33rd Annual INCOSE international symposium

hybrid event

Honolulu, HI, USA
July 15 - 20, 2023

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German Aerospace Center (DLR), Hamburg, Germany

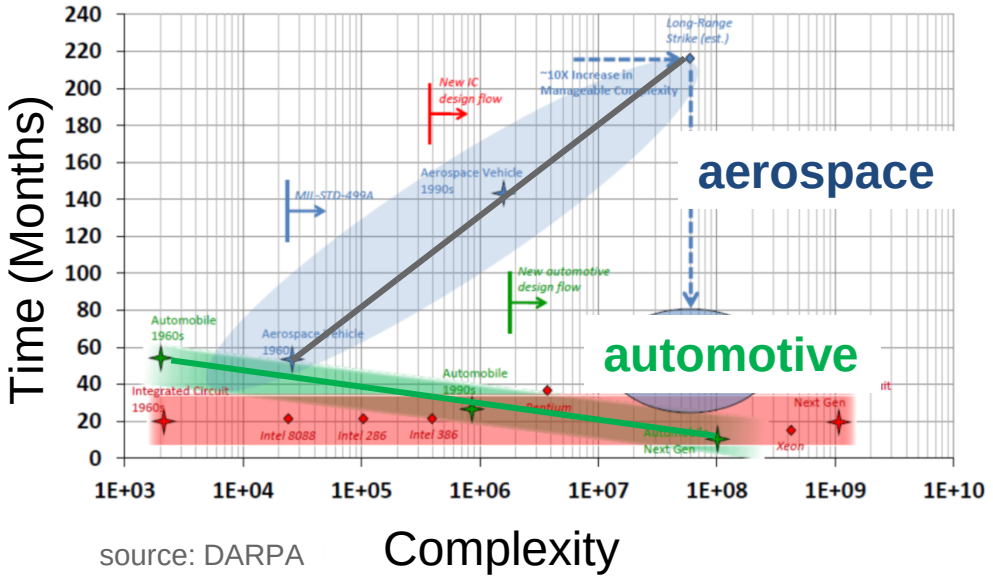
The AGILE4.0 Project: MBSE to Support Cyber-Physical Collaborative Aircraft Development

Development Challenges for Complex Aerospace Systems

- Increasing **complexity** and development **time** → **integration** of large number of **parts** and **sub-processes**
- **Cross-organizational** development → distributed and **heterogeneous** knowledge and expertise
- Increasing **interactions** → systems operating in **system of systems** scenarios

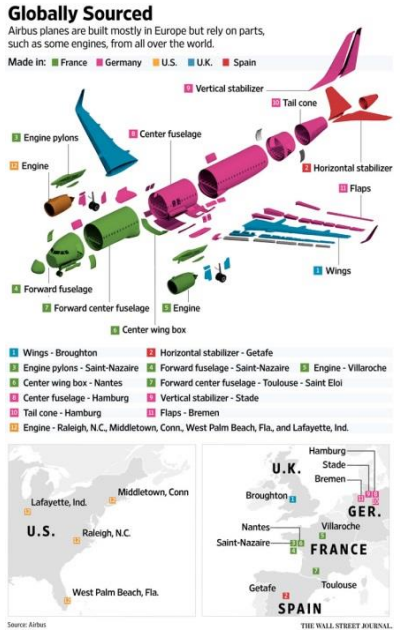
Target: **Managing complexity and accelerate the development time**

Increasing development times



source: DARPA

Distributed supply chain

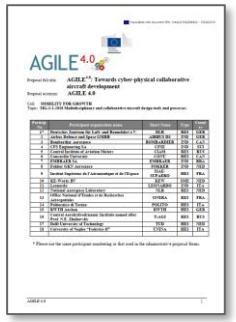


source: Airbus

System of Systems

source: DLR

AGILE4.0
Towards cyber-physical collaborative aircraft development

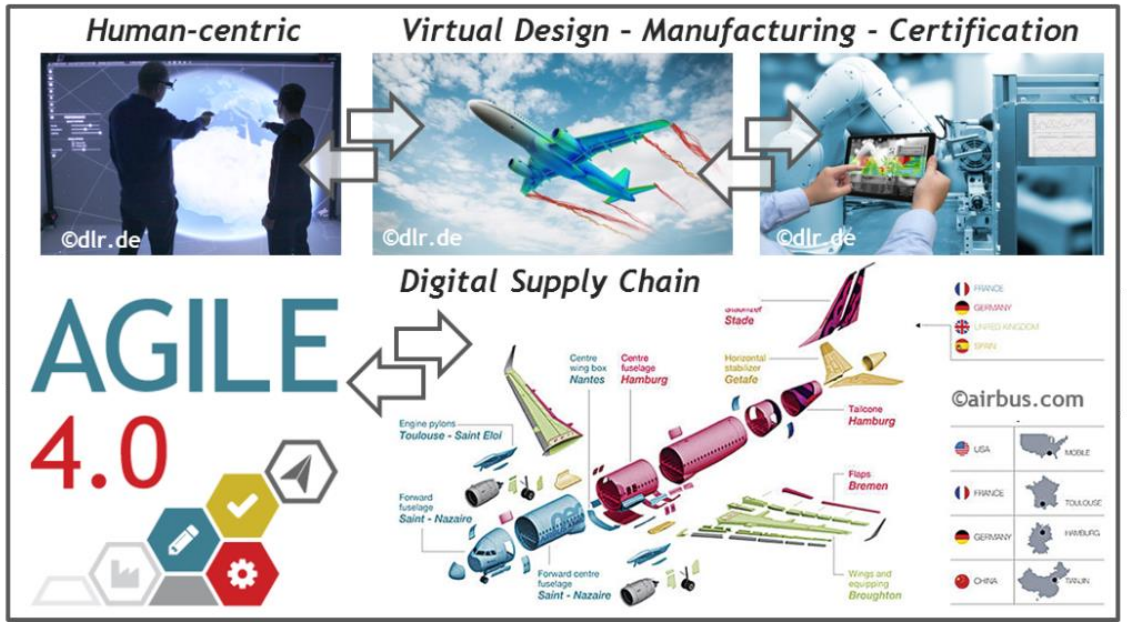


AGILE 4.0 project ambition:

*"The high-level objective of AGILE4.0 is to bring **significant reductions in aircraft development costs and time-to-market through the implementation of an integrated cyber-physical aeronautical supply chain**, thereby increasing the competitiveness of the European aircraft industry, from integrators and high-tiers suppliers to SMEs, **leading to innovative and more sustainable aircraft products**"*

Deutsches Zentrum für Luft- und Raumfahrt (DLR) · AIRBUS · BOMBARDIER · CFS Engineering · Concordia University · EMBRAER · Fokker (GKN Aerospace) · ISAE-SUPAERO · KE-works · LEONARDO · NLR · ONERA The French Aerospace Lab · Politecnico di Torino · ILR Institute of Aerospace Systems, RWTH Aachen University · TU Delft · Università degli Studi di Napoli Federico II

www.agile4.eu



*EU funded H2020 project: **September 2019 – February 2023***

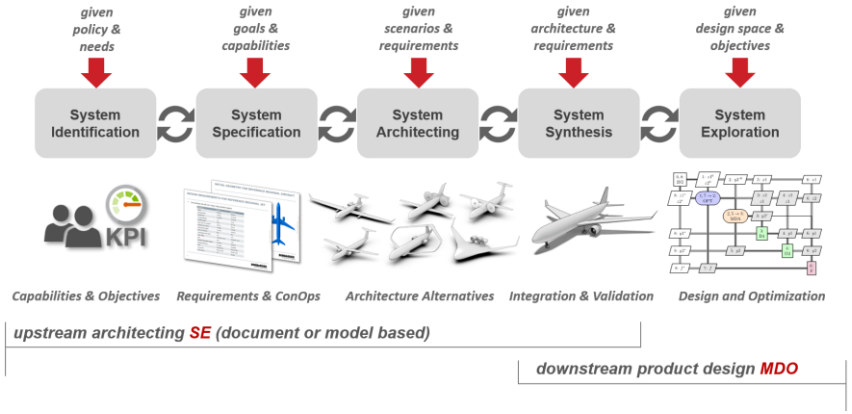
- *16 International Partners (EU, Brazil, Canada)*
- *Coordinated by DLR Hamburg*

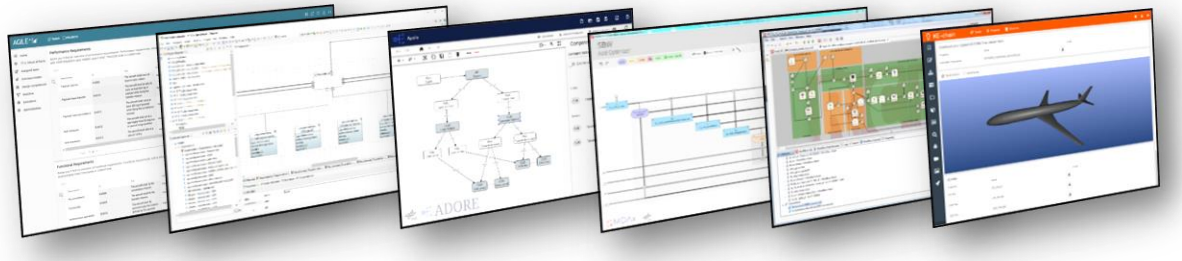
*Towards the next generation **MBSE-MDO** accelerating the development of complex systems*

AGILE 4.0

Contents

1. AGILE 4.0 MBSE-MDAO Development Framework
   - Upstream architecting phases
   - Downstream product design phases
2. Implementation in a collaborative environment
3. Demonstration: Design of a Business Jet Family





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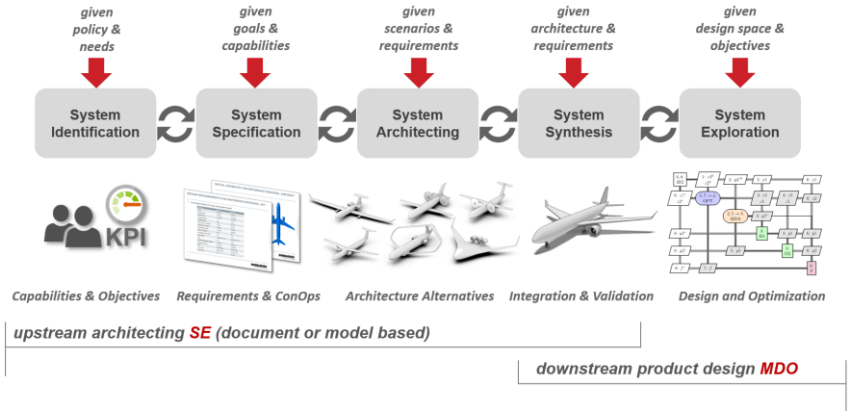
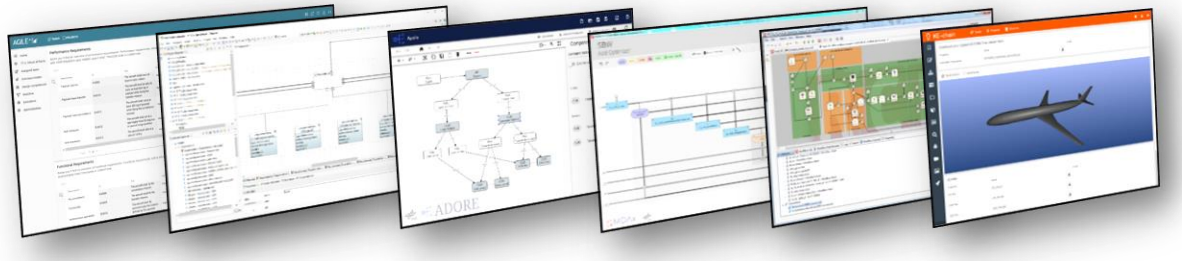




AGILE4.0 MBSE-MDAO Development Framework

System of Interest

given policy & needs

System Identification

given goals & capabilities

System Specification

given scenarios & requirements

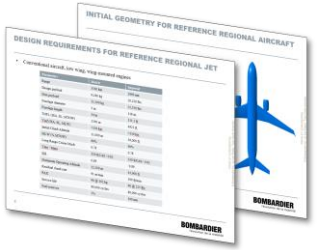
System Architecting

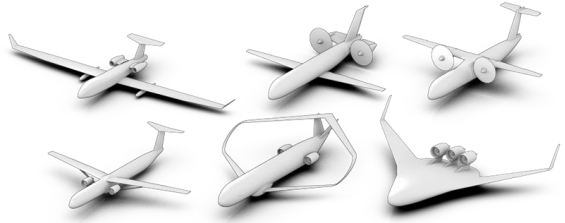
given architecture & requirements

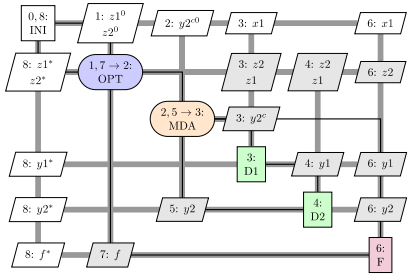
System Synthesis

given design space & objectives

System Exploration







Capabilities & Objectives | *Requirements & ConOps* | *Architecture Alternatives* | *Integration & Validation* | *Design and Optimization*

*upstream architecting **SE** (document or model based)*

*downstream product design **MDO***

AGILE 4.0

Requirement Types & Structure

Statements in natural language → Patterns: each type of requirement has a standard grammar, a set of mandatory and [optional elements] that ensure verifiability related to the type ***(Carson, 2015)***

- **Functional**
  The SYSTEM shall [exhibit] FUNCTION [while in CONDITION]
- **Performance**
  The SYSTEM shall FUNCTION with PERFORMANCE [and TIMING upon EVENT TRIGGER] while in CONDITION
- **Design (constraint)**
  The SYSTEM shall [exhibit] DESIGN CONSTRAINTS [in accordance with PERFORMANCE while in CONDITION]
- **Environmental**
  The SYSTEM shall [exhibit] CHARACTERISTIC during/after exposure to ENVIRONMENT [for EXPOSURE DURATION]
- **Suitability**
  The SYSTEM shall exhibit CHARACTERISTIC with PERFORMANCE while CONDITION [for CONDITION DURATION]

Examples:

The aircraft shall provide propulsive power [during the entire mission]

The aircraft shall fly at minimum Mach 0.8 during cruise

The aircraft shall have technologies with maturity TRL 9 [in 2020]

The aircraft shall be maneuverable in case of icing conditions [for the entire flight]

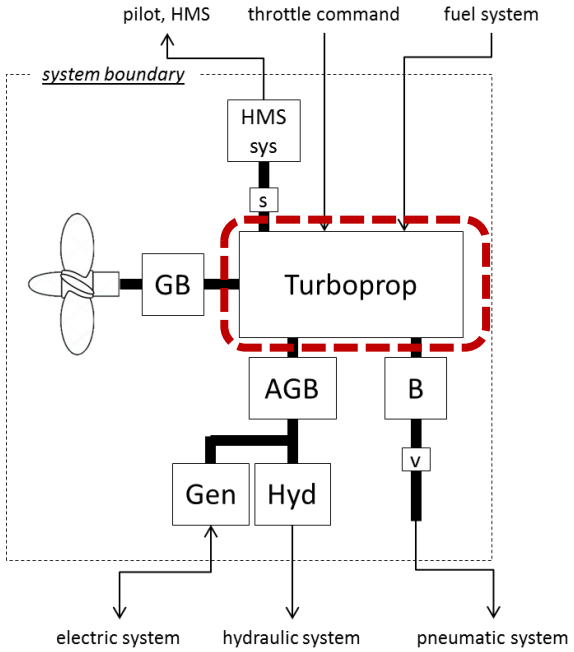
The aircraft shall have a steady gradient of climb of minimum 2.4% in case of one-engine-inoperative

Source: Boggero et al. "An MBSE Architectural Framework for the Agile Definition of System Stakeholders, Needs and Requirements", AIAA 2021

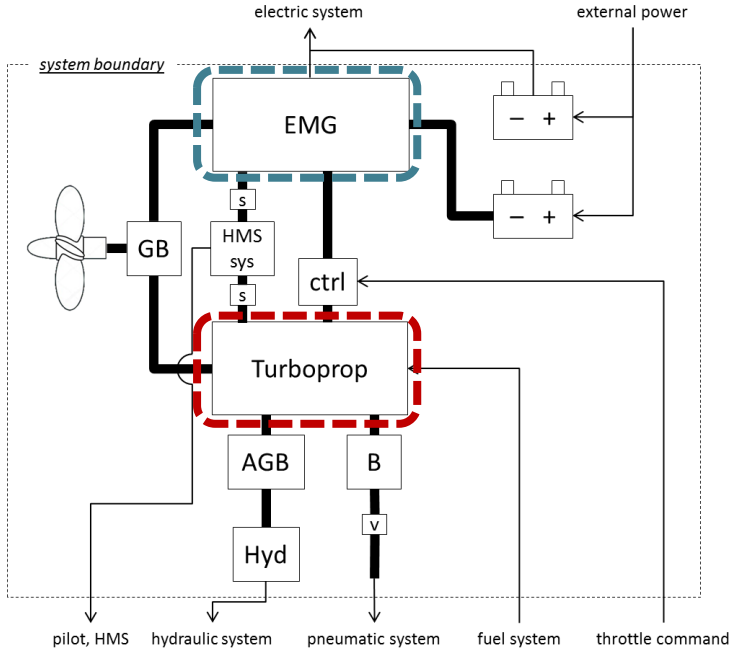
Generation and Modeling of System Architectures

System Architecture = formal **description** of a system. Representation of entities […] that describes behaviors and relationships amongst the entities[1].

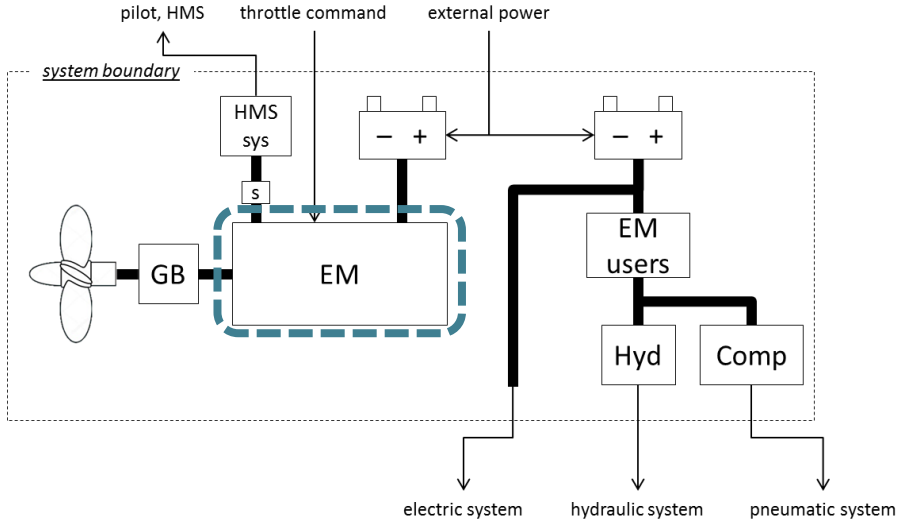
Top Function: "To provide propulsive power"



Conventional architecture



Hybrid-electric architecture



Electric architecture

many more other architectures….

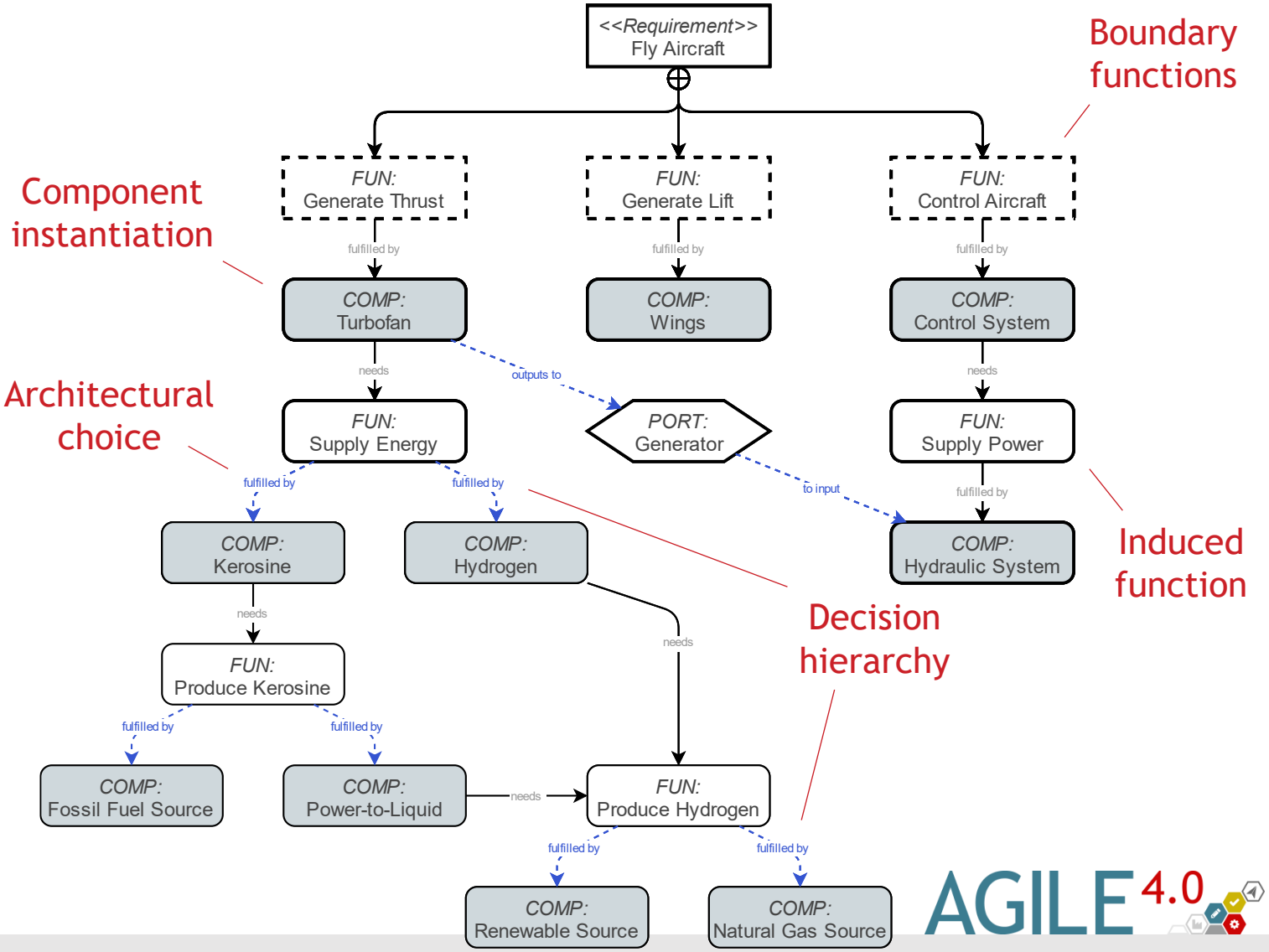
[1] MIT Definition

Function-based System Architecting Process

More details later today at 16:15:
***Bussemaker et al.*: Function-Based Architecture Optimization: An Application to Hybrid-Electric Propulsion Systems**
Session 2.3.1 Architecture Analysis

- Collect functional requirements for specific level of elaboration
- Identify boundary functions
- Allocate boundary functions to components
- Identify induced functions and fulfill these
- Model additional architectural choices

Function-based architecting benefits:
- Natural transition from problem to solution
- Less prone to solution bias
- Directly traceable to requirements



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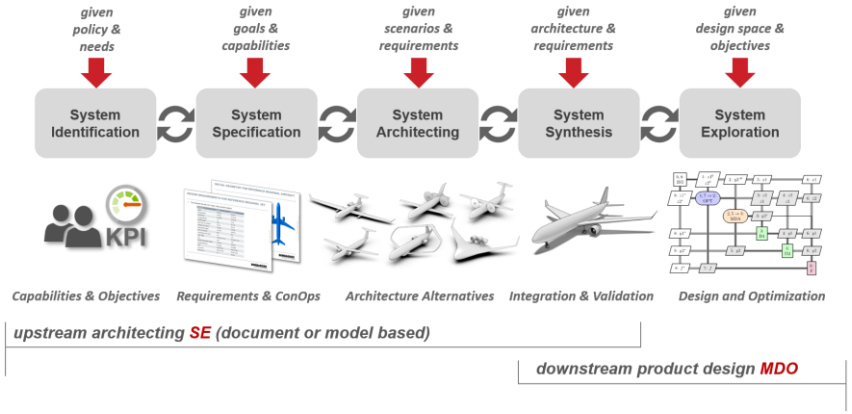
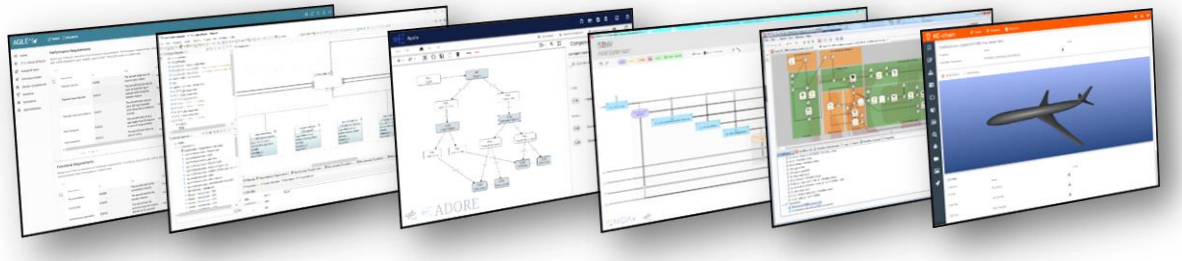
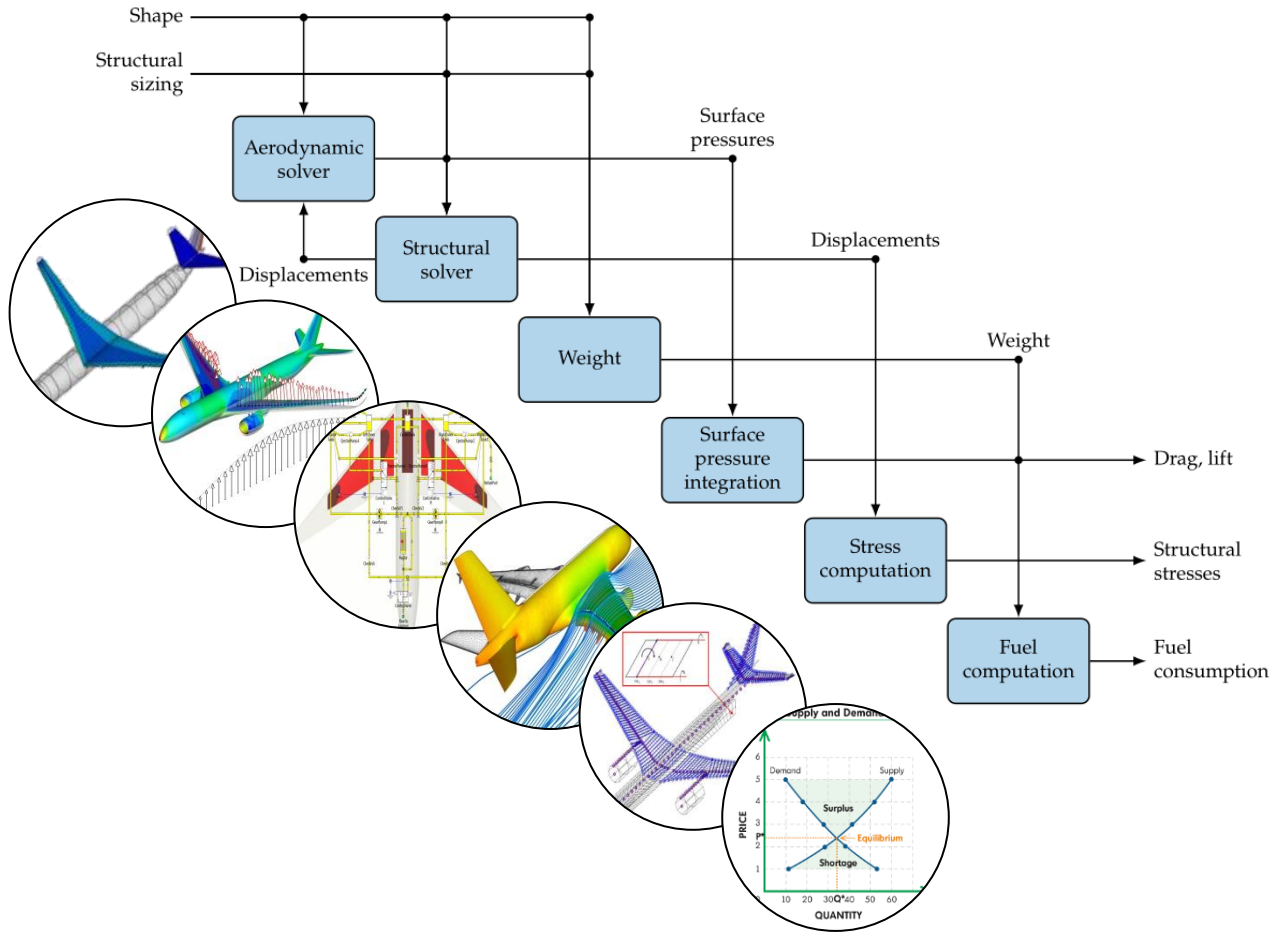




Multidisciplinary Design Analysis & Optimization (MDAO)

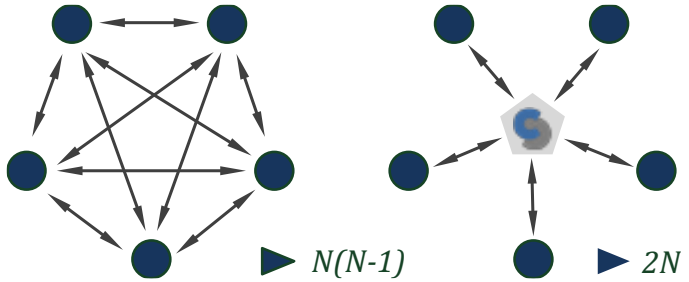
- Different system elements *influence performance* in different ways
- Engineering disciplines analyze the system from *different perspectives*

- **MDAO: numerical coupling of disciplinary analysis tools**
- Essential to enable *system-level* analysis
- How to deploy cross-organizational MDAO?



Collaborative MDAO Process

Common format for exchanging design data



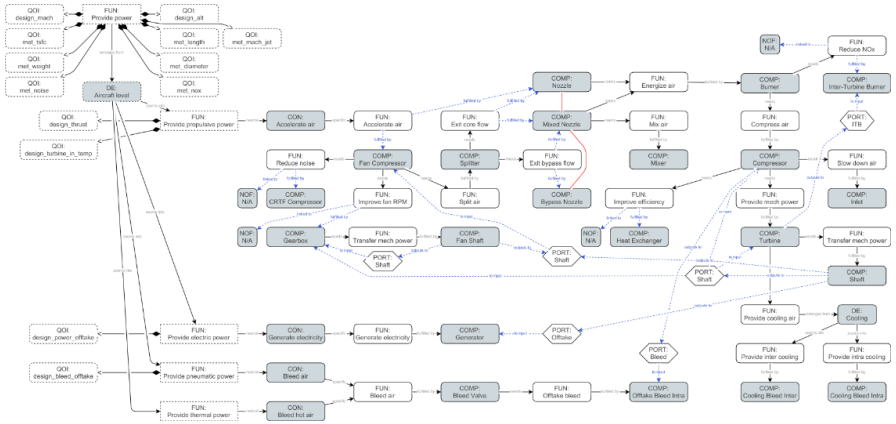
Automatic connection of tools

Cross-organizational data transfer via neutral server

Connecting MBSE and MDAO

MBSE Architecture Model

- Logical description of the SOI
- Described in terms of functions, components, QOIs, etc.
- Link to upstream requirements



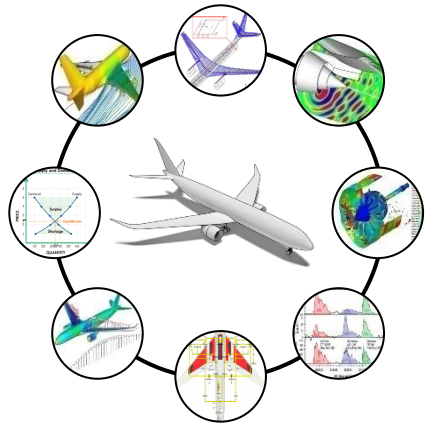
Define Design Problem

Sync Architectures

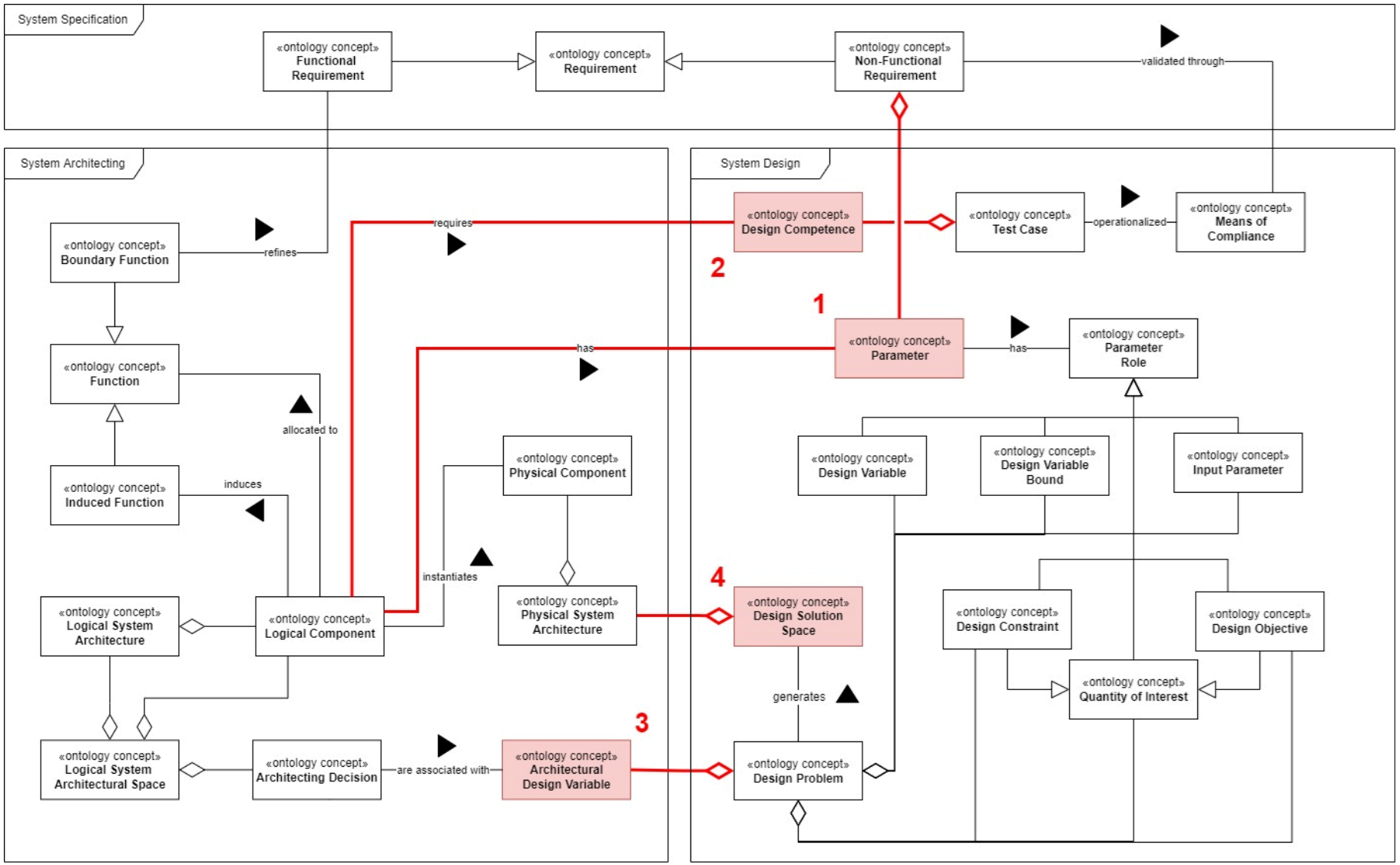
Performance Data

MDAO Product Model

- Physical description of the SOI
- Described using central data schema, in terms of geometry, performance data, etc.
- Connected to disciplinary tools



MBSE-MDAO Connection Ontology



1. Design parameters are specified from:
   - Architecture components
   - Non-functional requirements
2. Design competences (tools) are selected from:
   - The need to evaluate component influence
   - Specification in test cases
3. Design variables are additionally defined from architectural choices
4. Design solutions represent physical architectures

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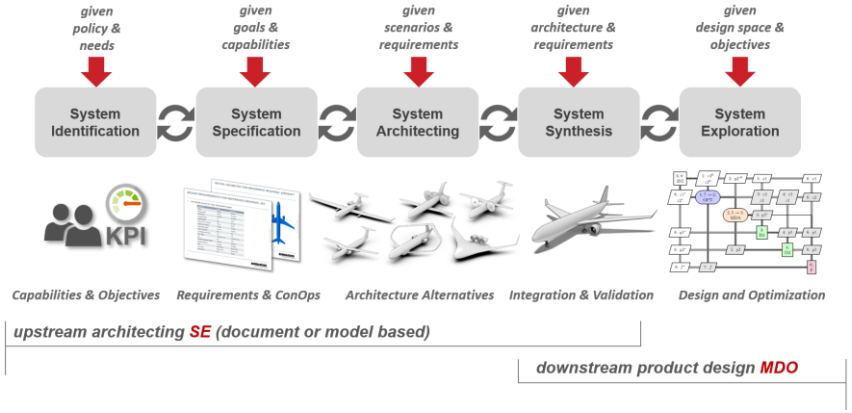
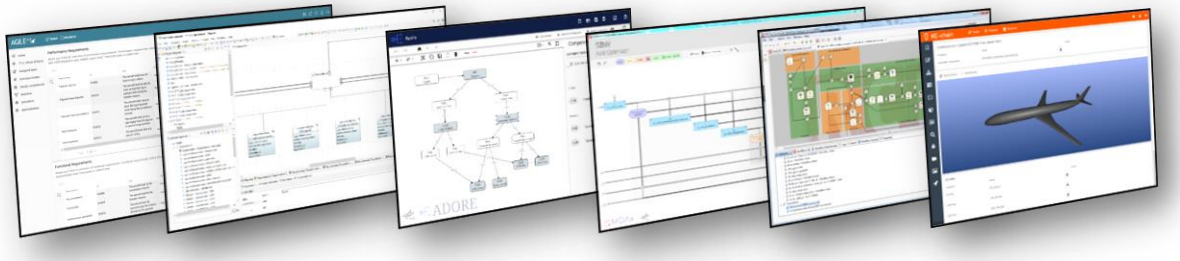




The Operational Collaborative Environment

Papyrus
Visualization of stakeholders, needs and requirements model

Capella
Operational scenarios modeling

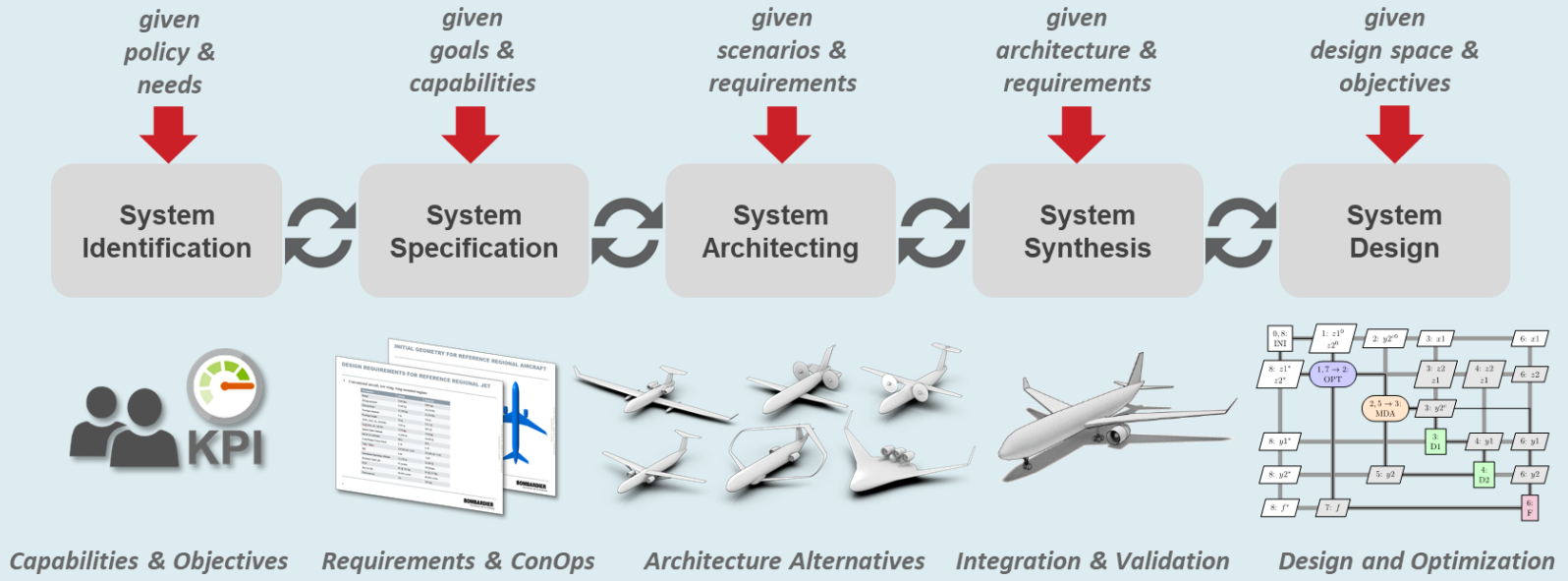
KADMOS
MDAx
MDO Workflow Design Accelerator
MDAO workflows modeling environments

SMR
WhatsOpt
Definition and sharing of executable surrogate models

MBSElib
Automatic generation of SysML models

BRICS
Enabling cross-organization collaborative simulation workflows

RVF
Requirements verification



RCE
Executing simulation workflows

ADORE
System architecture design space modeling and visualization

MULTILINQ
Bridging system architectures and MDAO

KE-chain
Web-based collaboration and process integration platform

ADORE: Architecture Design Space Editor

Architecture **design space** modeler

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

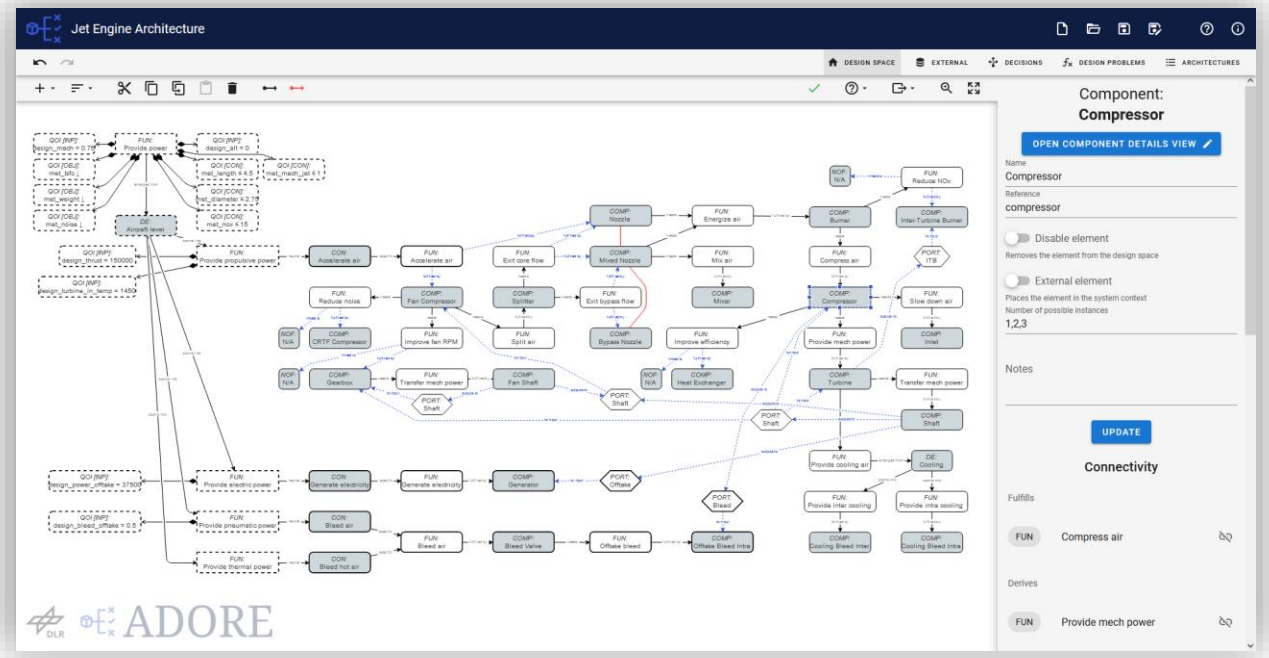
Architecture **generator**

- Make architectural choices to create architectures

Architecture **optimization** framework

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

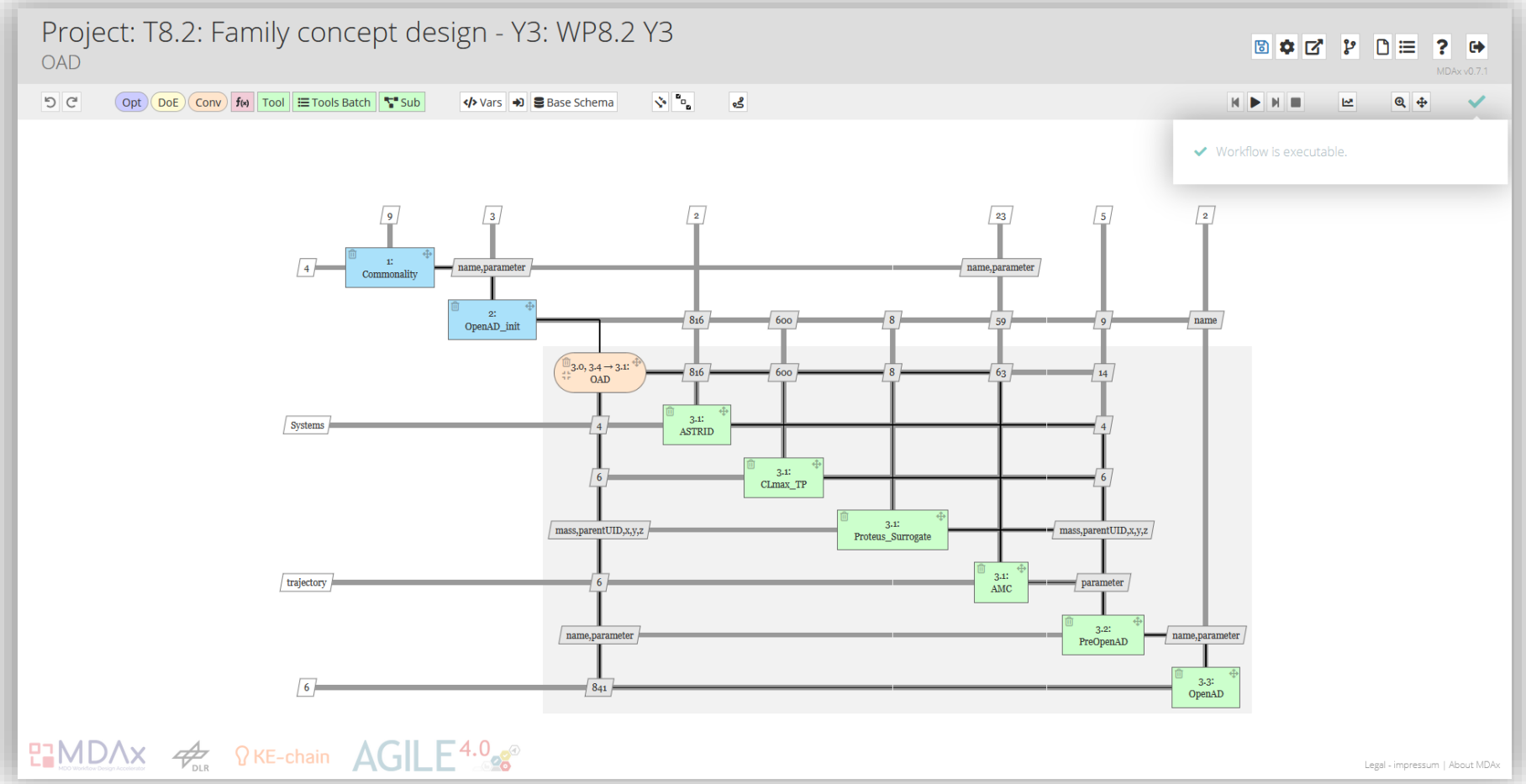
ADORE



More details later today at 16:15:
***Bussemaker et al.*: Function-Based Architecture Optimization: An Application to Hybrid-Electric Propulsion Systems**
Session 2.3.1 Architecture Analysis

Collaborative MDAO Workflow Modeling

- Import disciplinary tool I/O definitions
- Automatically discover data connections
- Interactively add MDAO elements like converger, optimizer, etc.
- One-click export to execution environment



MDAx
MDO Workflow Design Accelerator

AGILE 4.0

Architecture-to-MDAO with MultiLinQ

1. Map architecture elements to CDS nodes

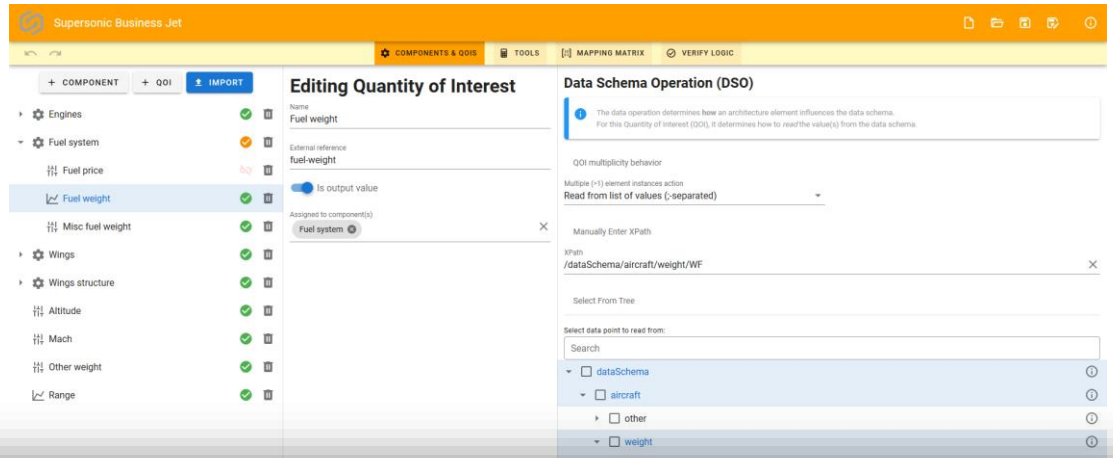
```
<mWingsStructure>
    <massDescription uID="mWingsStructure">
        <mass>1672.3220548910942</mass>
    </massDescription>
    <mWingStructure>
        <massDescription uID="wing_mass">
            <parentUID>wing</parentUID>
            <mass>1229.6052745879338</mass>
```

QOI:
Wing Weight: 1229.61

2. Support selection of MDAO disciplines

Using the *Component-Tool* matrix

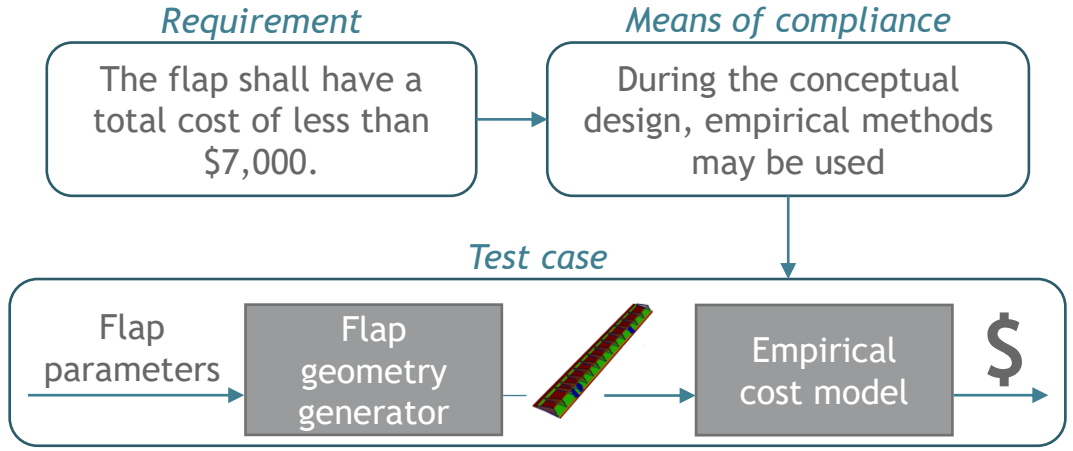
MULTILINQ



Components	QOIs	Tools: 02_CPACS_Update	03_CATIA_Update	04_Surface_Mesh	05_Volmesh_Deform	06_Struct_Mdl	08_TAU	10_Nastran	11_HyperSizer	12_Struct_Mdl_Upd	14_Nastran_Deform	15_FlowSimulator	16_Obj	18_FlowSim_TAU	19_Obj_Conv
Aircraft			✓		✓	✓	✓		✓				✓	✓	✓
Aircraft	Flight cond						✓							✓	
Wing		✓					✓	✓	✓		✓			✓	
Wing	DV	✓													
Wing	Aero forces						✓								
Wing	Deformation										✓				
Wing	L/D						✓							✓	
Wing	Loads							✓							
Wing	Mass								✓						
Wing	Thickness								✓						
	Objective												✓		✓

Requirements Verification Framework

- Goals:
  1) to enable automatic verification
  2) to integrate requirements in MDAO



- 5-step approach:

Machine readable requirements → Define verification methods → Assign roles to requirement parameters → Derive & execute the MDAO workflow → Check requirement compliance

- **Functional**
  The SYSTEM shall [exhibit] FUNCTION [while in CONDITION]
- **Performance**
  The SYSTEM shall FUNCTION with PERFORMANCE [and TIMING upon EVENT TRIGGER] while in CONDITION
- **Design (constraint)**
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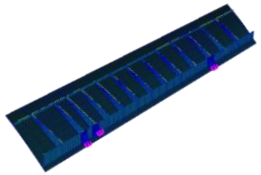
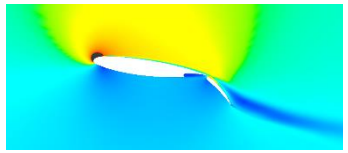
  The SYSTEM shall exhibit CHARACTERISTIC with PERFORMANCE while CONDITION [for CONDITION DURATION]





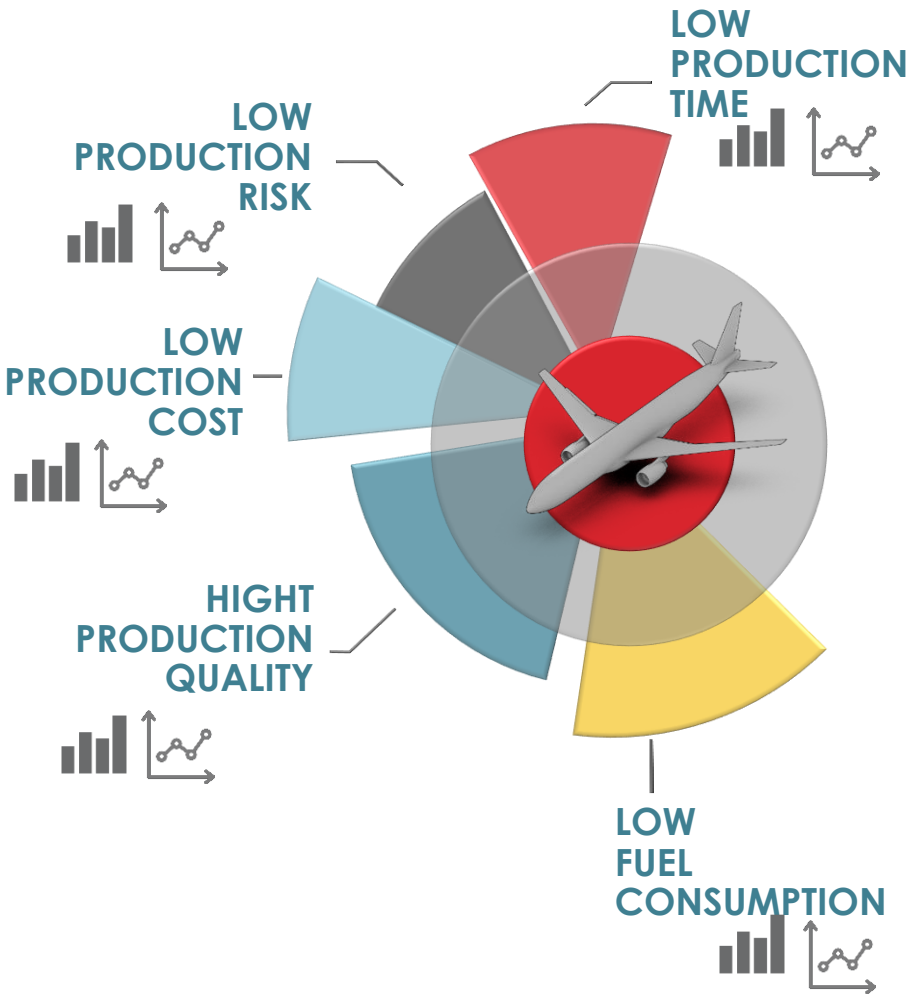
Objective

Constraint

Design variable

***Bruggeman:* From Requirements to Product: Digitalization of the Aircraft Design Process**
Monday poster sessions

Connect Stakeholder Expectations to MDAO with VALORISE



Web-based Interactive Dashboard

- Quantify & Assess Stakeholder Expectations
- Real-time Trade-Off
- Explore Strategic Decision Scenarios

VALORISE

Stand-Alone Tool

- Tool-chain Integration

Tuesday at 13:30:
***Donelli et al.*: Value-driven SE Approach addressing Manufacturing, Supply-Chain and Aircraft Design in the Decision-Making Process**
Session 5.4.1 Supply Chain

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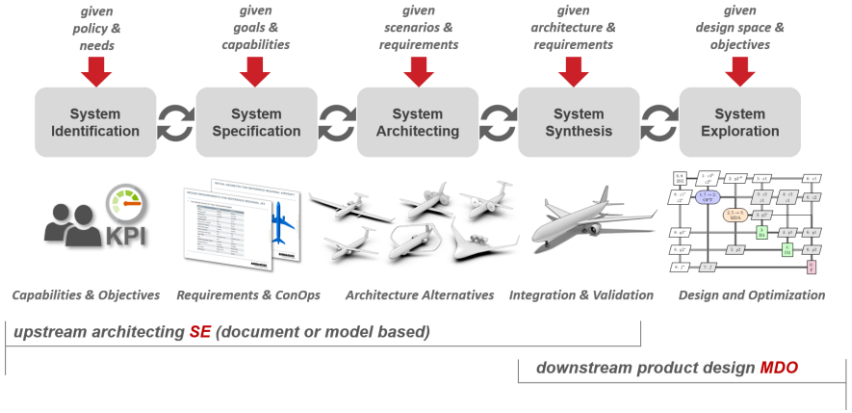
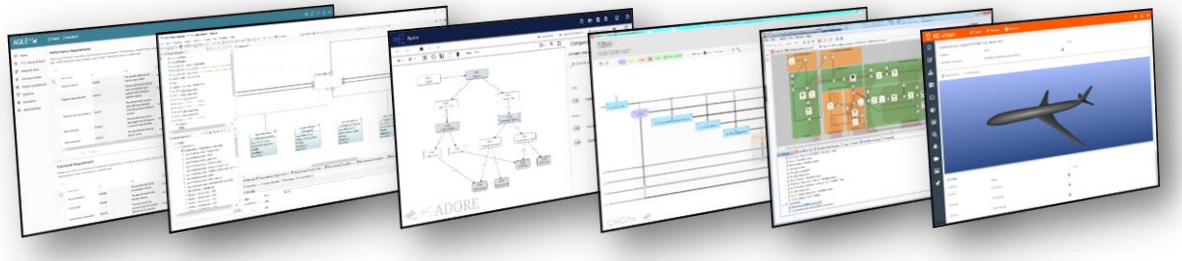




Business Jet Family Design Case

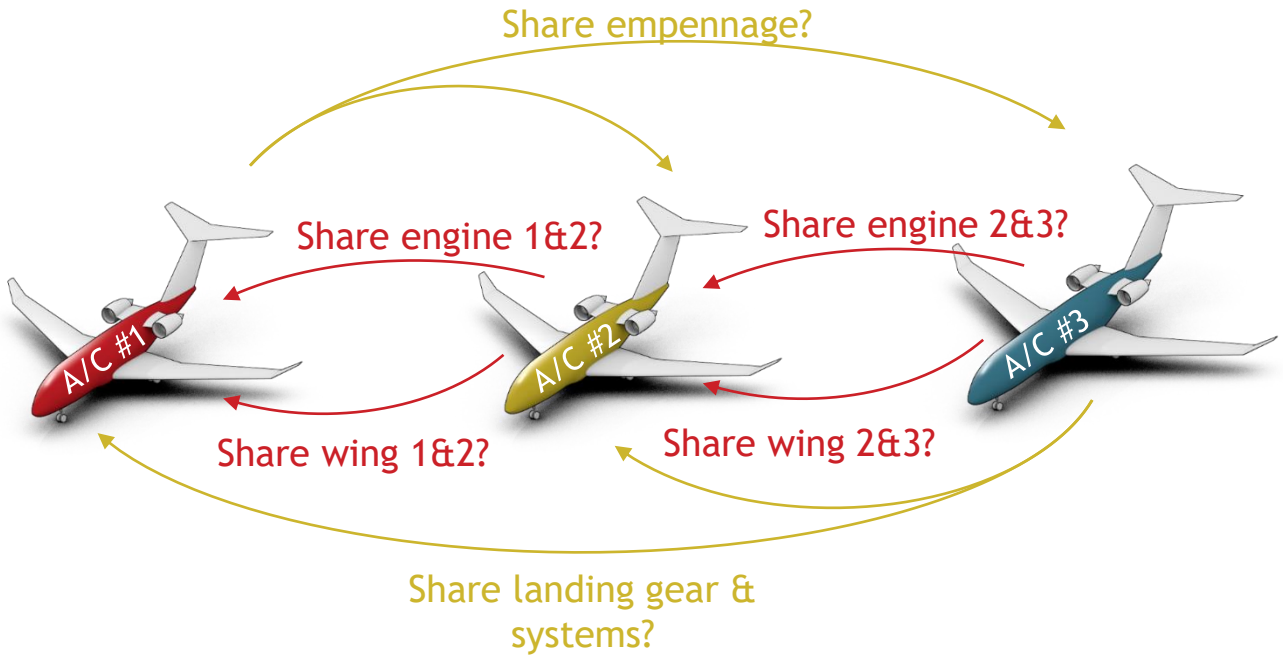
- Tradeoff between OEM NRC and DOC
- Sharing more components:
  - Decreasing investment costs
  - Increasing operating costs

Parameter	Unit	Aircraft Values		
Long-range cruise speed	M	0.85		
High-speed cruise speed	M	0.90		
Design payload	Pax	8		
Design range	nm	2500	3000	3500
Cabin length	ft	25	25	35
Balanced field length	ft	5000		
Landing field length	ft	2500		
Initial cruise altitude	ft	41000		

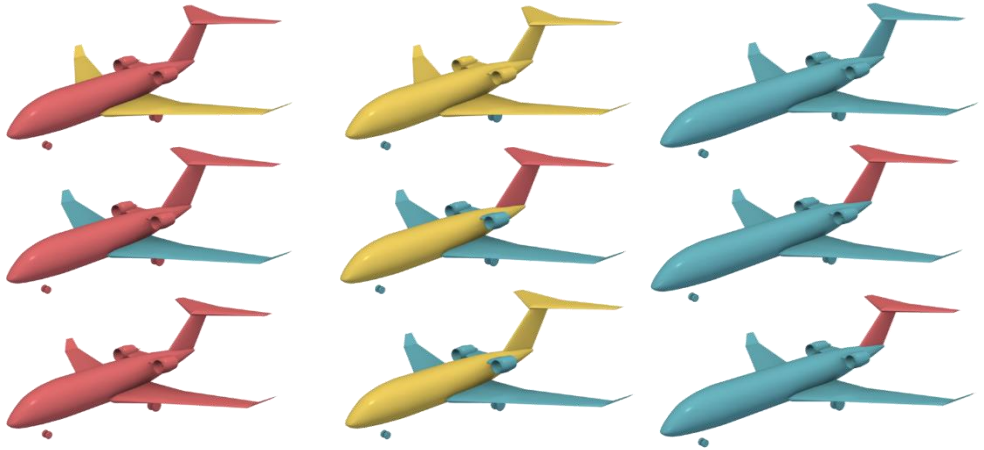
Commonality Sharing Decisions

No sharing: high performance

Max sharing: low investment costs

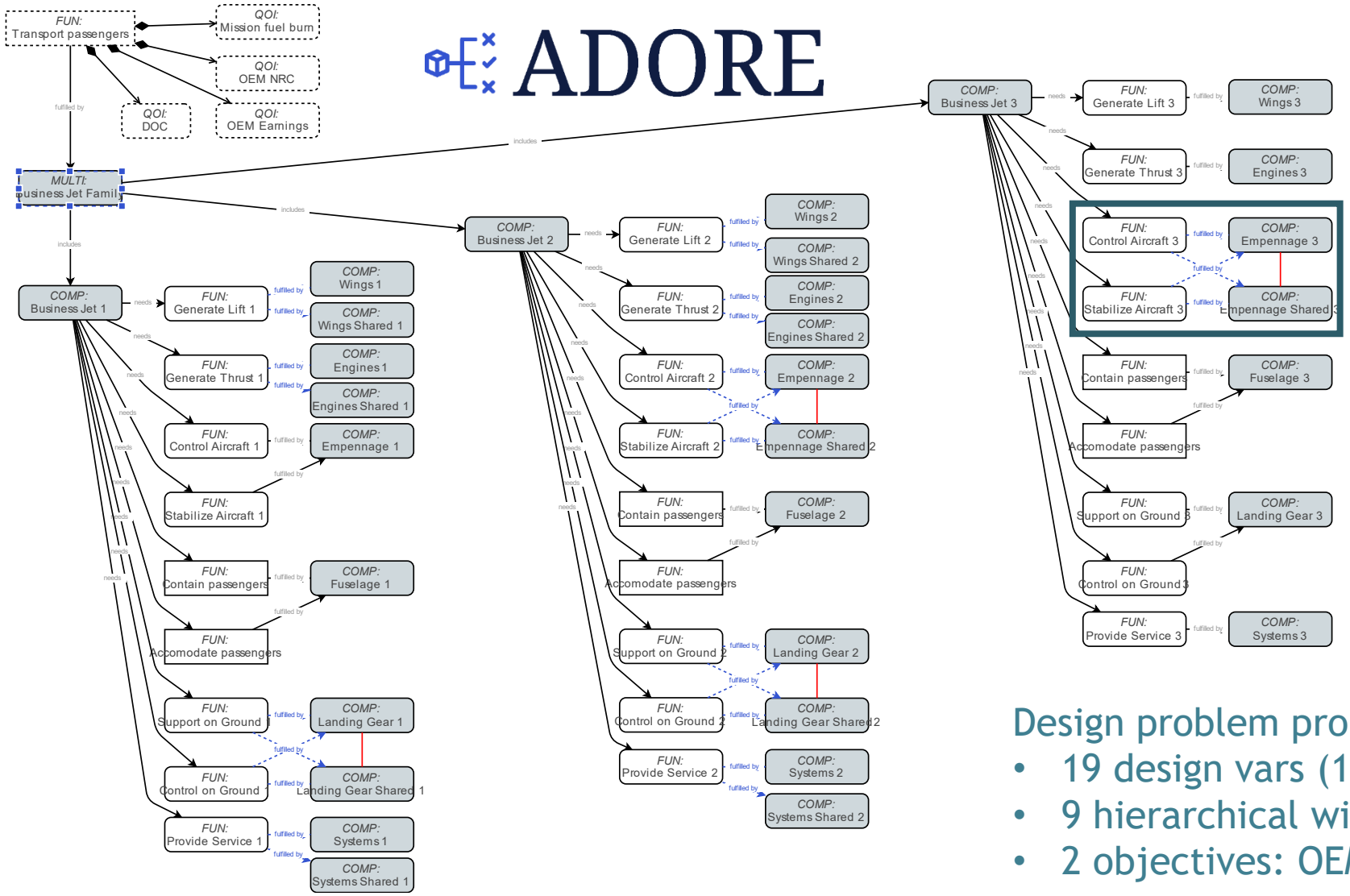


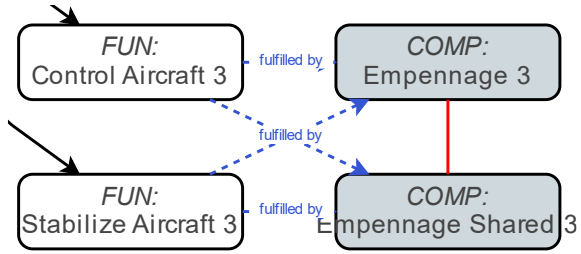
1024 possible family architectures



Architecture Design Space Model

ADORE



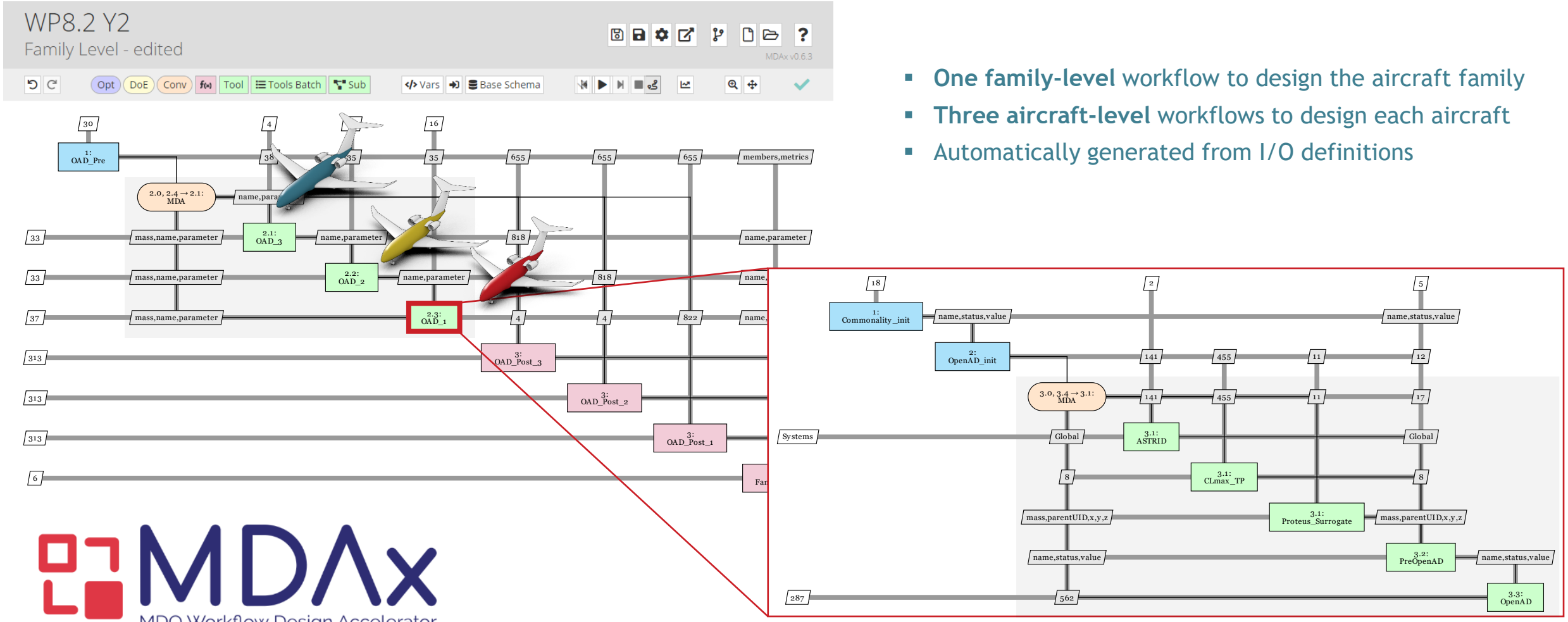


Share empennage?

Design problem properties:

- 19 design vars (10 discrete)
- 9 hierarchical wing design vars
- 2 objectives: OEM NRC, DOC

Multilevel MDAO Workflow



- **One family-level** workflow to design the aircraft family
- **Three aircraft-level** workflows to design each aircraft
- Automatically generated from I/O definitions

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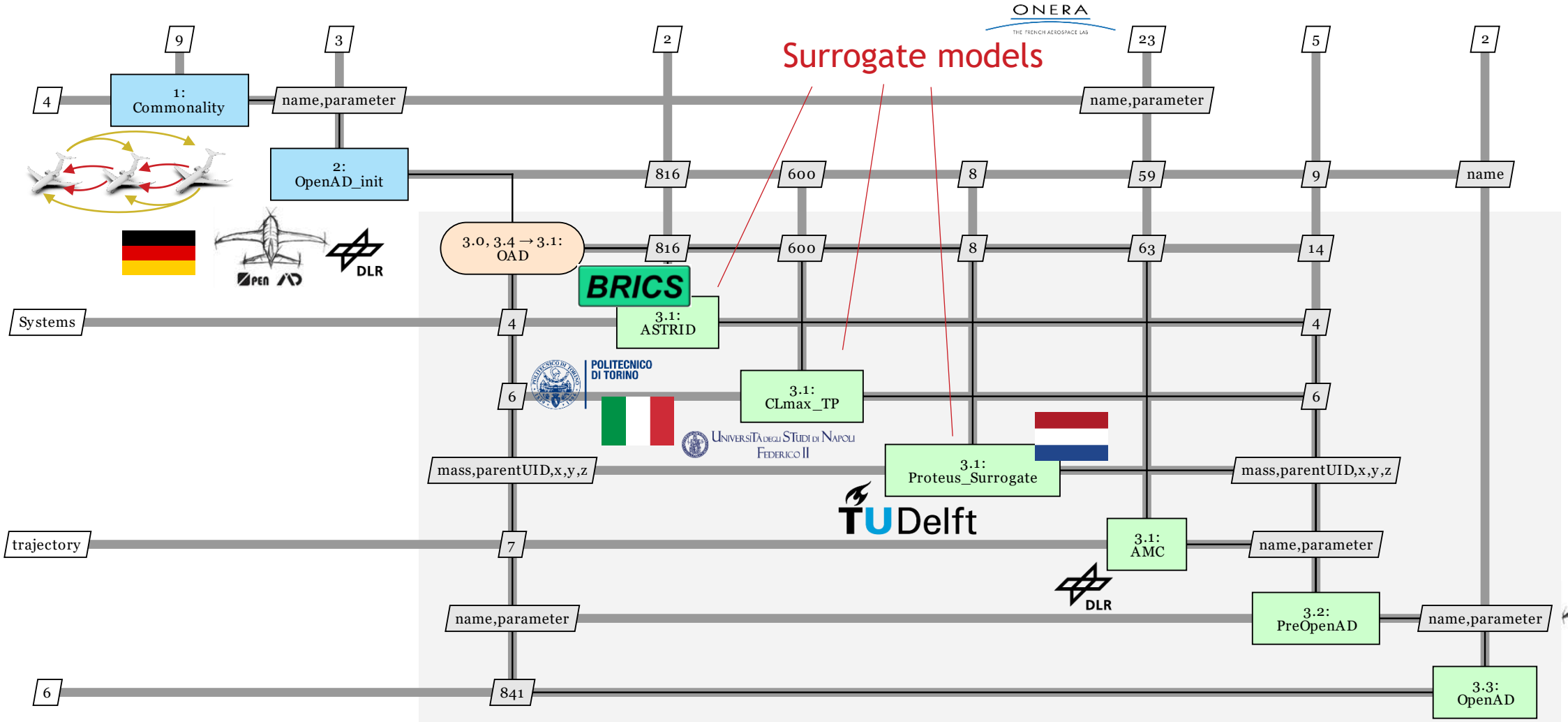
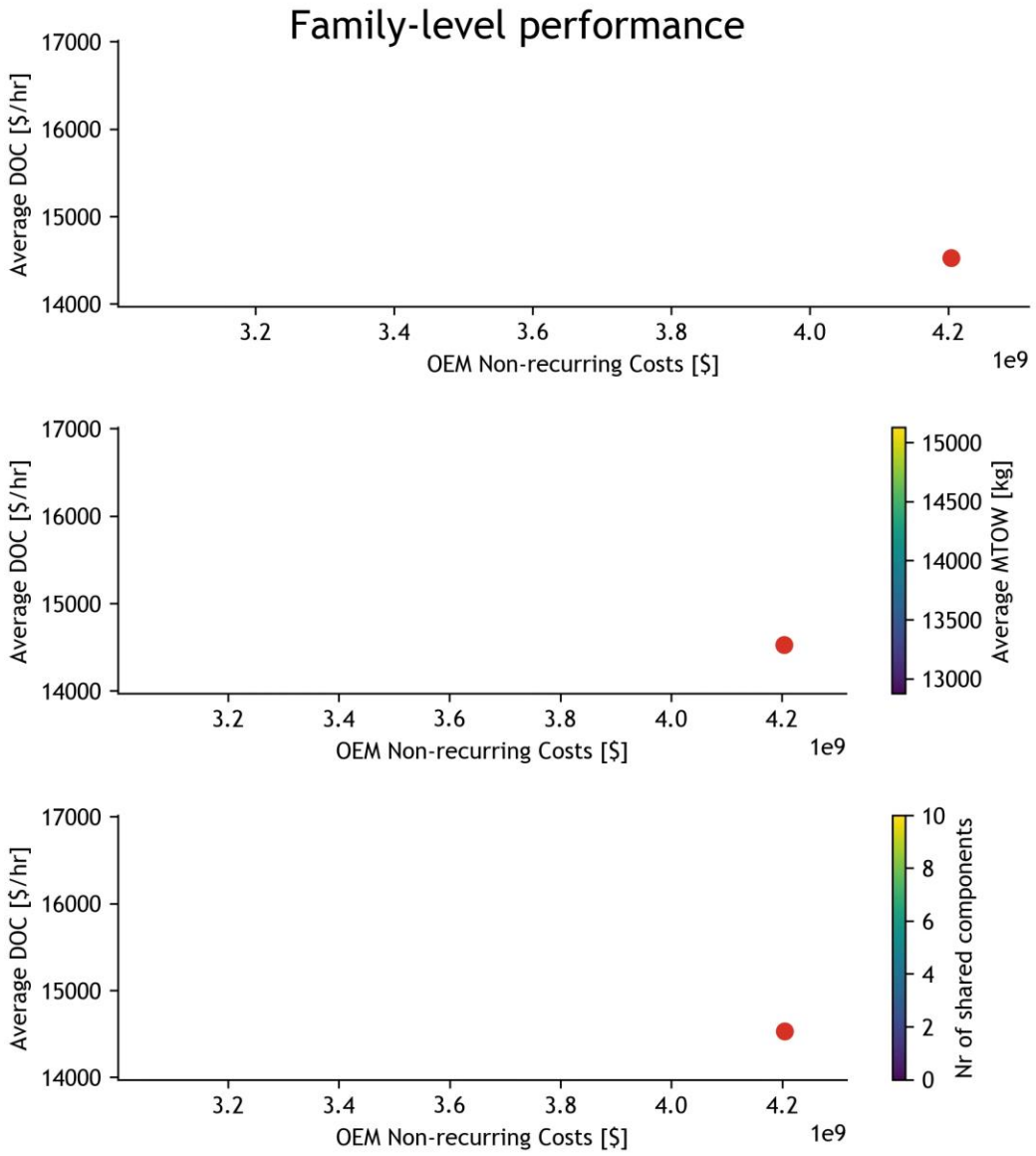
Aircraft-level MDAO Workflow



Business Jet Family Results



Aircraft #1
25ft cabin, 2500NM range

Aircraft #2
25ft cabin, 3000NM range

Aircraft #3
35ft cabin, 3500NM range

BOMBARDIER

DLR Deutsches Zentrum für Luft- und Raumfahrt

Università degli Studi di Napoli Federico II · Politecnico di Torino · ONERA · TU Delft · ILR RWTH Aachen University

Business Jet Family #1 (DOE)

Design variables

	AC 1	AC 2	AC 3
Wing sized for	AC 1	AC 2	AC 3
Engine sized for	AC 1	AC 2	AC 3
Ldg gear sized for	AC 1	AC 2	AC 3
Systems sized for	AC 1	AC 2	AC 3
Empennage sized for	AC 1	AC 2	AC 3
Wing sweep (LE) [deg]	36.0	30.1	36.6
Rear spar position [%]	77.0	81.5	81.6
Thickness ratio [%]	8.5	10.1	7.2

Output metrics

	AC 1	AC 2	AC 3
MTOW [kg]	12000	13060	14940
Block fuel [kg]	3580	4340	5140
DOC [$/hr]	12700	14680	16200
Wing area [m2]	48.9	48.8	59.6
Rated thrust [kN]	20.6	22.4	25.6
Mean DOC [$/hr]	14520		
OEM NRC [M$]	4200		

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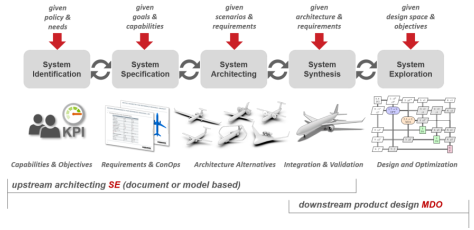
Overview

1. AGILE 4.0 MBSE-MDAO Development Framework



2. Implementation in a collaborative environment

ADORE
MDAx
MDO Workflow Design Accelerator
MULTILINQ
RCE
ALORISE

3. Demonstration: Design of a Business Jet Family

Publications, technologies, use cases:
www.agile4.eu

Monday poster sessions:
***Bruggeman et al.*: From Requirements to Product: Digitalization of the Aircraft Design Process**

Monday 16:15, session 2.3.1:
***Bussemaker et al.*: Function-Based Architecture Optimization: An Application to Hybrid-Electric Propulsion Systems**

Tuesday 13:30, session 5.4.1:
***Donelli et al.*: Value-driven SE Approach addressing Manufacturing, Supply-Chain and Aircraft Design in the Decision-Making Process**

Thursday 11:30, session 11.5.3:
***Merola et al.*: Value-driven Optimization Campaign Addressing Manufacturing, Supply Chain and Overall Aircraft Design Domains in the Early Development Stage**

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