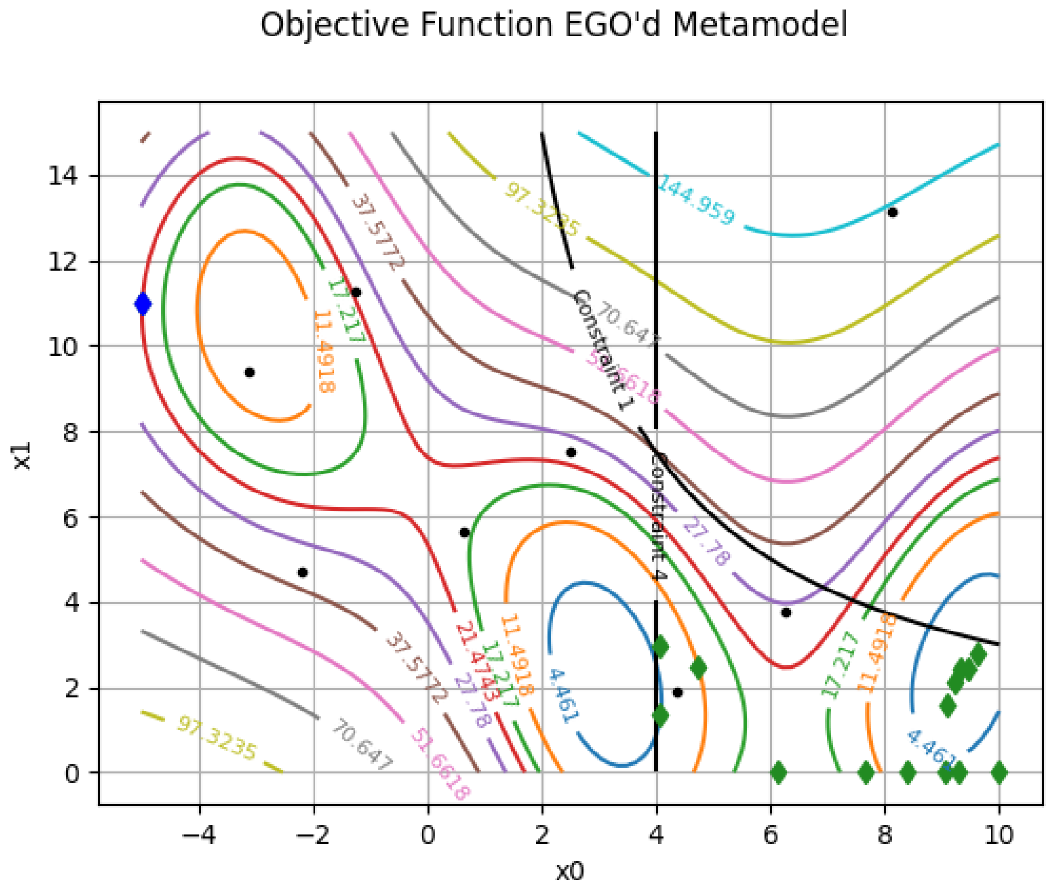
EGO optimisation – 13 additional points



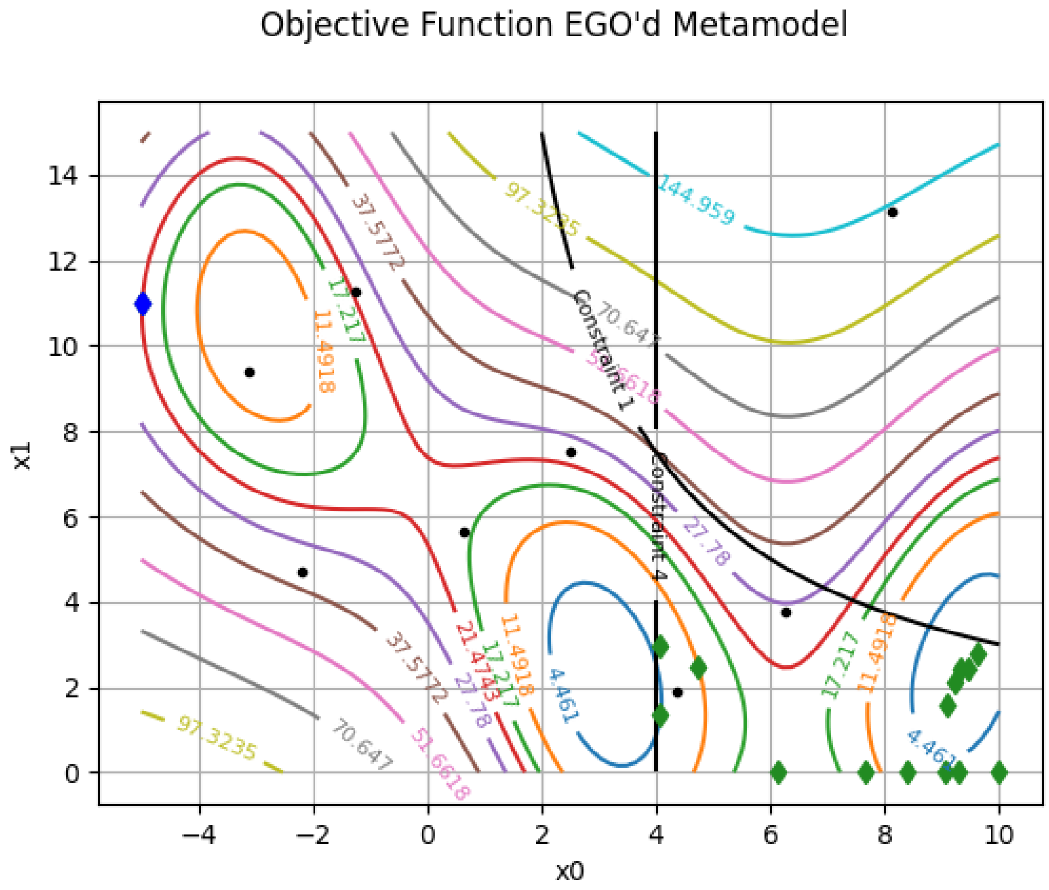
EGO optimisation – 14 additional points



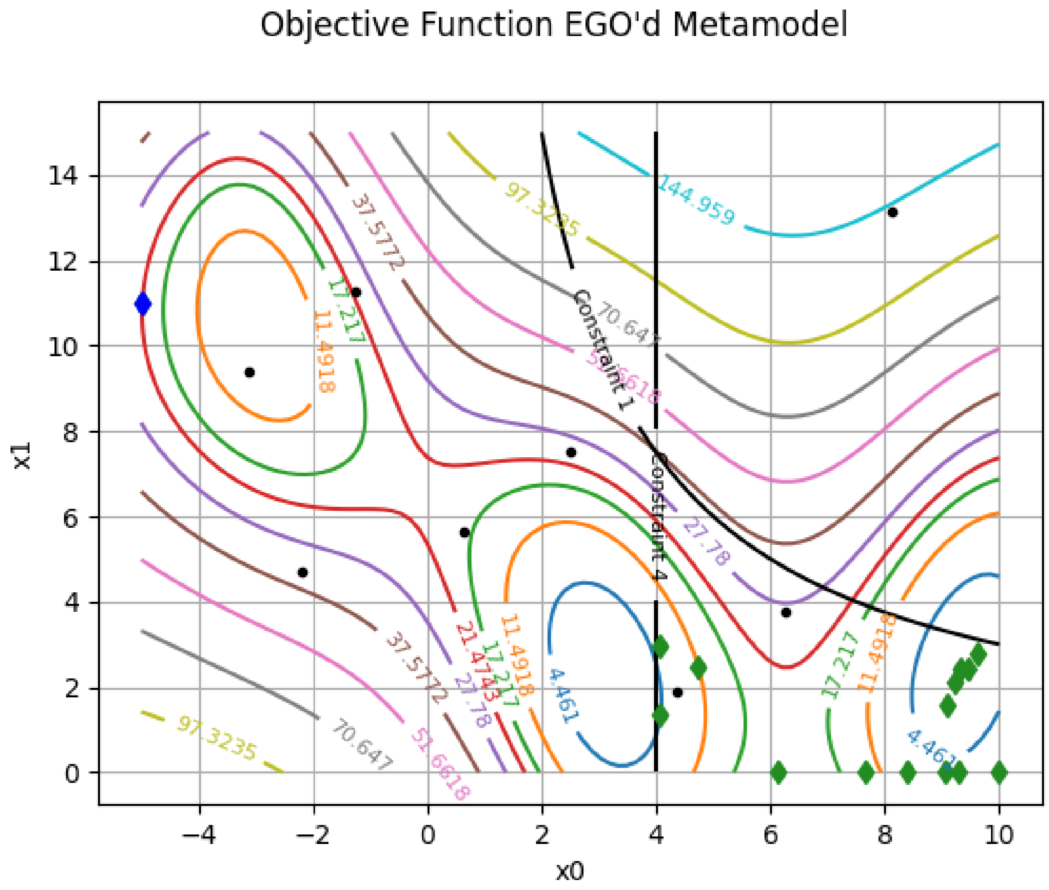
EGO optimisation – 15 additional points



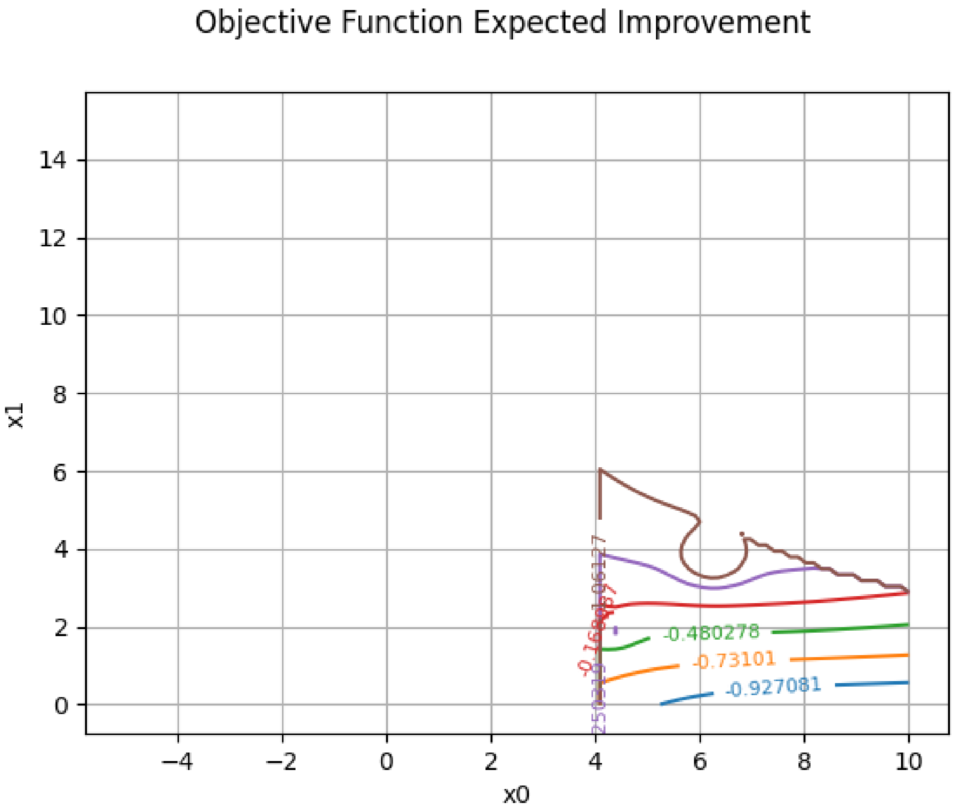
EGO optimisation – 16 additional points

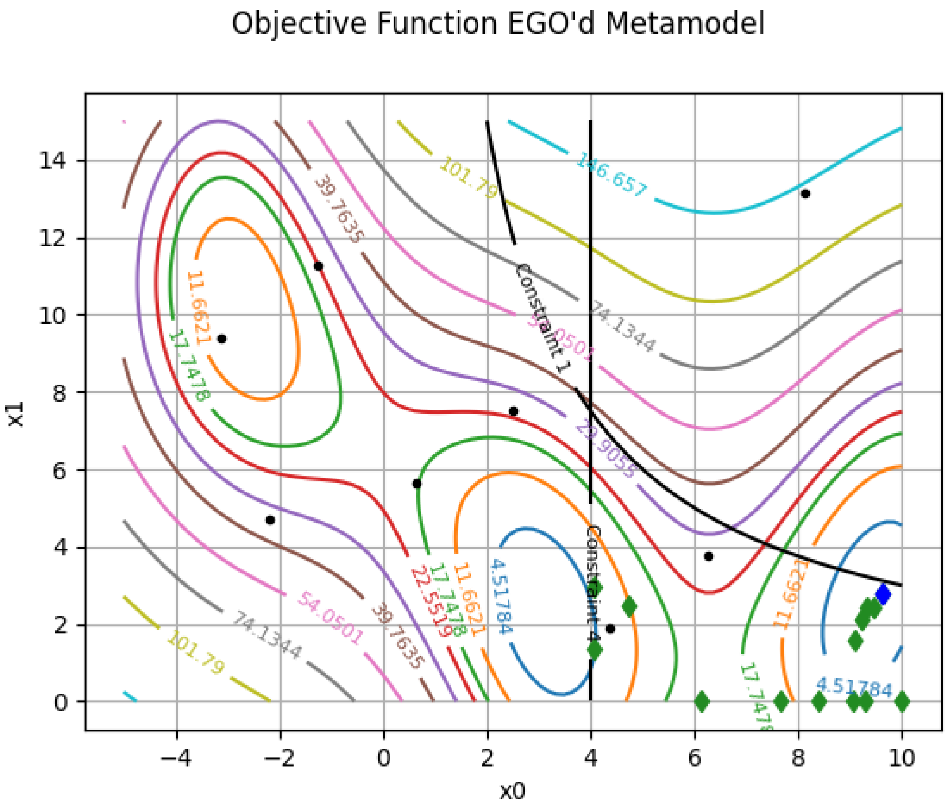


EGO optimisation – 17 additional points



Example: Branin-Hoo - Results

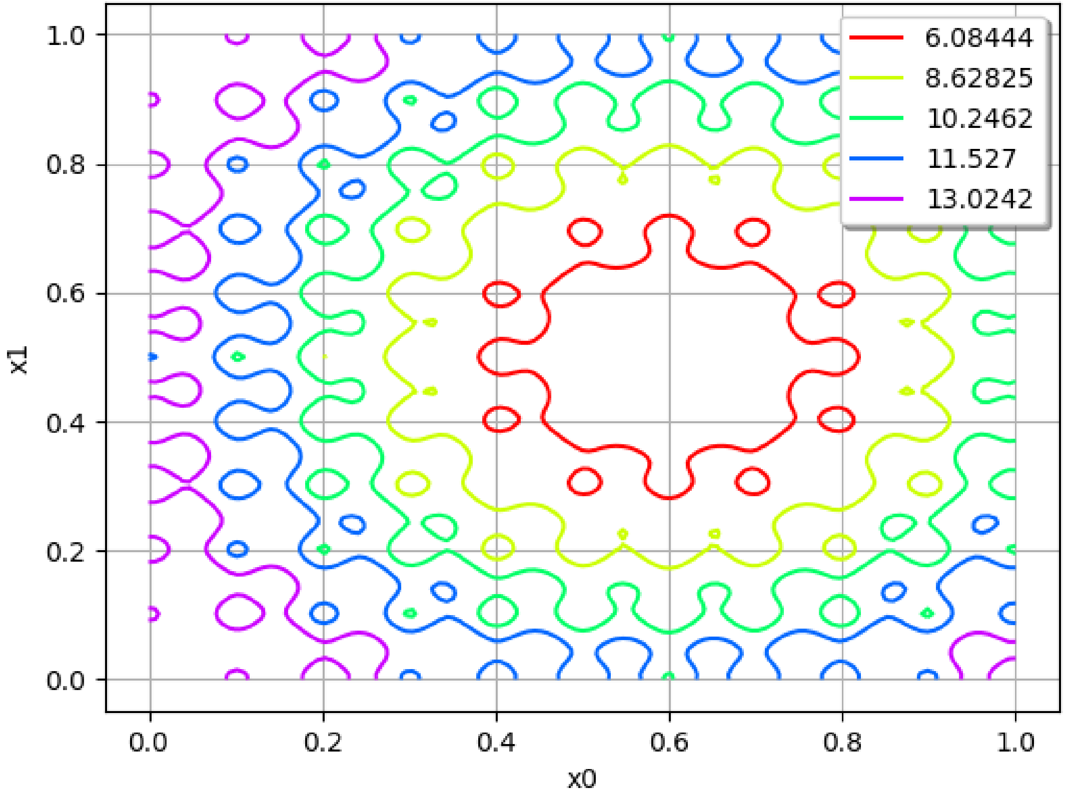


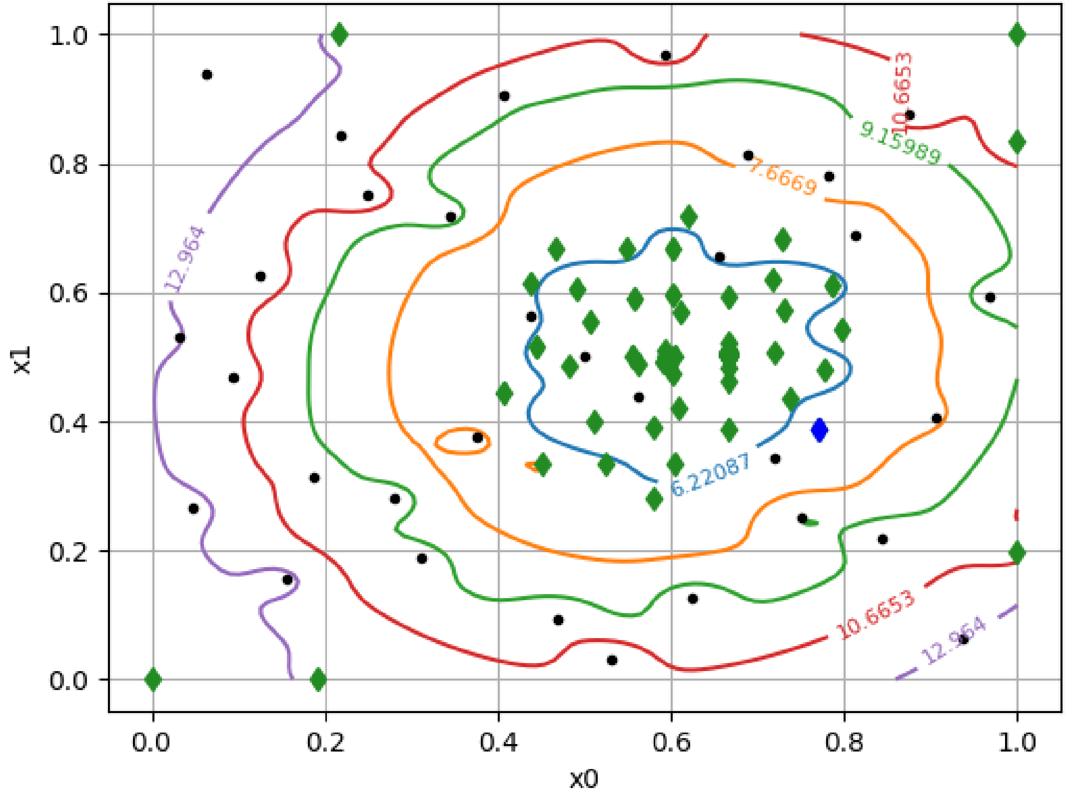


True: $x0_{opt}$=9.424 $x1_{opt}$=2.475 y_{opt}=0.397887

Optim: $x0_{opt}$=9.424 $x1_{opt}$=2.475 y_{opt}=0.397887

Global optimisation: Ackley function





True: $x0_{opt}=0.6$ $x1_{opt}=0.5$ $y_{opt}=0$

Optim: $x0_{opt}=0.6$ $x1_{opt}=0.5$ $y_{opt}=0.00$

Verification in SUAVE

Integration into SUAVE

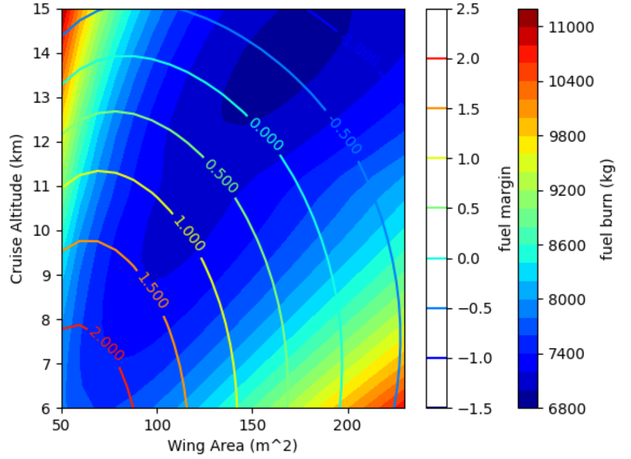
- SUAVE itself offers methods for optimisation
  - Big advantage: compilation only has to be performed once (30s)

- Full constrained EGO implemented as additional optimisation option
  - Advantage for project: full control over every part of the optimiser
    → No ‚black box' as pre-made functions would provide

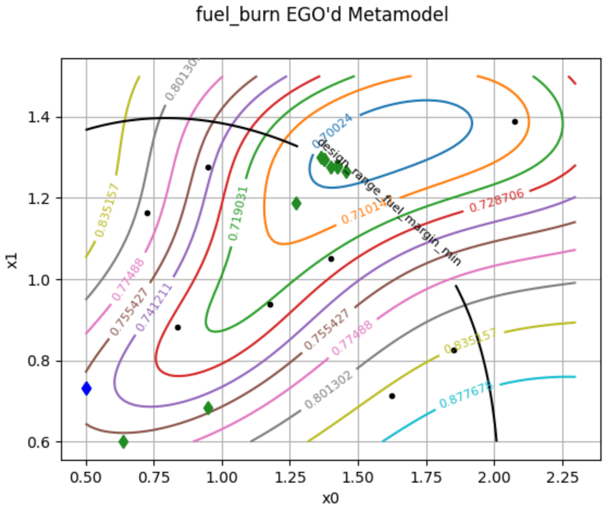
→ <u>Optimisation method and SUAVE implementation can be evaluated independently</u>

Verification: EGO optimisation

- Based on E190 regional jet
  - Simulation of a full mission with multiple segments
  - Design variables: cruise altitude and wing area
  - Constraint: fuel margin



- Performance:
  - SUAVE : time – 152 s, obj – 7283 kg
  - EGO : time – 87 s, obj – 6953 kg (true: 6949 kg)



Verification: Design framework

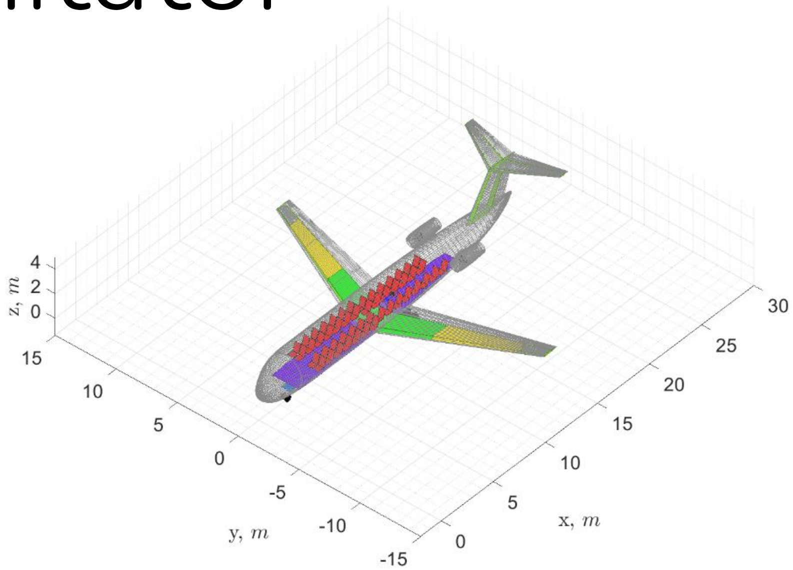
- Clean Aviation SAT E/STOL EIS2032
- 19 passenger serial electric
  - Battery/turbine power split
- 600 nm design mission
- Strut-braced wing

Ma, Y., Karpuk, S., & Elham, A. (2022). Conceptual design and comparative study of strut-braced wing and twin-fuselage aircraft configurations with ultra-high aspect ratio wings. *Aerospace Science and Technology*, *121*, 107395.

Parameter	E/STOL [t]	Our Model [t]	Difference
Payload	1.73	1.73	0
Structure	5.92	6.0	+ 1.3 %
OEW	9.92	8.8	- 12 %
MTOM	12.8	11.7	- 8 %

Verification SUAVE - TUD Initator

- 50 passenger boosted turbofan
- 500 NM design mission



Parameter	TUD [t]	Our Model [t]	Difference
Payload	5.3	5.3	0
Battery	10.5	10.0	- 5.1 %
Fuel	2.07	1.89	- 8.6 %
OEW	28.4	29.5	+ 3.9 %
MTOM	35.7	36.7	+ 2.6 %

CHYLA-SUAVE

- Higher fidelity propulsion network models
  - 4 distinct architectures
  - Possibility to combine models into more complex architectures
- Significant runtime improvements
  - 8x general mission simulation
  - 4 -15x energy network simulation
- Detailed propulsion system mass estimations
- Variable power split along the mission profile
- New global optimisation option
  - Efficient surrogate-based (EGO)
- Strut-braced wing implementation

Thank you for your attention

CREDIBILITY-BASED MDO

CREDIBLE HYBRID ELECTRIC AIRCRAFT

Thank you for your attention

CREDIBILITY-BASED MDO METHODOLOGY

TU Delft

University of Southampton

Technische Universität Braunschweig

CHYLA

CREDIBLE HYBRID ELECTRIC AIRCRAFT

Clean Sky 2