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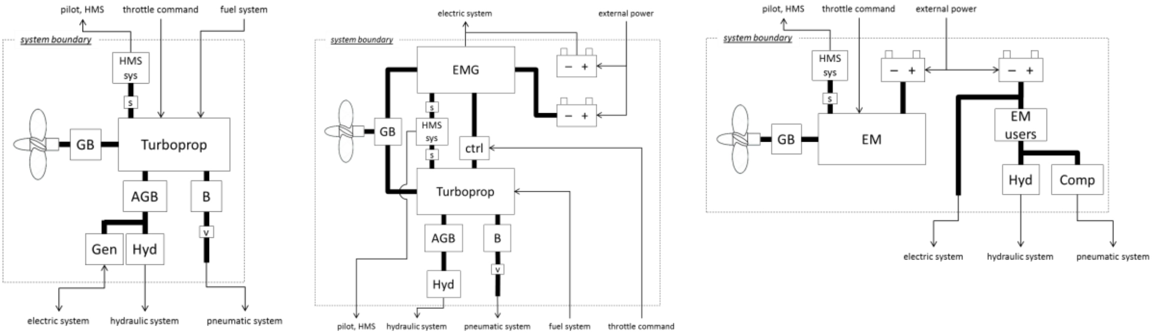
Jasper Bussemaker, Raúl García Sánchez, Mahmoud Fouda, Luca Boggero & Björn Nagel
German Aerospace Center (DLR), Hamburg, Germany

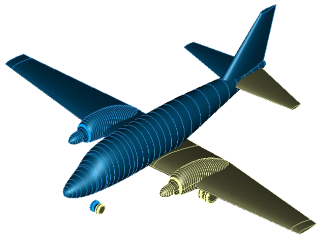
Function-Based Architecture Optimization: An Application to Hybrid-Electric Propulsion Systems

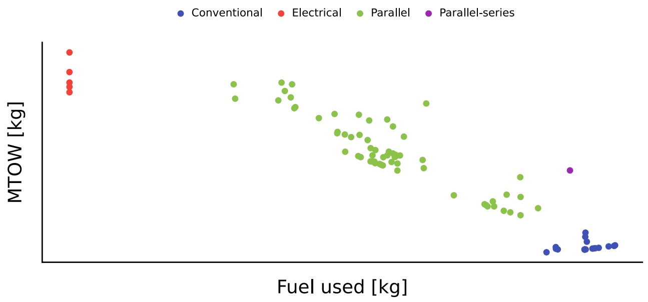
Research Objectives

- Architecture optimization: automatically generate and evaluate system architectures



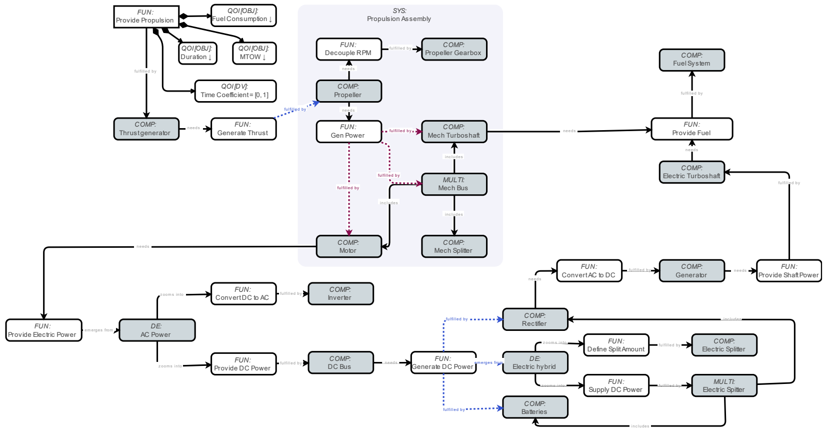
- Demonstration: hybrid-electric aircraft propulsion system

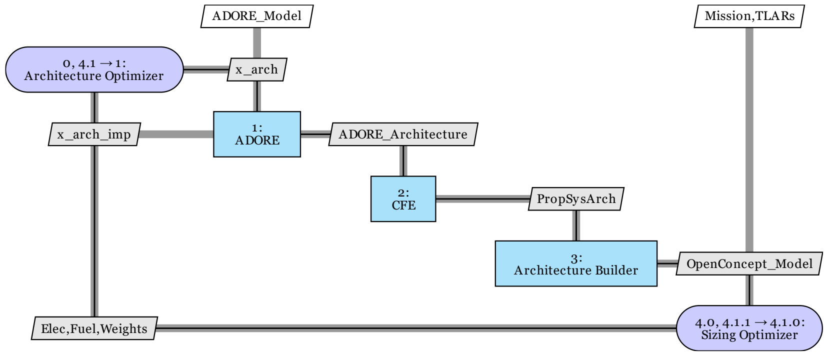


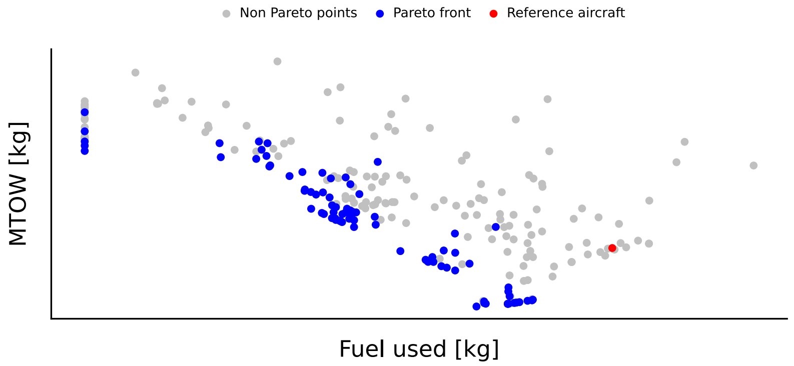


Contents

- System architecting
- Architecture **design space** model
- **Bi-level optimization problem:**
  - System architecture optimization loop
  - Sizing multidisciplinary optimization loop
- **Results**



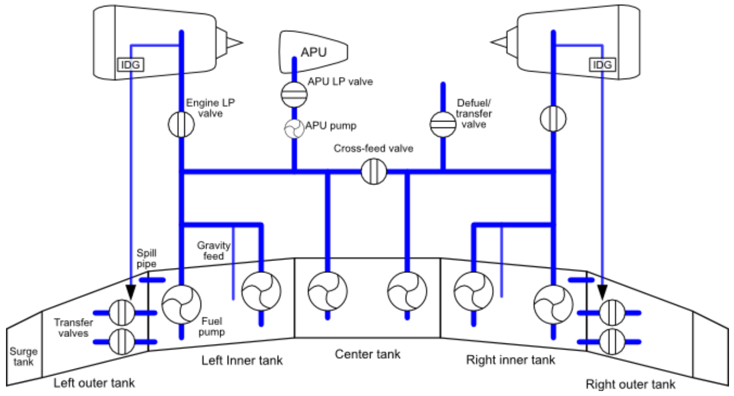




System Architecture

- Formal description of a system; represents elements and relations among them
- Great influence on system performance
- Challenges when designing new systems:
  - Many possible architectures
  - Limited expertise to build on
  - Conflicting stakeholder goals

- **Traditional** process: manually choose several architectures and evaluate them
- System architecture **optimization**: evaluate many architectures automatically, obtaining an optimized solution

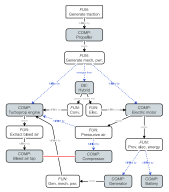


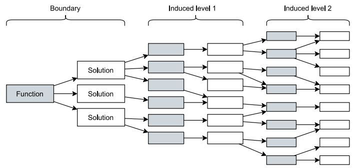
E. Crawley, B. Cameron, and D. Selva, “System Architecture: Strategy and Product Development for Complex Systems”, Harlow (UK), 2016

Architecture Optimization Framework

Architecture Generator	architecture → ← metrics	Architecture Evaluator

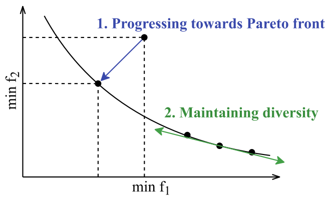
1. Formalize the Architecture Design Space

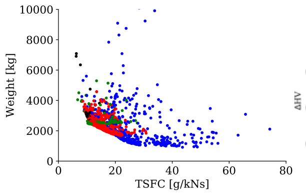


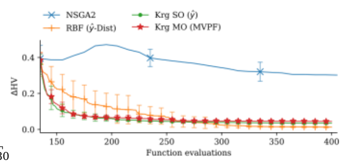


$$
\begin{aligned}
\textit{minimize} \quad & f_m(\mathbf{x}, \mathbf{y}), && m = 1, 2, \ldots, \mathcal{M} \\
\textit{where} \quad & x_i \in \mathbb{R} && i = 1, 2, \ldots, n \\
& y_j \in \mathbb{Z} && j = 1, 2, \ldots, \mathcal{J} \\
\textit{w.r.t.} \quad & g_k(\mathbf{x}, \mathbf{y}) \leq 0, && k = 1, 2, \ldots, \mathcal{K} \\
& x_i^{(L)} \leq x_i \leq x_i^{(U)}
\end{aligned}
$$

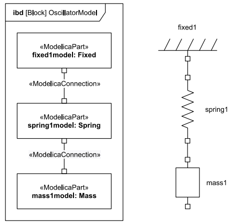
2. Systematically Explore the Design Space

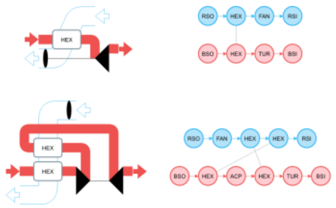




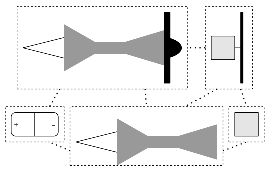


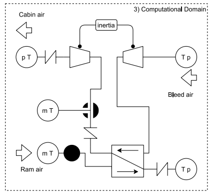
3. Interpret Architecture Model for Simulation





4. Flexible/Modular Architecture Evaluation





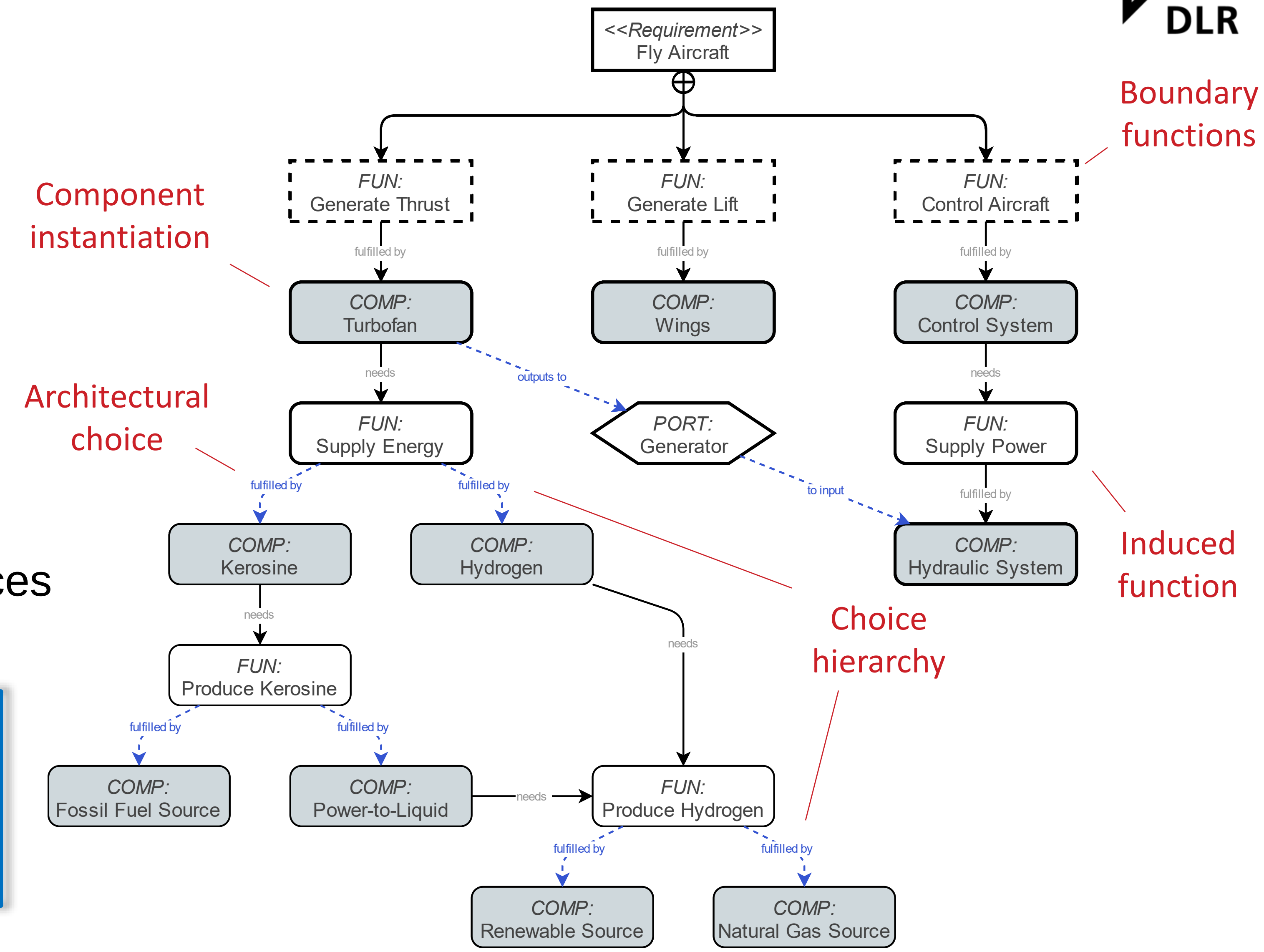
Function-Based Architecture Optimization, J.H. Bussemaker et al.,
INCOSE Symposium 2023

Architecture Design Space Modeling Process

- Collect functional requirements
- Identify boundary functions
- Allocate boundary functions to components
- Identify induced functions and fulfill these; iterate
- Model additional architectural choices

<u>Some benefits:</u>

- Natural transition from problem to solution
- Less prone to solution bias
- Directly traceable to requirements



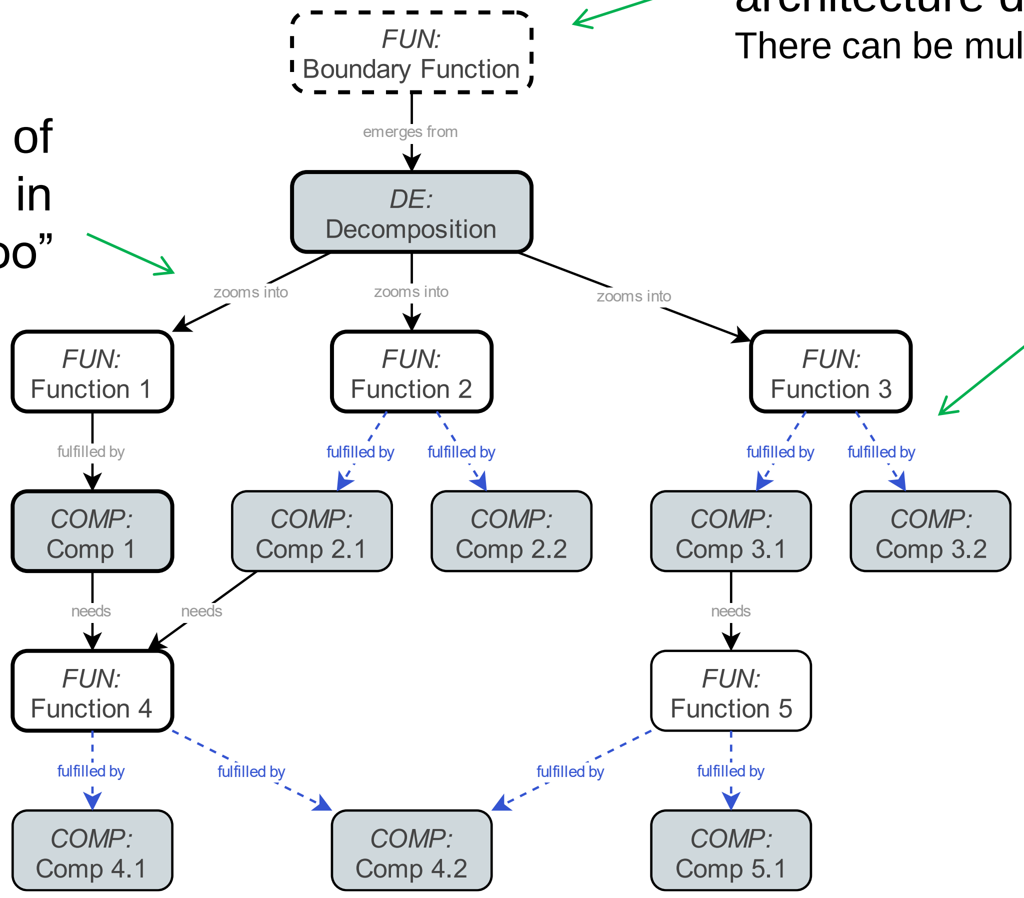
Bussemaker, J.H., Ciampa, P.D. and Nagel, B., 2020. System architecture design space exploration: An approach to modeling and optimization. In *AIAA Aviation 2020 Forum* (p. 3172).

The Architecture Design Space Graph (ADSG)

Starting point of architecture derivation
There can be multiple

Arrows point in the direction of derivation: “if source is included in an architecture, the target is too”

Blue-dashed arrows indicate selection choices (mutually-exclusive options)



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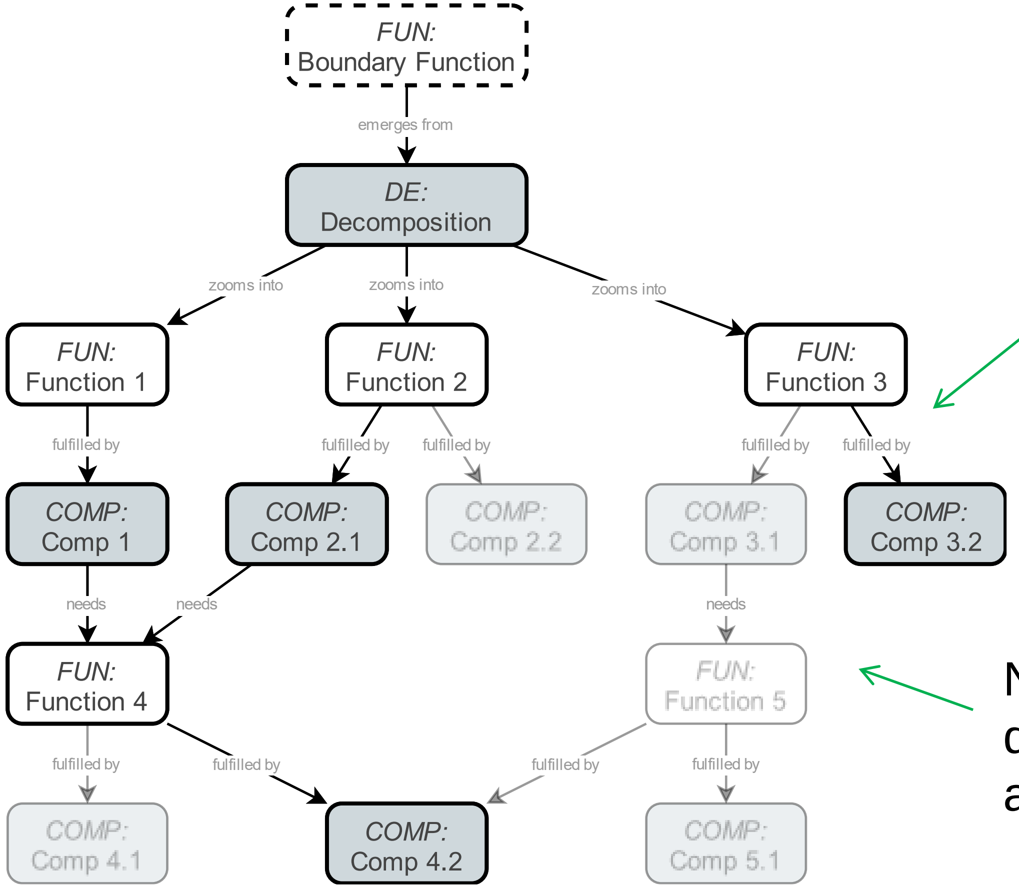
Generating an Architecture Instance

This represents an architecture *instance*, because there are no more choices



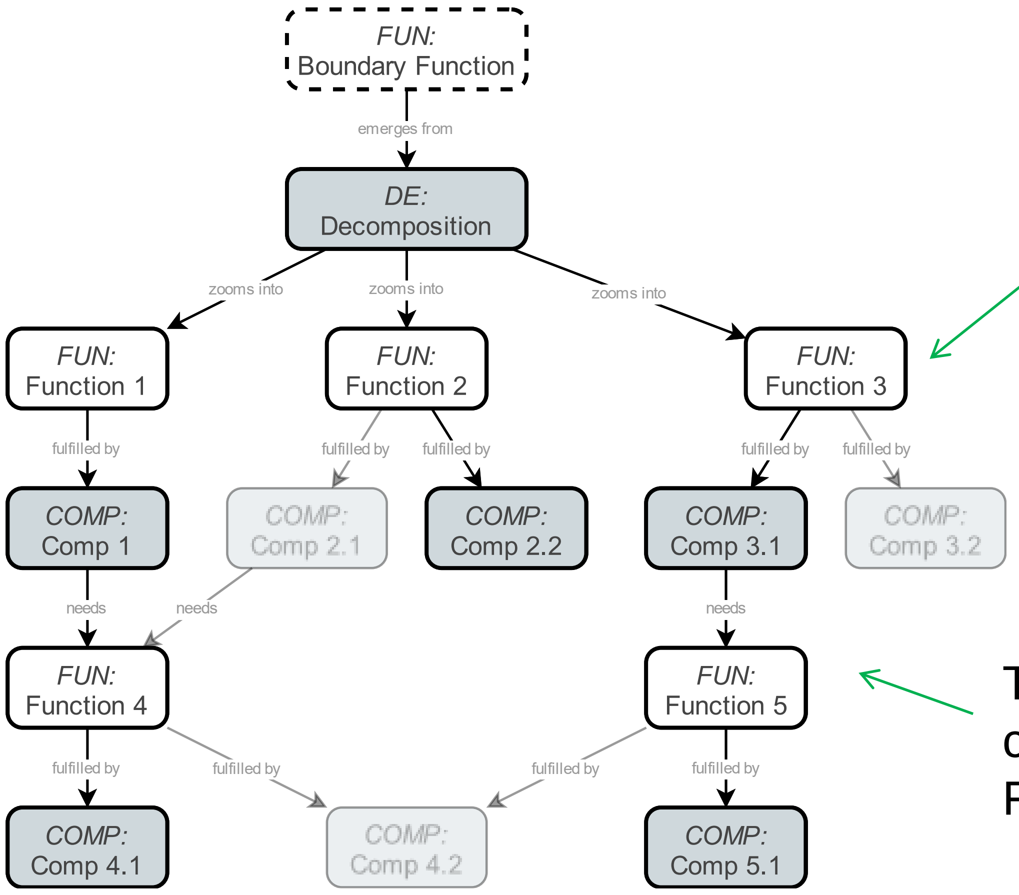
Select one of the options for each selection choice

Manually (in GUI) or from a design vector

Not-selected options and their derived nodes (and choices) are marked for removal

Bussemaker, J.H., Ciampa, P.D. and Nagel, B., 2020. System architecture design space exploration: An approach to modeling and optimization. In *AIAA Aviation 2020 Forum* (p. 3172).

Generating an Architecture Instance



Select some other options

This time also the choice for fulfillment of Function 5 is active

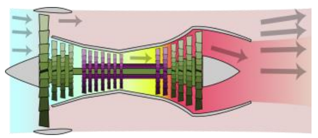
Bussemaker, J.H., Ciampa, P.D. and Nagel, B., 2020. System architecture design space exploration: An approach to modeling and optimization. In *AIAA Aviation 2020 Forum* (p. 3172).

Architectural Choice Types

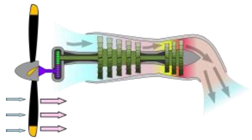
Fulfilling Functions

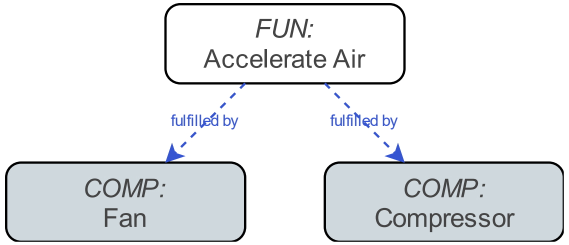
- Which component fulfills which function?

Provide thrust



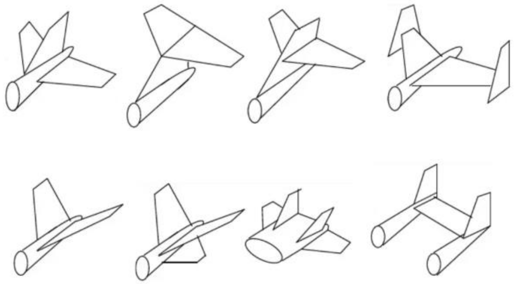
or

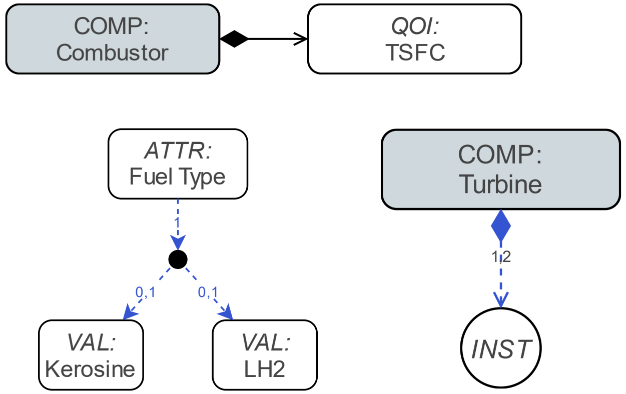




Characterization

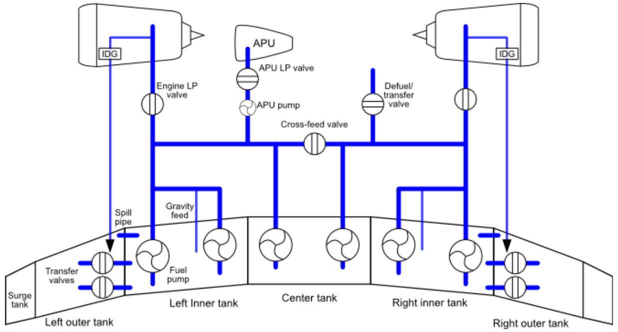
- Number of instances
- Property values

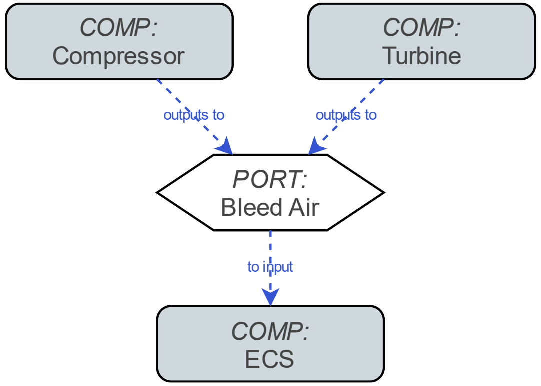




Connections

- Connect output to input ports
- Assignment problem





Bussemaker, J.H., Ciampa, P.D. and Nagel, B., 2020. System architecture design space exploration: An approach to modeling and optimization. In *AIAA Aviation 2020 Forum* (p. 3172).

Design Space Editor

Architecture design space modeler

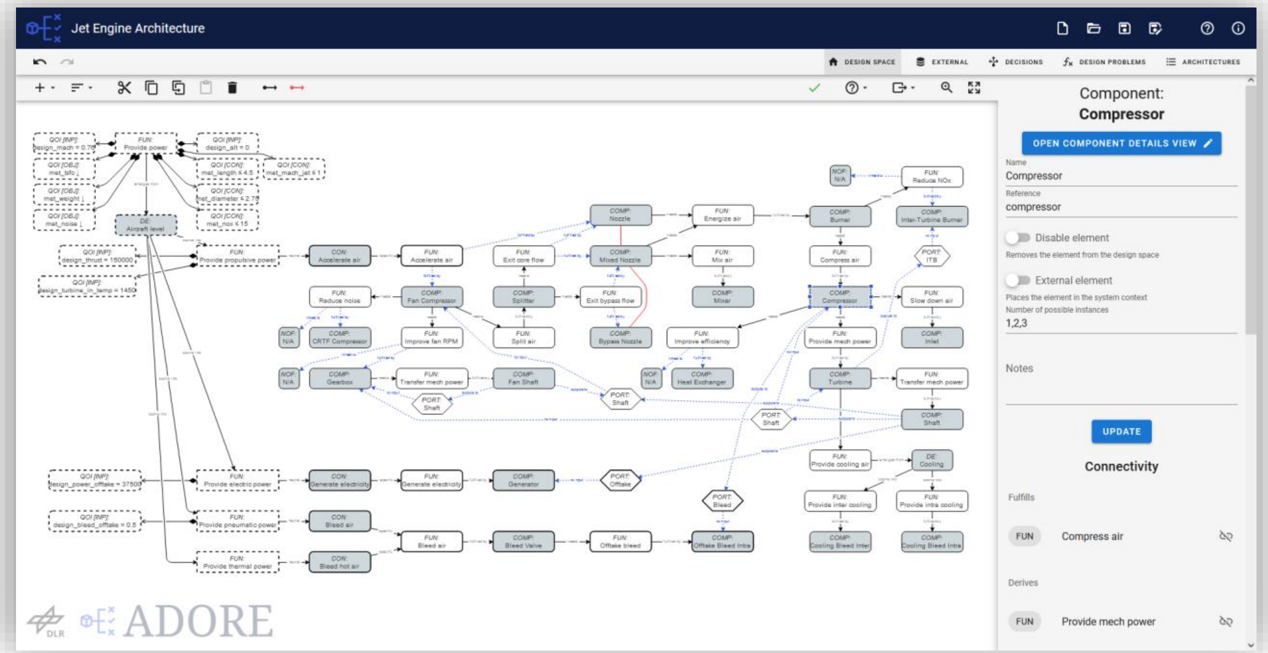
- Define functions, components, connections
- Identify architectural choices
- Define input parameters and metrics

Architecture generator

- Take architectural decisions to create architectures
- Connect to evaluation environment

Architecture optimization framework

- Define design variables, objectives, constraints
- Connect to optimization library



Bussemaker, J., Boggero, L. and Ciampa, P.D., 2022, July. From system architecting to system design and optimization: A link between MBSE and MDAO. In *INCOSE International Symposium* (Vol. 32, No. 1, pp. 343-359).

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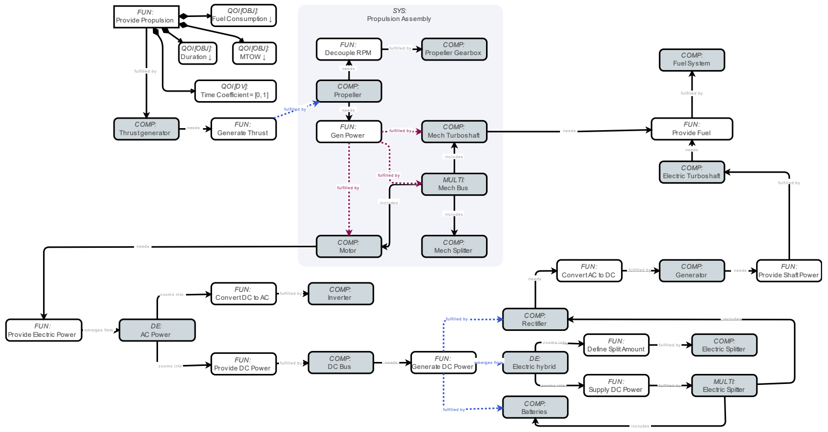
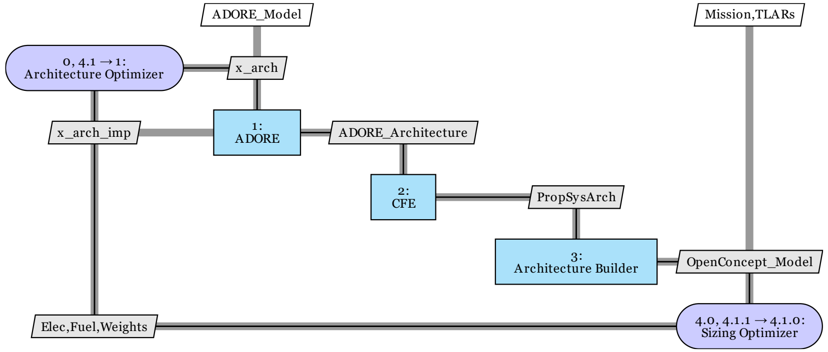
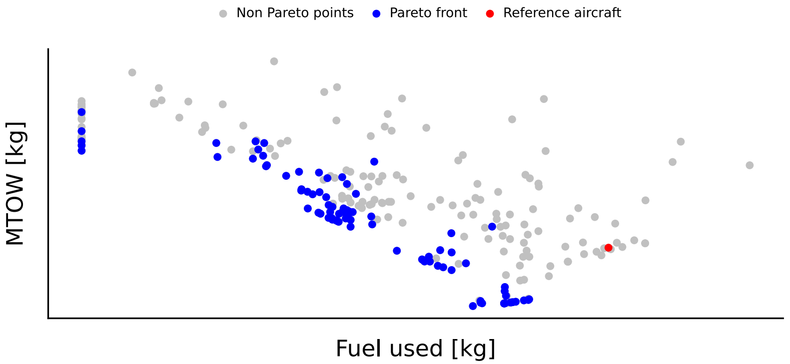
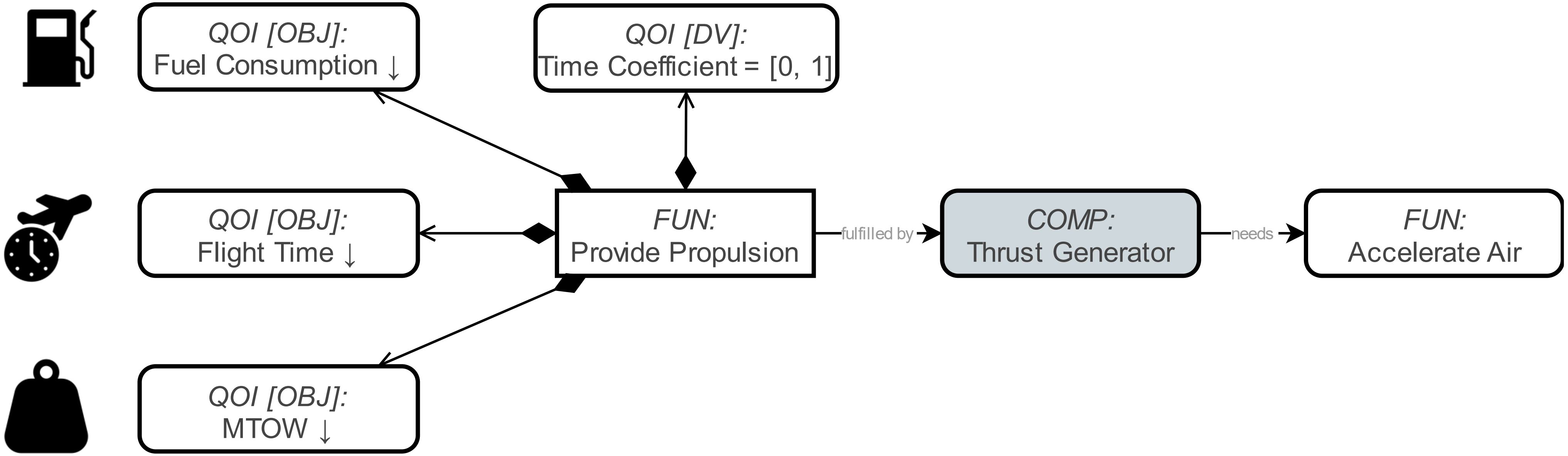






Boundary Function and Objectives

- Boundary function: Provide Propulsion
- Three performance objectives: MTOW, Fuel Consumption and Flight time



Propulsion Functions

- **Decouple the RPM:**

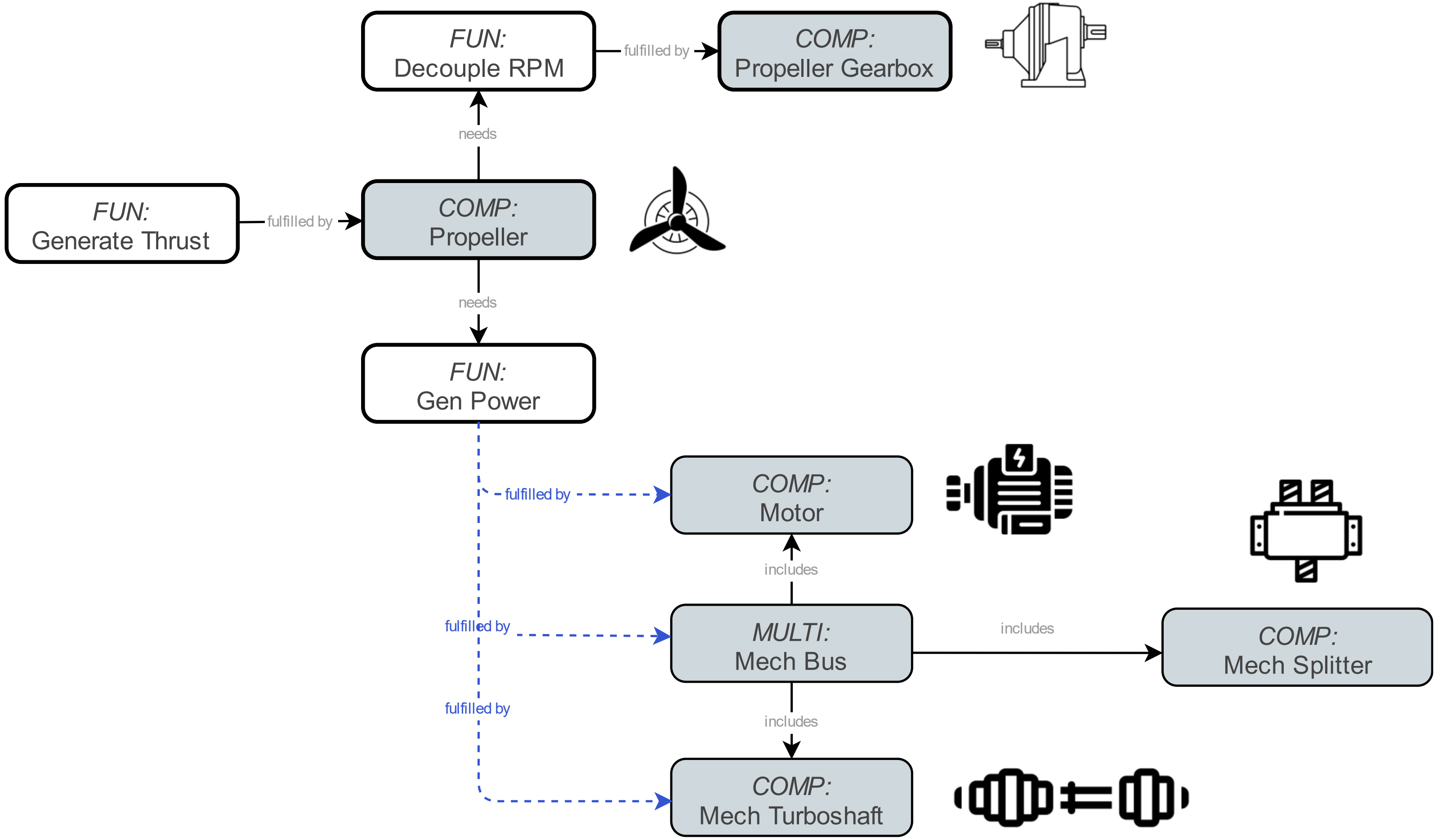
 - Propeller Gearbox

- **Provide Shaft Power:**

 - Electric Motor

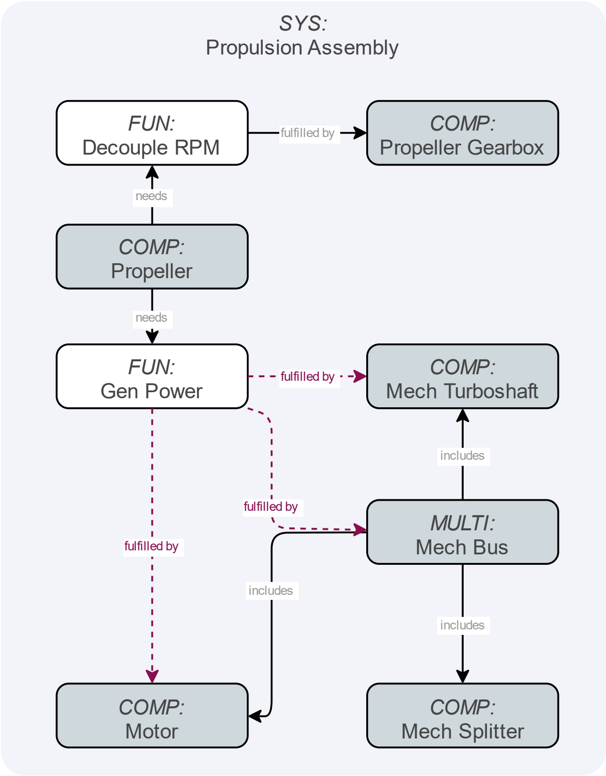
 - Mech Bus

 - Turboshaft



Propulsion Choices

- Number of engines: 2 to 10
- For each propeller:
  - Number of blades: 3 or 4
  - Mechanical power source

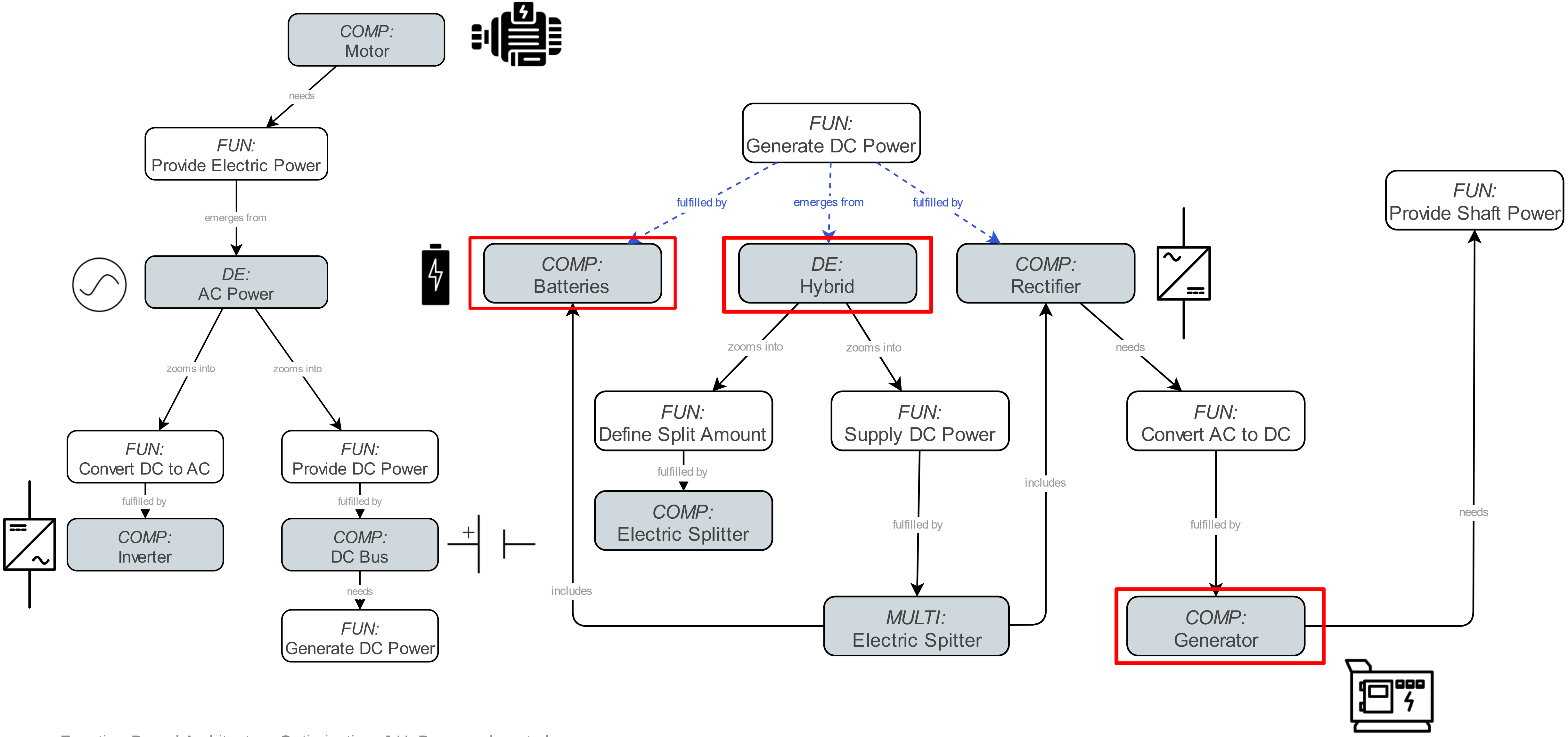


Assumptions:

- Symmetry
- Power source order is irrelevant

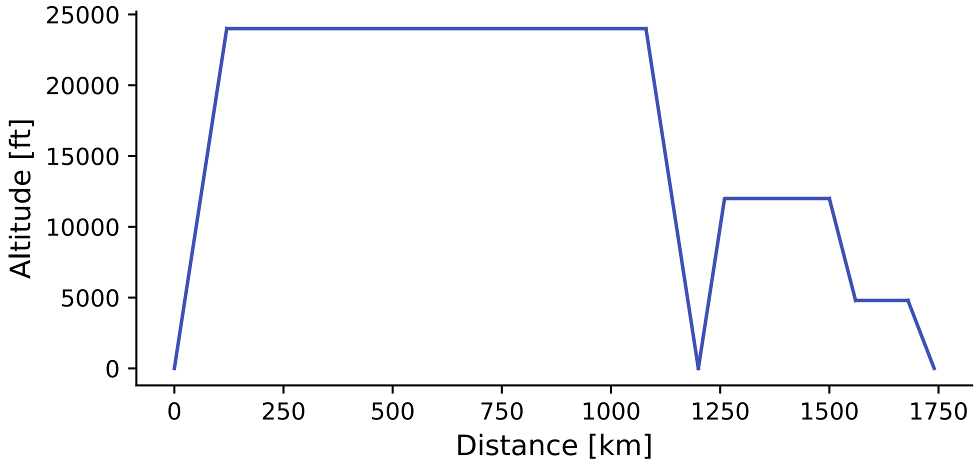
First Choice	Subsequent Choices
Electric	Electric, Hybrid, Conventional
Hybrid	Hybrid, Conventional
Conventional	Conventional

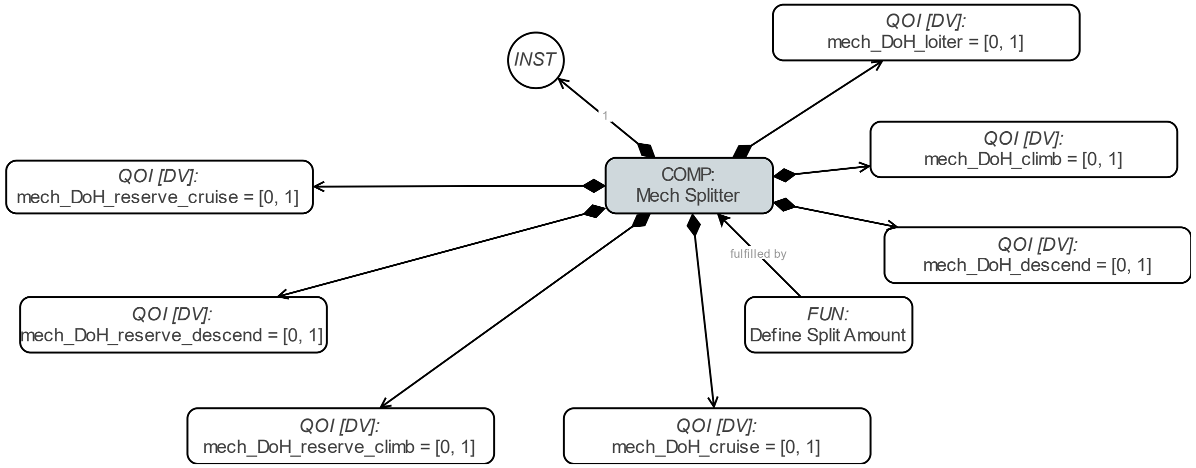
Electrical Power Generation



Degree of Hybridization

- DoH: fraction of power coming from electrified sources
- Mechanic DoH (parallel)
- Electric DoH (series)
- One for each of the 7 mission segments

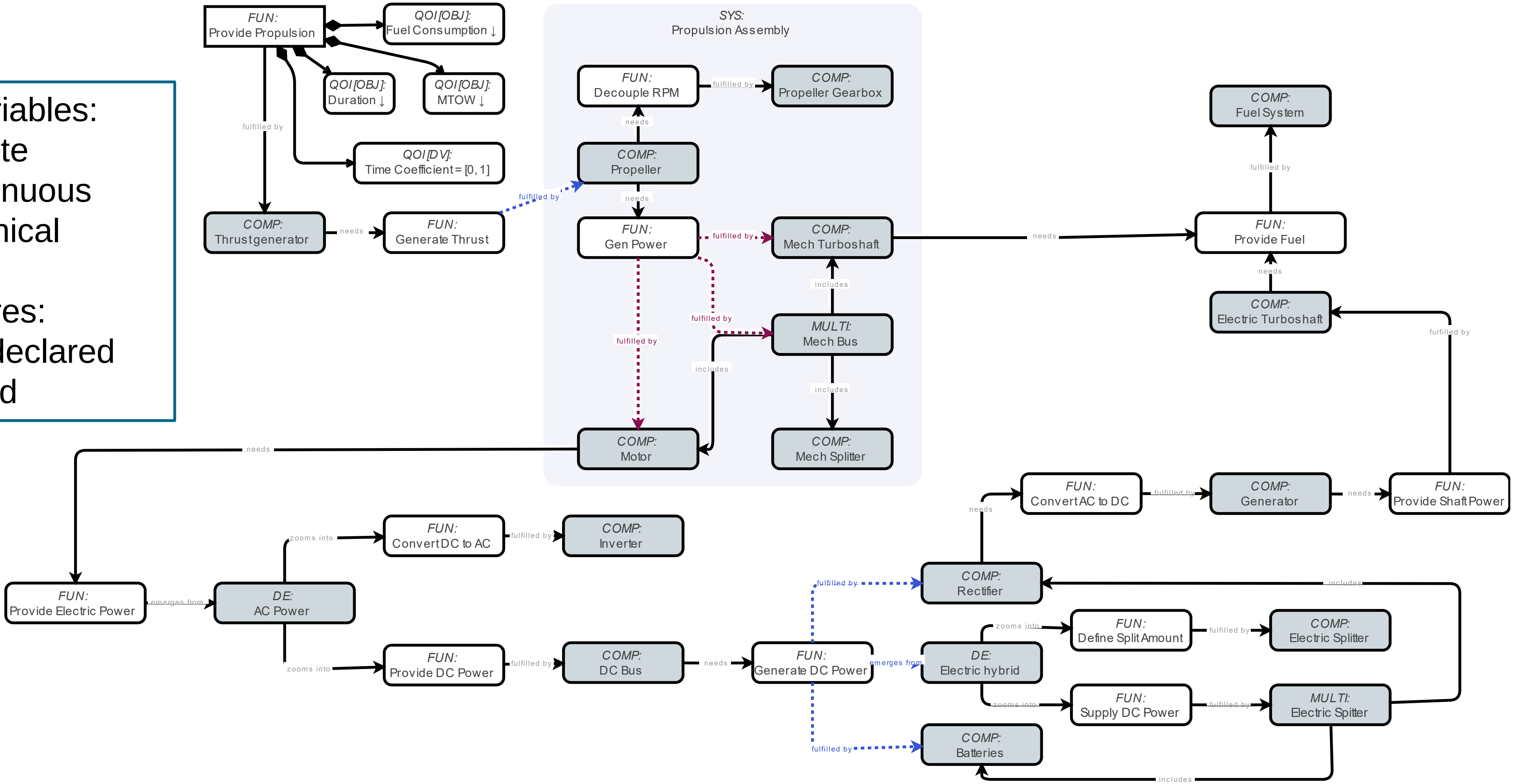




Hybrid-Electric Propulsion System Design Space

Design variables:
- 8 discrete
- 15 continuous
- Hierarchical

Architectures:
- +8000 declared
- 310 valid



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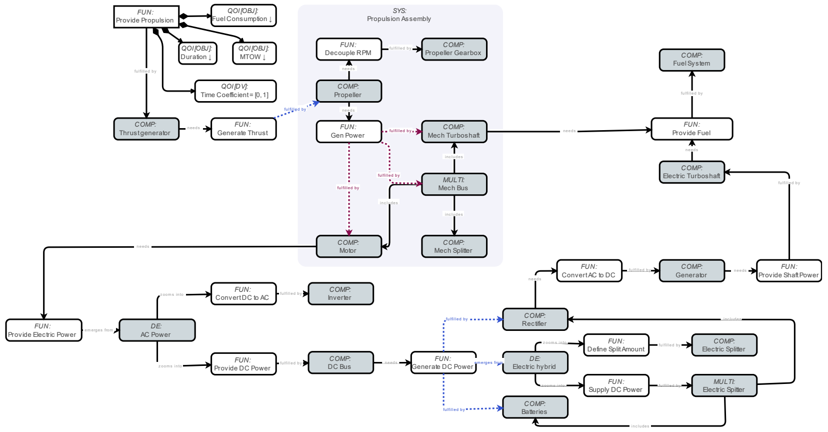
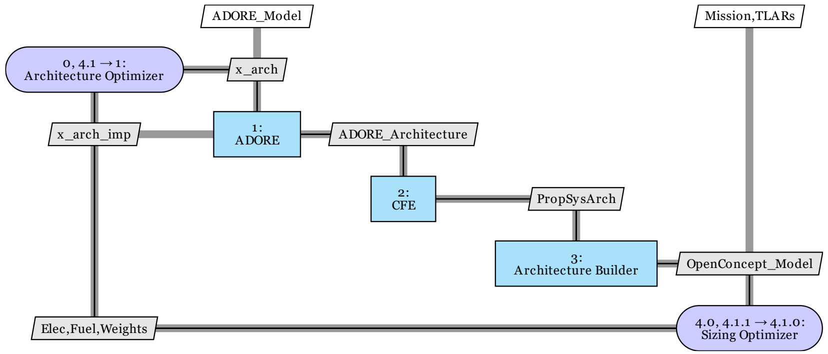
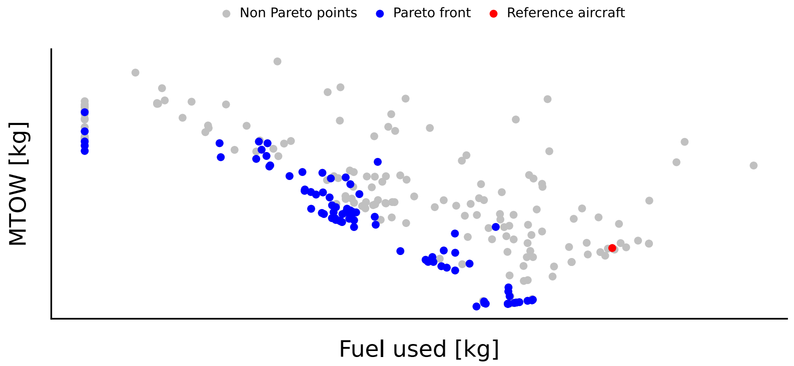






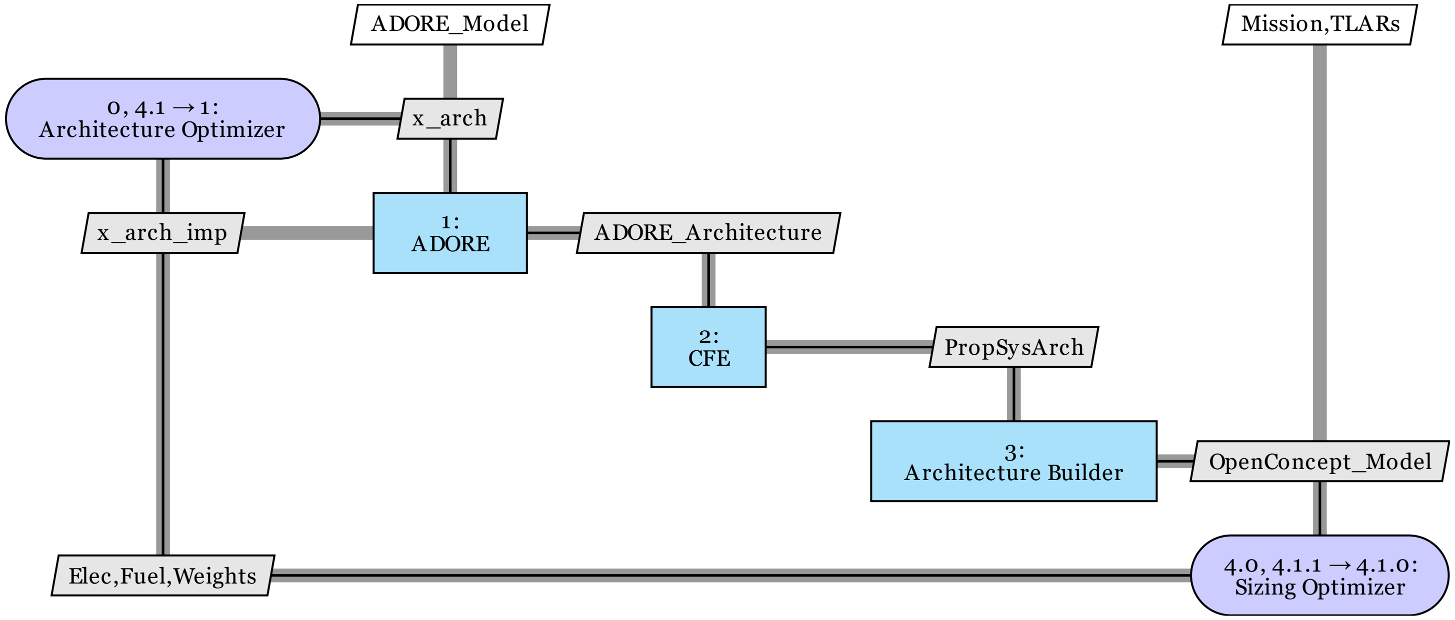
Optimization problem implementation

Outer optimization loop:

- Multi-objective
- Pareto front: architectures
- Mixed-discrete design variables

Inner optimization loop:

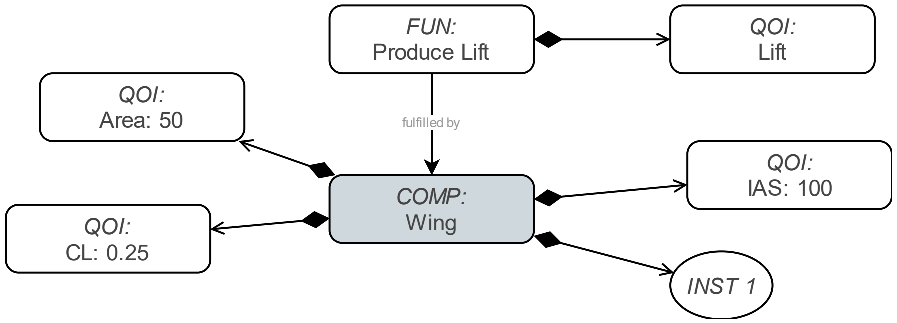
- Single-objective, gradient-based
- Unique solution: sized architecture
- Continuous design variables



Class Factory Evaluator

- Python API for instantiating classes based on architecture elements
- Example: instantiate the `Wing` class for every "Wing" component instance; set properties to linked QOI's

```python
@staticmethod
def get_class_factories() -> List[ClassFactory]:
    return [
        ClassFactory(
            el=ExternalComponentDef(name='Wing', n_inst=[1], auto_match_pattern='/W.*/'),
            cls=Wing,
            props={
                'area': ExternalQOIDef(
                    name='Wing Area', qoi_type=QOIType.DESIGN_VAR, bounds=(40., 60.), auto_match_pattern='area'),
                'cl': ExternalQOIDef(
                    name='Lift Coefficient', qoi_type=QOIType.DESIGN_VAR, bounds=(0., .5),
                    auto_match_pattern=['cl', 'L* Coefficient']),
                'ias': ExternalQOIDef(
                    name='Indicated Airspeed', qoi_type=QOIType.INPUT_PARAM, value=100., auto_match_pattern='i?s'),
            },
        )
    ]
```

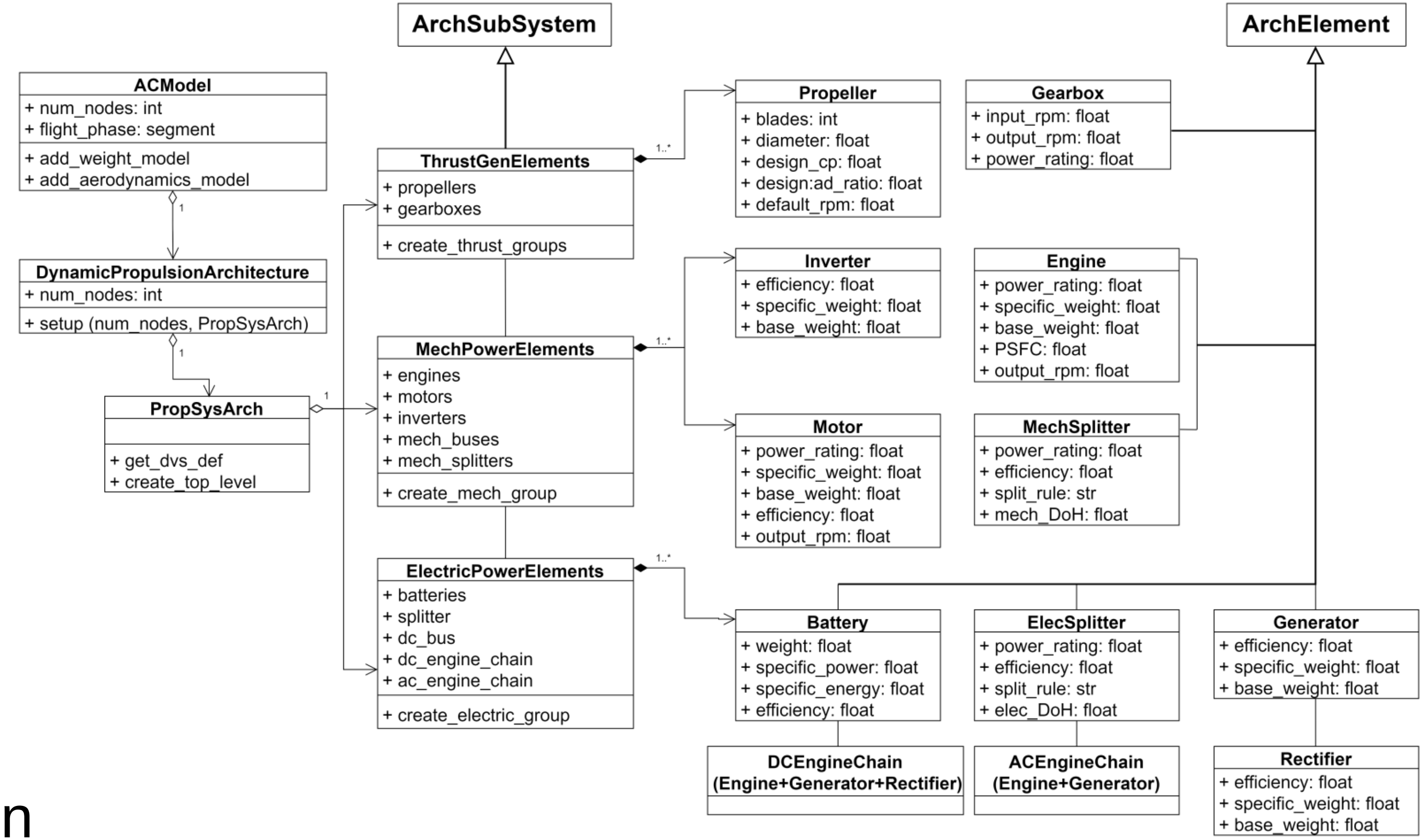



```python
@dataclass
class Wing:
    area: float  # m2
    cl: float
    ias: float  # kts
```

```
classes = {list: 1} [Wing(area=50.0, cl=0.25, ias=100.0)]
  0 = {Wing} Wing(area=50.0, cl=0.25, ias=100.0)
    area = {float} 50.0
    cl = {float} 0.25
    ias = {float} 100.0
  __len__ = {int} 1
```

Architecture Evaluation with PropSysArch

- Classes describing the propulsion system
- Each component has an equivalent class
- 3 elements groups:
  - Thrust generation elements
  - Mechanical power elements
  - Electrical power elements
- Automatic inner-loop multidisciplinary optimization problem construction



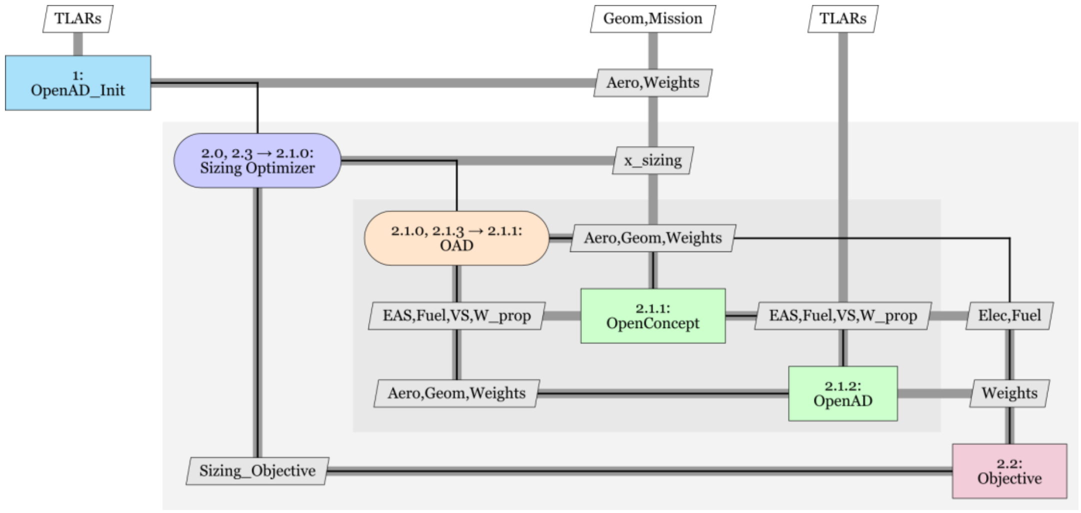
Fouda, M.E.A. et al., 2022, September. Automated hybrid propulsion model construction for conceptual aircraft design and optimization. In ICAS 2022.

Inner Optimization Loop

- Single-objective optimization problem

$$f_{sizing}(x_{sizing}) = \underbrace{(1 - t_{coeff}) * (W_{fuel} + 0.01MTOW)}_{\text{Energy usage}} + \underbrace{t_{coeff} * t_{flight}/100}_{\text{Flight time}}$$

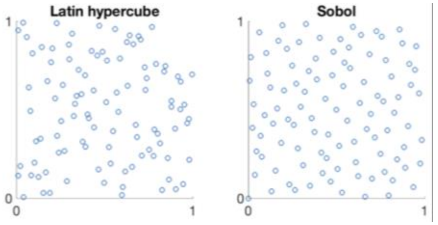
- Multidisciplinary optimization (MDO) loop:
  - Overall aircraft design
  - Mission analysis & component sizing

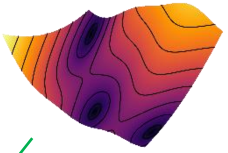


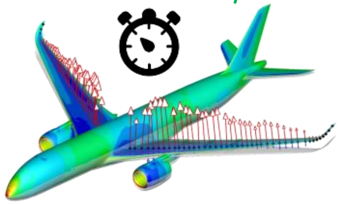
Outer Loop Optimization Algorithm

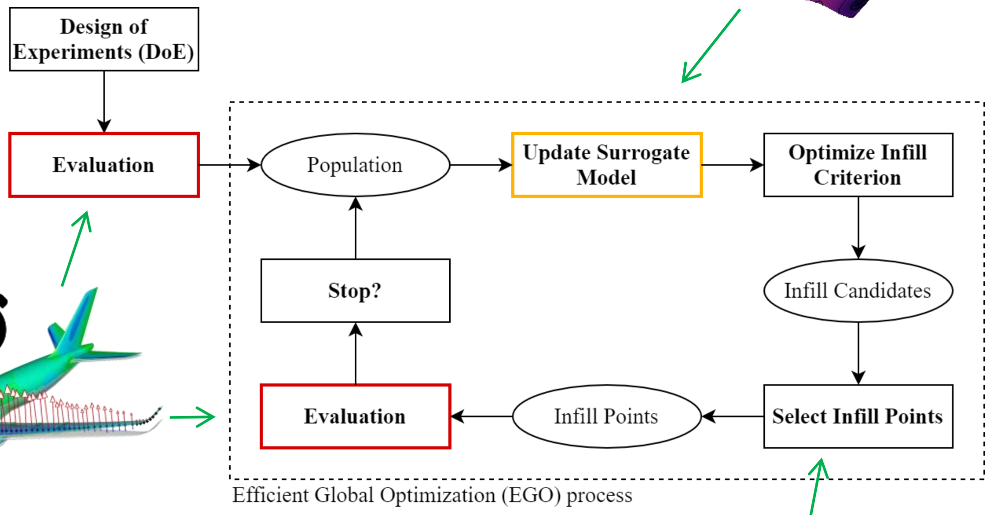
Surrogate-Based Optimization

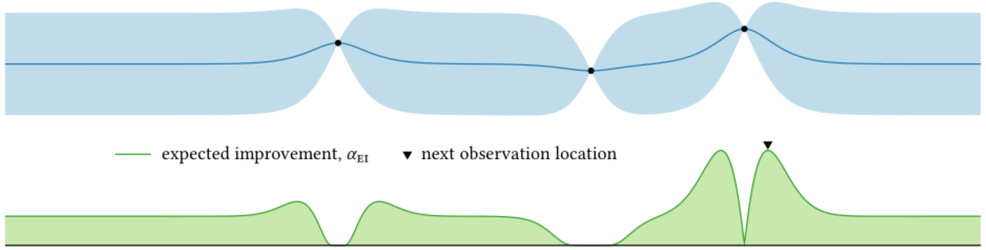
- Search a surrogate model of the design space for interesting infill points
  - Hierarchical, mixed-discrete Gaussian Process
  - Multi-objective infill criteria
- Less evaluations needed to find the optimum compared to evolutionary algorithms





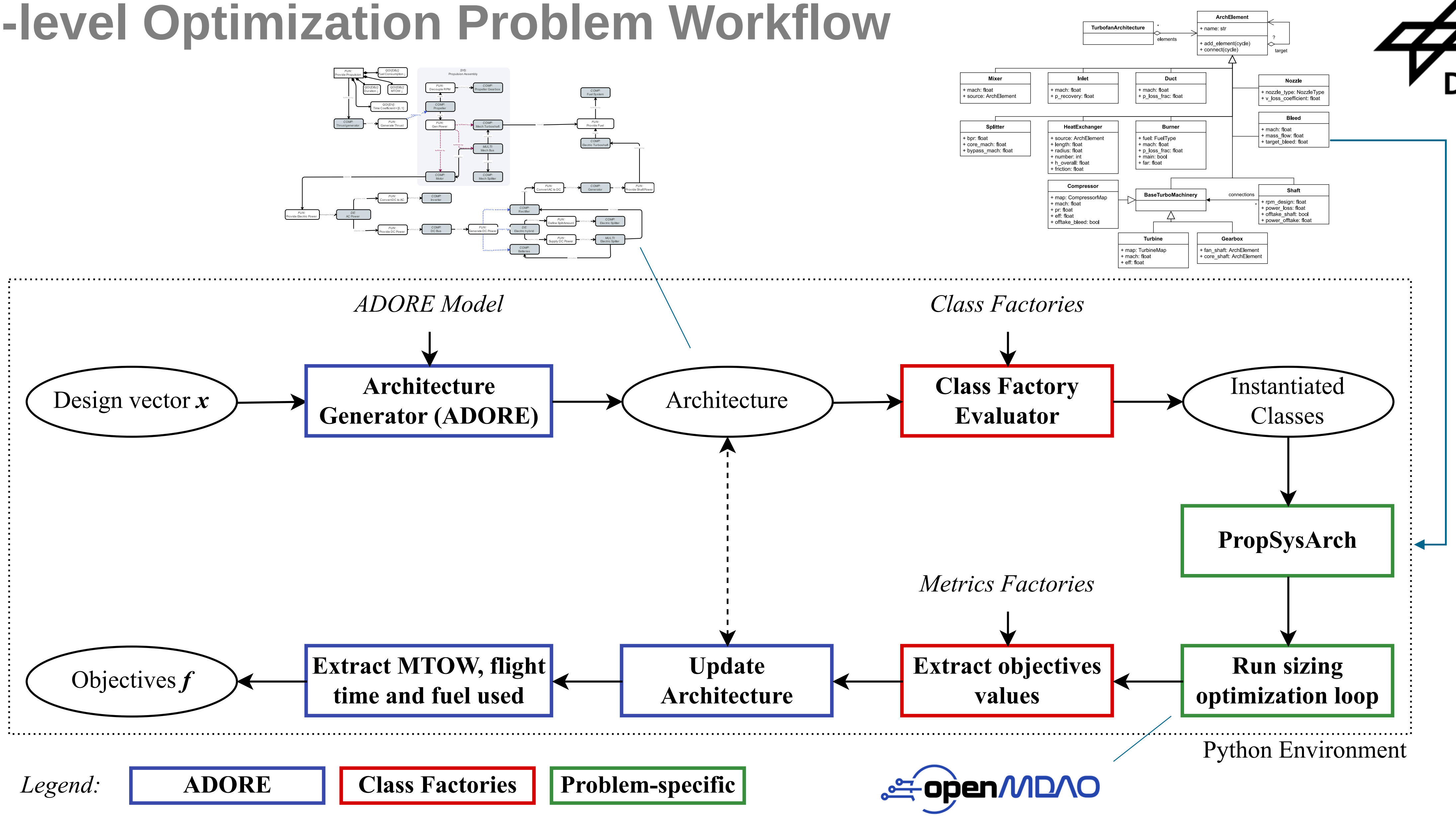






J.H. Bussemaker, N. Bartoli, T. Lefebvre, P.D. Ciampa, and B. Nagel, "Effectiveness of surrogate-based optimization algorithms for system architecture optimization", AIAA AVIATION 2021
Garnett, R., 2023, “Bayesian optimization,” Cambridge University Press

Bi-level Optimization Problem Workflow



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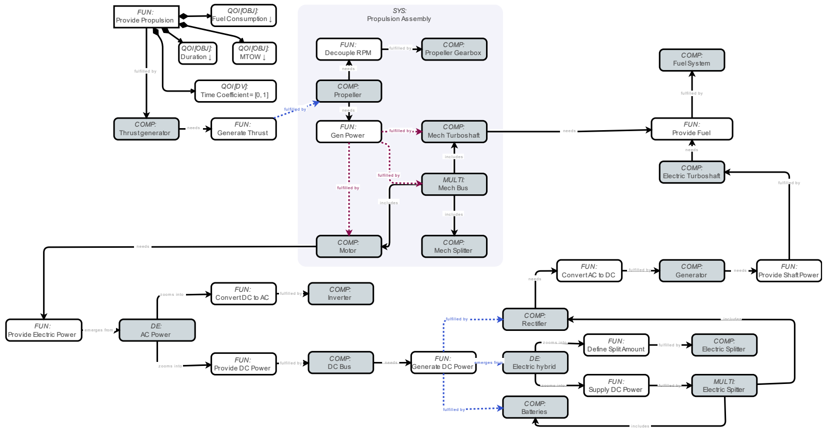
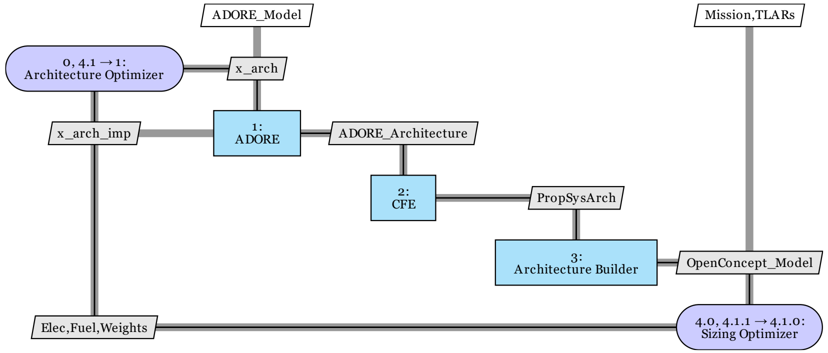
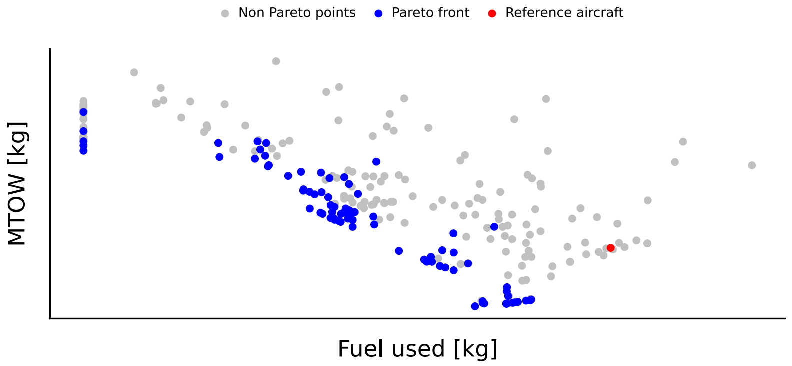
- **Results**

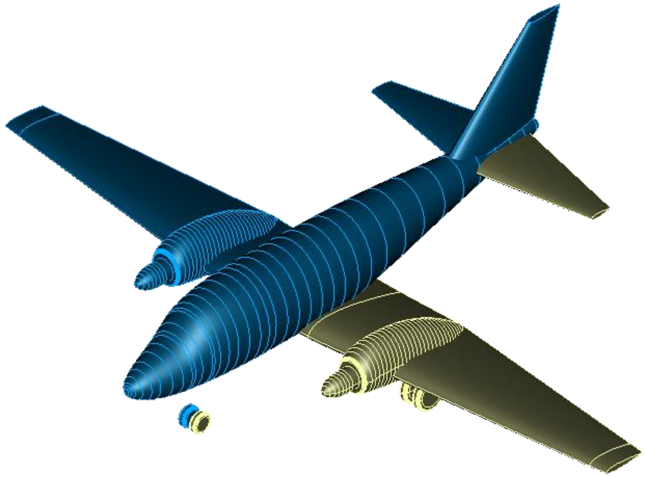






Application Case

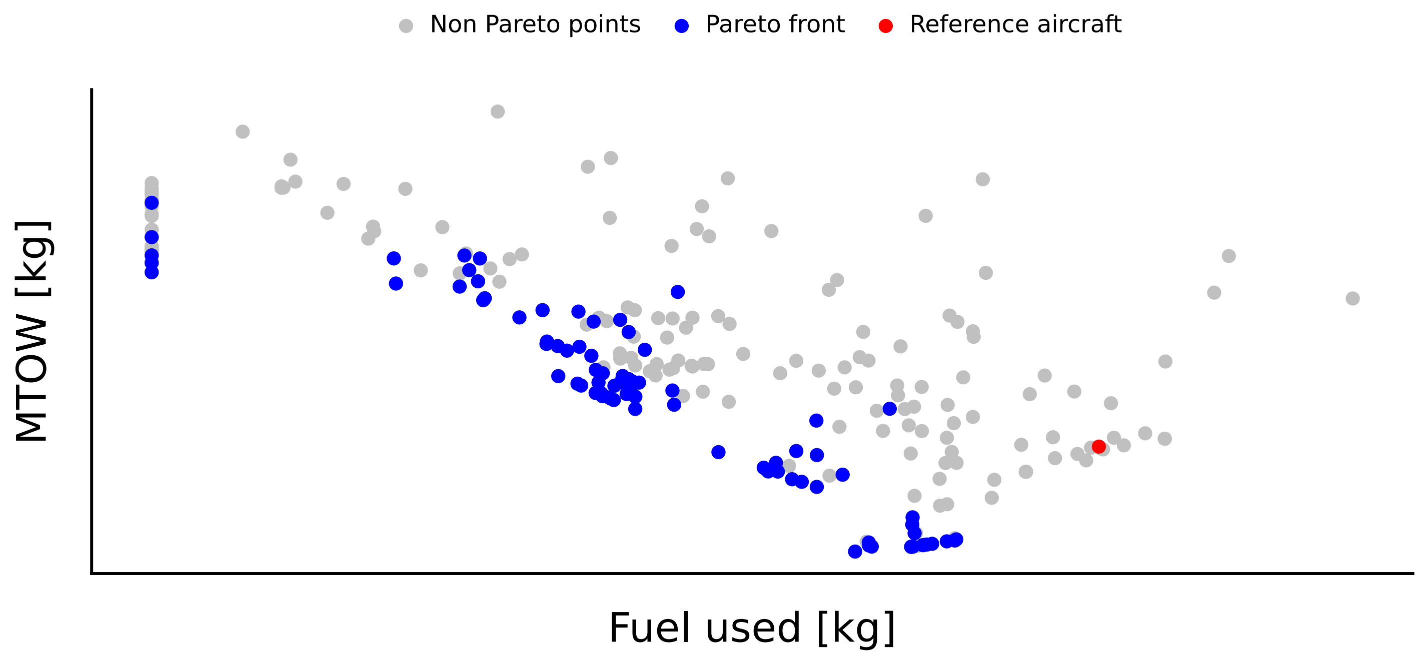
Commuter aircraft
Beechcraft KingAir C90GT



Requirement	**Value**
Design Mission Range	1539 km
Cruise Altitude	24000 ft
Take Off Distance	729 m
Landing Distance	718 m
Passengers seats	6
Payload mass	363 kg
Wing loading	168 kg/m2

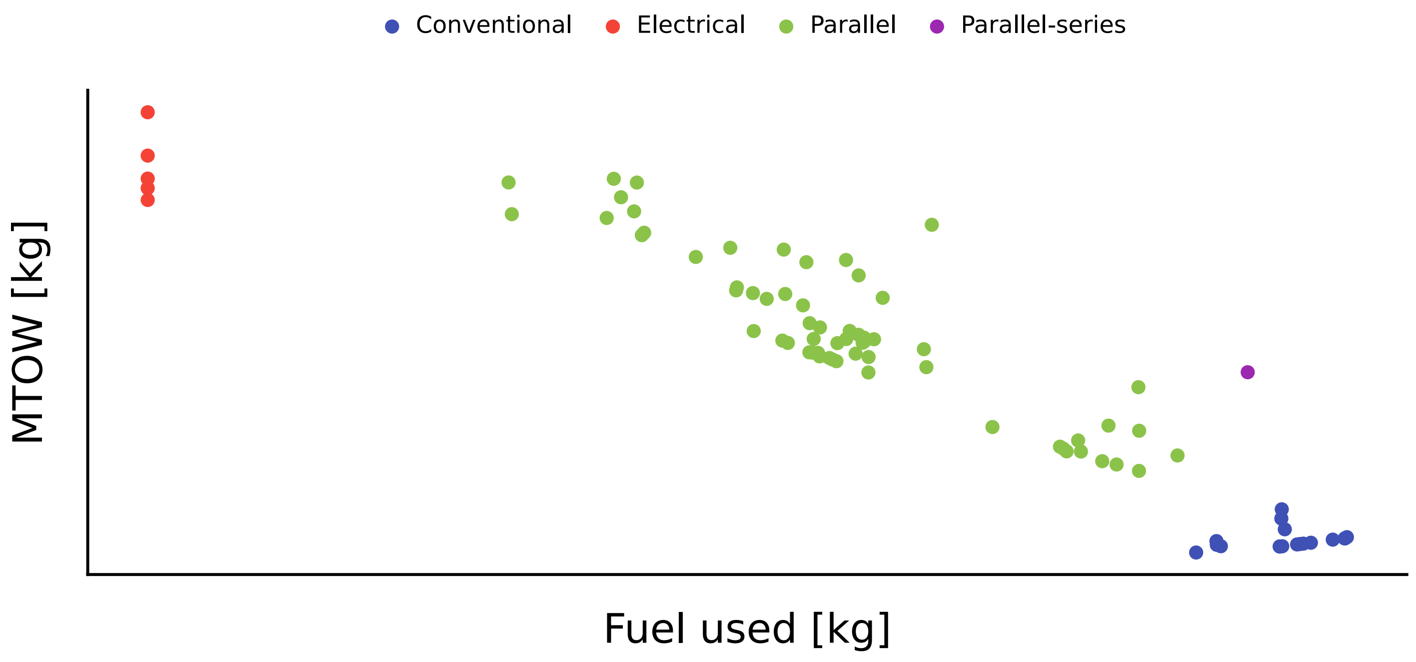
Pareto Front

- Surrogate-based optimization algorithm:
  - 100 initial DoE points
  - 150 infill points
- Pareto front: 88 non-dominated design points
- Trade-off between 3 objectives:
  - MTOW, fuel burn, flight time



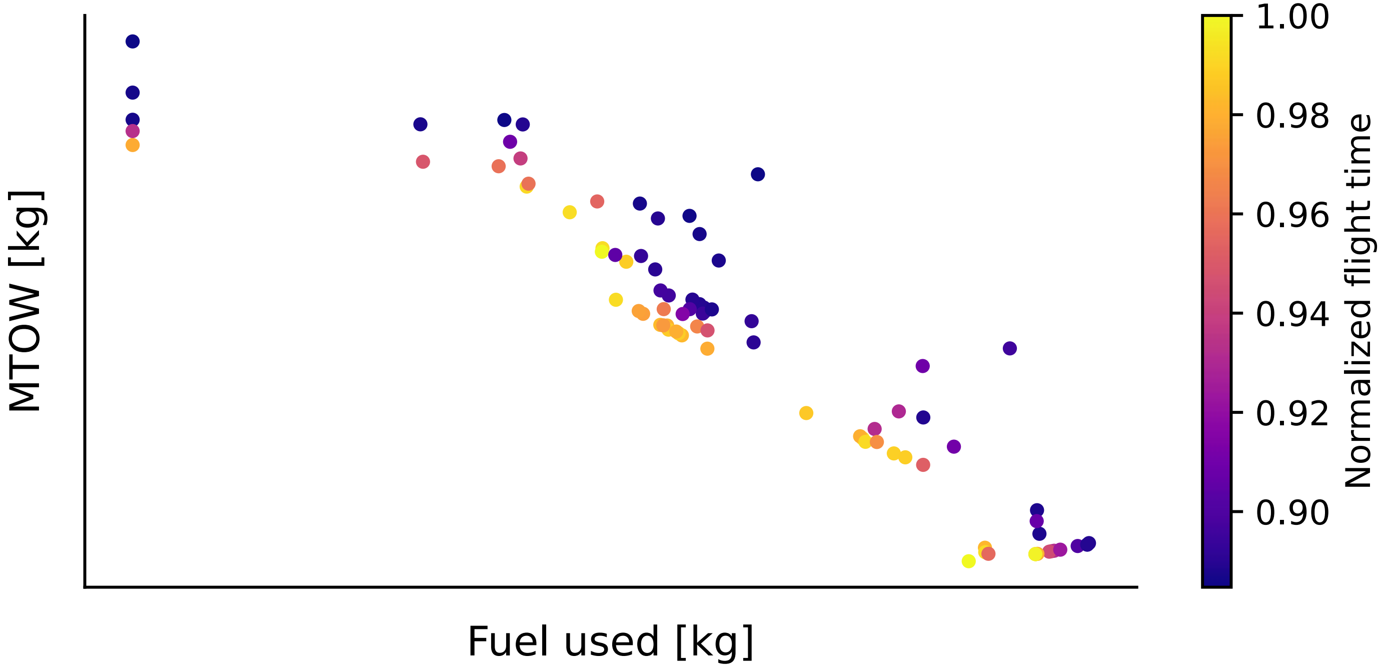
Pareto Front: Source of Power

- Lowest fuel consumption:
  Electric propulsion
- Lowest MTOW:
  Conventional propulsion
- Balanced:
  Parallel-hybrid propulsion



Pareto Front: Flight Time

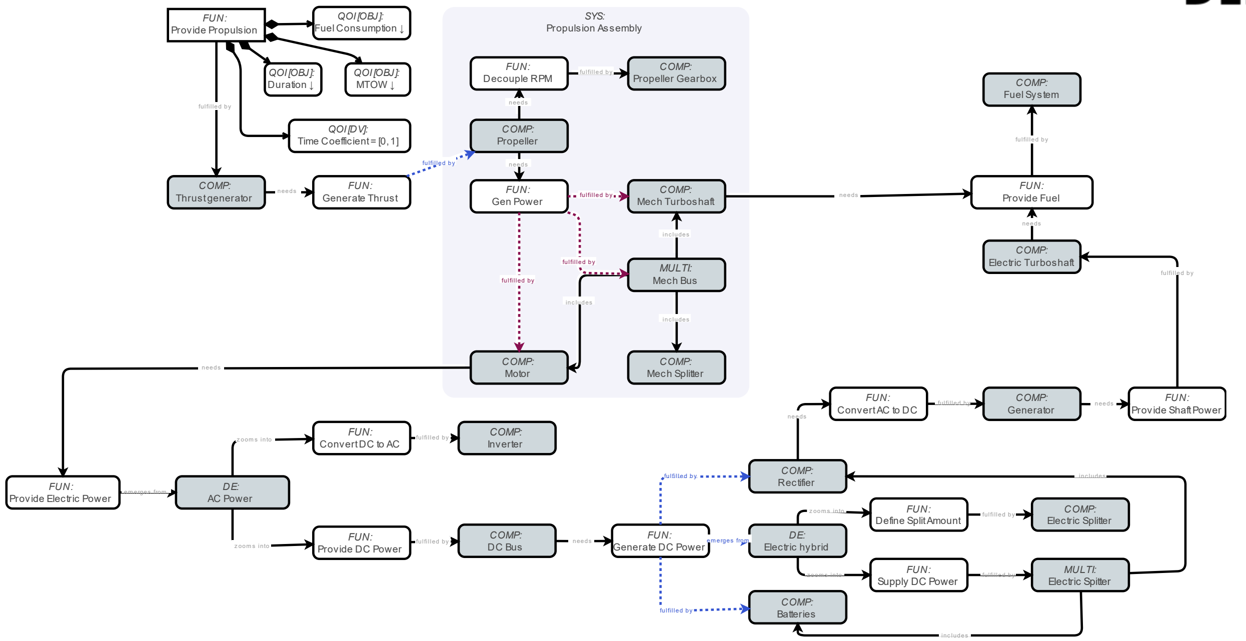
- Lower flight time:
  - Higher fuel consumption
  - Heavier aircraft



Conclusions

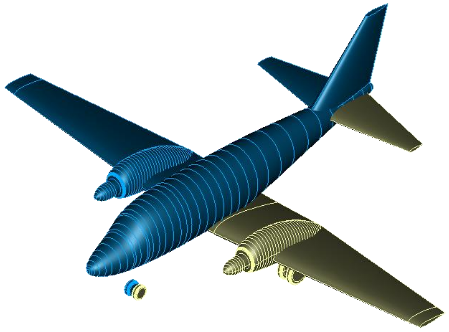
Architecture optimization demonstrated:

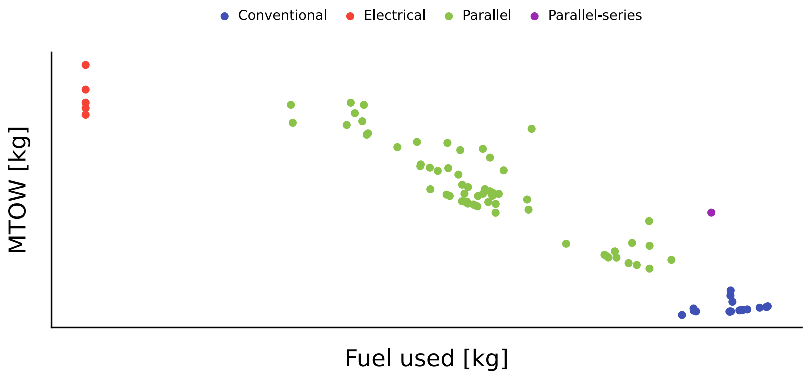
- Design space modeled using the Architecture Design Space Graph (ADSG)*
- Bi-level optimization coupling architecture to MDO using the Class Factory Evaluator
- Architecture-level Pareto front: 88 designs found with a surrogate-based optimizer



Future work:

- Demonstrate for larger design spaces on more system levels (e.g. SoS)
- Develop more reusable methods for integrating with MDO
- Integrate architecture optimization with other MBSE platforms, including SysMLv2





* Bussemaker, J.H., Ciampa, P.D. and Nagel, B., 2020. System architecture design space exploration: An approach to modeling and optimization. In *AIAA Aviation 2020 Forum* (p. 3172).