DELIVERABLE D 7.5

CERTIFICATION DRIVEN STREAM MDO FRAMEWORK DESCRIPTIONS AND TRADE OF RESULTS

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GLOSSARY

Acronym	Signification
A4F	AGILE 4.0 framework
AC	Application Case
AEA	All-Electric Aircraft
CS	Certification Specifications
DOE	Design of Experiments
ECS	Environmental Control System
EMC	Electromagnetic Compatibility
FCS	Flight Control System
IPS	Ice Protection System
LCC	Life Cycle Cost
L/D	Lift-over-drag ratio
MEA	More-Electric Aircraft
MDO	Multi-Disciplinary Optimization
MTOM	Maximum Take-Off Mass
MTTR	Mean Time To Repair
OBS	On-Board System
OCE	Operational Collaborative Environment
OEM	Original Equipment Manufacturer
PS	Pneumatic System
QoI	Quantity of Interest
RSM	Response Surface Method
RVF	Requirements Verification Framework
SE	System Engineering
SOI	System Of Interest
TLARs	Top Level Aircraft Requirements
XSDM	eXtended Design Structure Matrix
VCS	Virtual Certification System

1 EXECUTIVE SUMMARY

1.1 Introduction

The activities carried out in the framework of WP7 are described in the present deliverable. With the aim to provide a complete view of the different Application Cases (ACs), some parts of the activities already presented in the previous non-public deliverables (D7.1, D7.2, D7.3 and D7.4) are here briefly summarized.

In Fig. 1 all the steps connecting the System Engineering (SE) approach to the Multidisciplinary Design Optimization (MDO) are formalized. Each AC is described complying with those steps dividing the report into the following sub-sections:

- System identification; definition of a list of stakeholders and their needs, scenario description.
- System specification; complete list of requirements from mission to aircraft and subsystems level within a fully traceable process.
- System architecting; formalization of the architecture of the most important system/sub-systems where different options of possible architectures are defined.
- System synthesis; among the different possible system/subsystems architectures the most suitable architecture is selected.
- System design; considering the stakeholders' needs, related requirements, and the architectures selected, the aircraft is designed throughout a Multidisciplinary Design Optimization process.

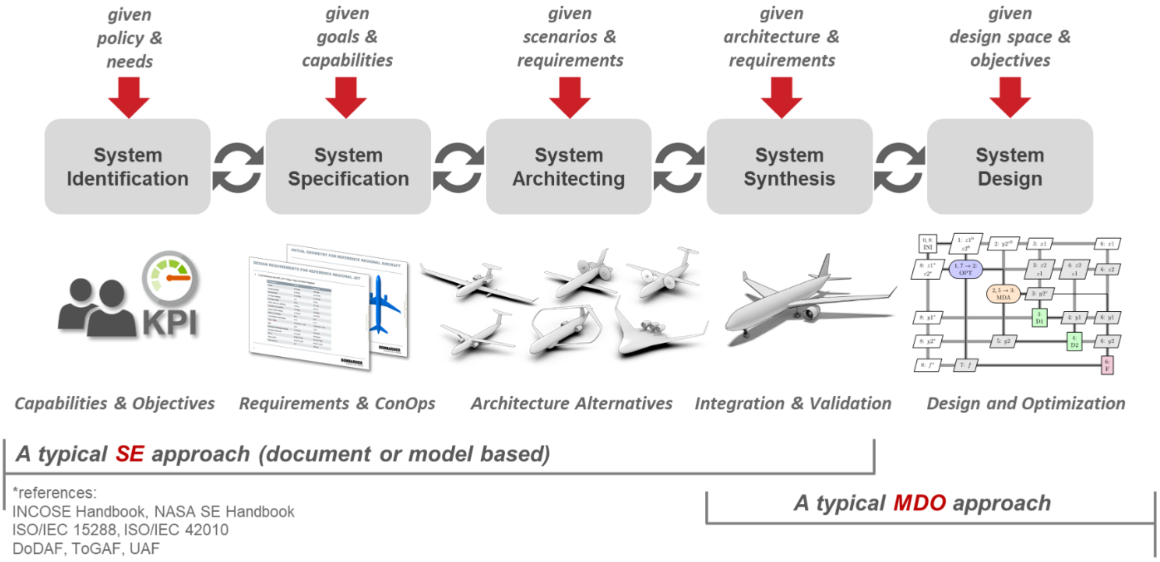


Fig. 1 : AGILE 4.0 Overall Steps

Many results and models have been produced in work package 7, which are presented and explained in the deliverable and made publicly available on the AGILE 4.0 project website, respectively in https://www.agile4.eu/ac3-electrification/ (AC3), https://www.agile4.eu/ac4-maintenance/ (AC4), and https://www.agile4.eu/ac5-certification/ (AC5).

1.2 Brief description of the work performed and results achieved

The technologies developed within the AGILE4.0 framework have been applied to three different ACs starting from the needs and the requirements formalization to the MDO definition including certification related disciplines.

In particular, the main achievements for each AC are:

- AC3 – MDO formulation adding external noise limits, minimum performance during takeoff and landing and systems safety assessment within an aircraft design loop
- AC4 – MDO formulation adding maintenance and thermal risk constraints resulting in an optimal positioning of equipment in the electric bay
- AC5 – MDO formulation and execution including the Lightening Indirect Effects (LIE), On-Board System (OBS) Design, Thermal Risk Analysis (TRA) and Aero-structural Analysis and Optimization. The Trade-Off between avionics costs and structural weight is investigated including different design scenarios consisting of different set of avionics reference costs.

1.3 Deviation from the original objectives

1.3.1 Description of the deviation

According to the project extension, the WP7 activities required more time due to the inevitable inefficiencies caused by Covid pandemic and the delay of other WPs whose results were required by WP7.

1.3.2 Corrective actions

The D7.5 release date has been shifted to the end of February 2023.

2 Application Case 3

The main objective of the AC3 is to add certification constraints in the MDO problem formulation [1]. In particular, the external noise, the minimum performance during take-off and landing operation and the systems safety regulation constraints are considered. The reference aircraft (Fig. 2) is a small regional turboprop, 19 seats, having a maximum take-off mass close to the maximum acceptable value for CS23 (Certification Specifications) regulation. In this way, the aircraft can be studied separately applying CS23 and CS25 regulation constraints to understand their effects on the aircraft design [2]. Different electrification levels of the On-Board Systems (OBS) are considered defining four systems architectures (Fig. 3) [3]. Considering the aim of the AC3, the MDO objectives are the minimization of the aircraft Life Cycle Cost (LCC) and the maximization of the certification margins. The main variables are the OBS electrification level and the wing surface.

Fig. 2: Application Case 3. Systems electrification.

To understand the differences of the different OBS electrification level (Fig. 3), a brief description of them is here provided:

- Conventional (Conv) architecture: flap and landing gear actuators use hydraulic technology, powered by 3000 psi (≈207 bar) hydraulic system. The Ice Protection System (IPS) is pneumatic (de-icing boots) using the bleed air tapped from aircraft engines. The environmental control system (ECS) that regulates the cabin air pressure and temperature is conventional and it is supplied by pneumatic power bled by aircraft engine. The electric system generates 28VDC by brushed generators.

- More Electric Aircraft, first configuration (MEA1): All actuators (flaps and Landing gear) are electric, powered by high voltage electric system. The IPS is conventional (de-icing boots). The air conditioning system (ECS) is also conventional (bleed air tapped from engines) and regulated in pressure and temperature. Hydraulic system is not present. Electric system generates 270 VDC.

- More Electric Aircraft, second configuration (MEA2): all actuators (flaps and Landing gear) are hydraulic, powered by 5000 psi (~345 bar) hydraulic system with electric driven hydraulic pumps. The IPS is electric and it uses high voltage electrical resistance. The ECS is electric. It uses external air, which is pressurized by dedicated compressors driven by electric motors. The electric generators and power buses use 270 VDC.

- All Electric Aircraft (AEA) architecture: All actuators (flaps and Landing gear) are electric, powered by high voltage electric system. The IPS is electric with high voltage electrical resistance. The ECS is electrical. It uses external air pressurized by dedicated compressors driven by electric motors. The hydraulic system has been removed. The electric system generates at 270VDC.

As for many aircraft belonging to small regional / commuter category, in all the architectures the Auxiliary Power Unit (APU) has been removed since the batteries can provide for engine starting.

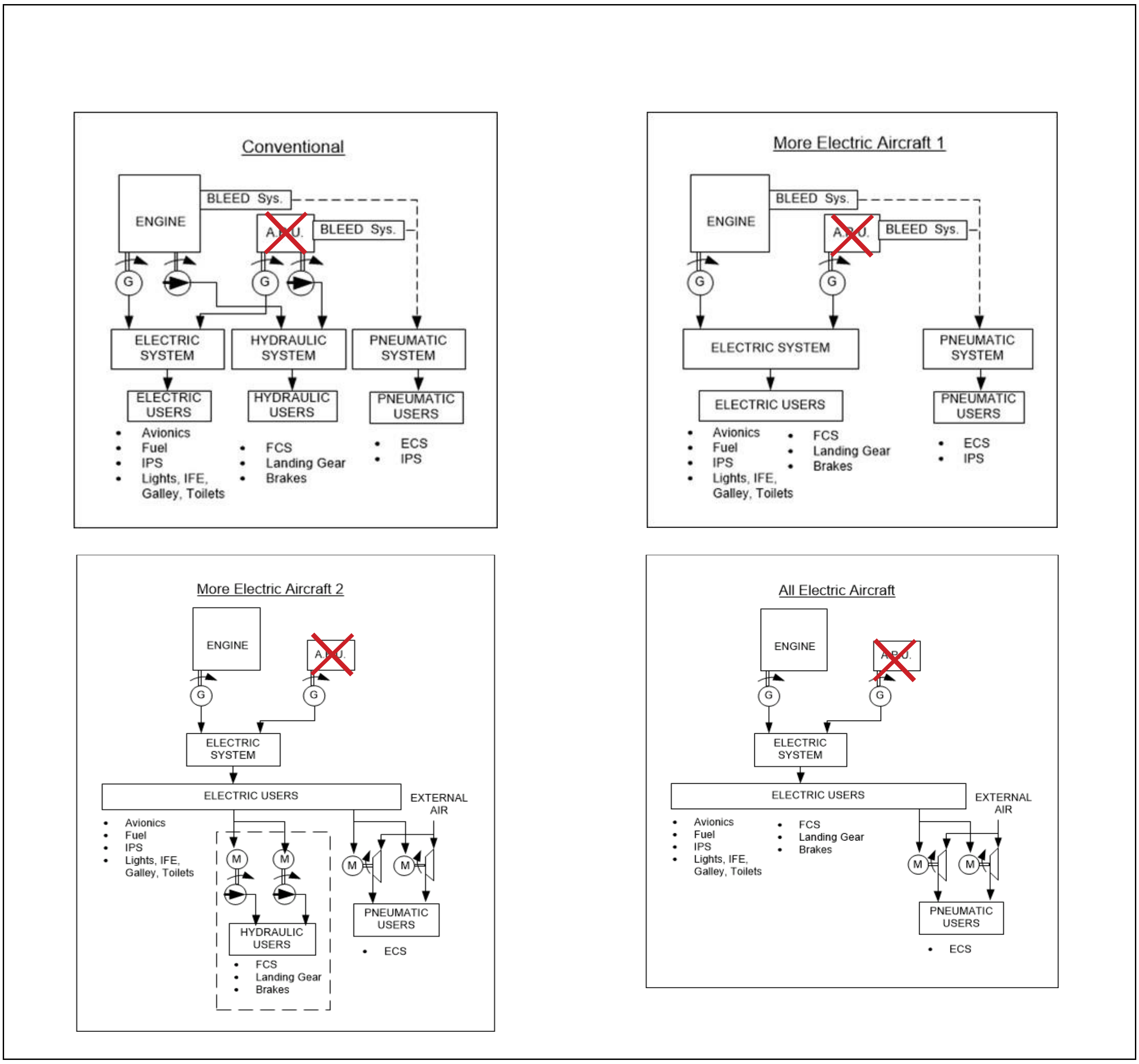


Fig. 3 On-Board Systems architectures. Four levels: Conventional, More Electric Aircraft 1, More Electric Aircraft 2 and All Electric Aircraft

2.1 System Identification

The first step of the overall process is the system identification (Fig. 4) where the scenario of the AC is identified. Considering the aim of the AC3, the aircraft certification process has been analysed as the main scenario. The scenario involves the certification authority and the Original Equipment Manufacturer (OEM) stakeholders. The main activities are:

- Technical familiarisation and certification basis
- Establishment of the certification programme

- Compliance demonstration
- Technical closure and issue approval

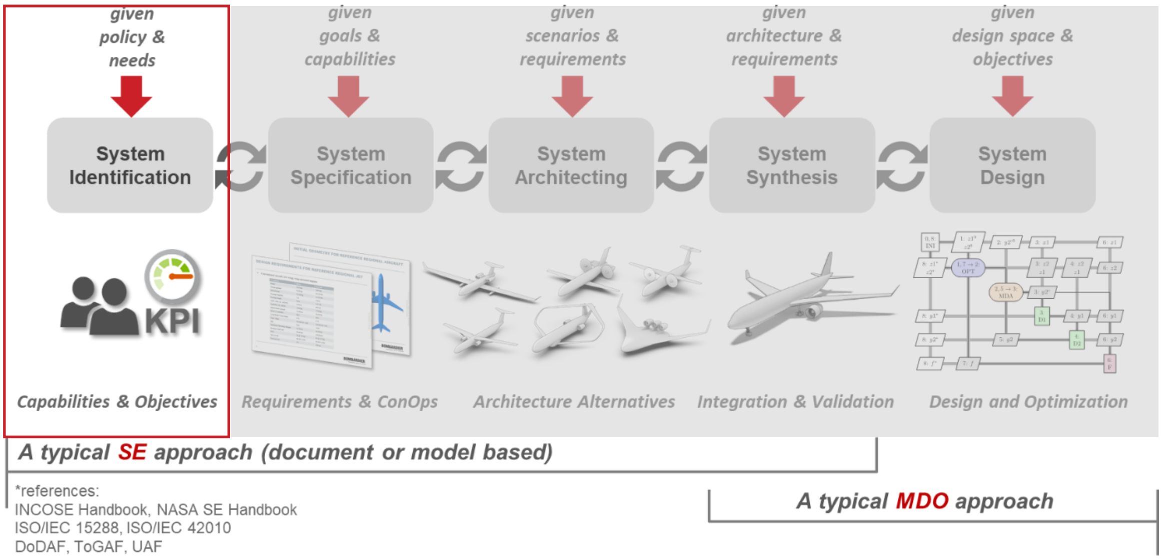


Fig. 4: AGILE 4.0 Step I: System Identification.

The activities, the actors (i.e. the stakeholders) and the entity (i.e. the product to be certified) are defined in the Operational Collaborative Environment (OCE). The OCE automatically generates a Capella file. Using Capella different diagrams are defined. The Sequence Diagram depicted in Fig. 5 represents the entire scenario. The OEM, with the support of the certification authority, define the certification rules. Then the OEM establishes the certification program defining the means to demonstrate compliance of the aircraft type with each requirement of the certification basis. Then by means of the aircraft project and prototype the OEM demonstrate to the certification authority the compliance demonstration. Finally, the certification authority issues the certificate if all the certification basis is satisfied.

This scenario intends to validate all the needs connected to the certification process and listed in Tab. 1.

Tab. 1 List of needs to be validated through the AC3 scenario

Need	Stakeholder	Need id.
Low certification time	OEM	2.7
Low certification cost	OEM	2.4
Ability to enter controlled airspace	Airliner	1.15
Clearly defined maintenance procedure	Maintenance Organization	3.10
clear certification process from OEM	Certification Authority	7.2
no impact of maintenance process on certification	Certification Authority	7.3
The maintenance program development process shall follow certain rules (CFR 14 Part 145 (Repair stations), Part 23 Appendix A (Instructions for continued airworthiness), Part 43 (Maintenance and Alteration), Part 35 (Airworthiness standard: Propellers), Part 135 (Commuter & on demand), ...)	Certification Authority	7.4
Piloting the aircraft should not be stressful	Pilot	8.7

In order to validate the needs collected in Tab. 1, the proposed scenario focuses on the demonstration of compliance to the certification process done by the OEM as demanded by the Certification Authority (Needs 7.2, 7.3 and 7.4). In particular, the aircraft that is compliant with the certification programme would have the ability of entering controlled airspaces (Need 1.15), a clearly defined maintenance procedure (Need 3.10) and its controllability should not affect pilot's workload (Need 8.7). Moreover, an OEM which follows each steps of scenario from the beginning of the project should reduce the time and cost for certification (Needs 2.4 and 2.7).

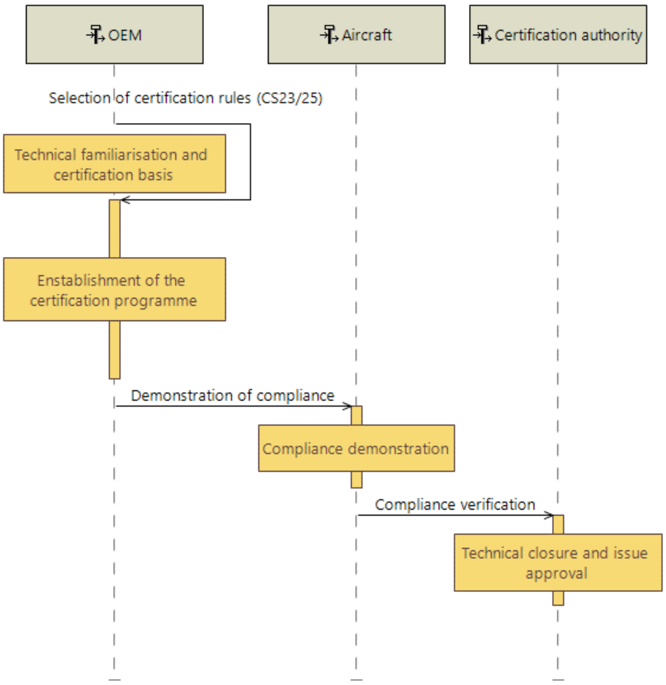


Fig. 5: Scenario sequence diagram for the certification process.

2.2 System Specification

The second step of the process is represented by the system specification (Fig. 6).

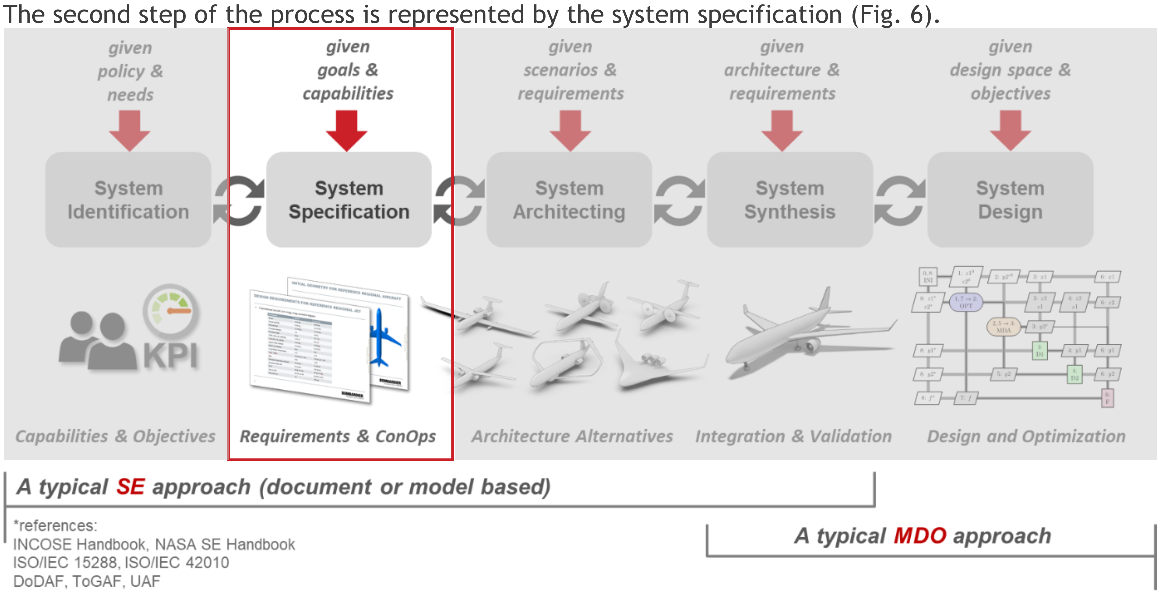


Fig. 6: AGILE 4.0 Step II: System Specification.

The system is specified by a list of requirements derived from the stakeholders' needs (Tab. 2). An extract of the requirement list is provided in Tab. 3 where the mission requirements can be seen. However, these requirements are further derived to define the list of aircraft and sub-systems requirements. The needs and the subsequent requirements are defined to provide a general perspective of the aircraft with a focus on certification and maintenance of electrified systems architectures. In general, the requirements describe the performance of a reference 19 passenger turboprop aircraft with an entry into service date below 2035. The complete requirements list as well as their definition process can be found in [4] and [5].

Tab. 2 AC3 and AC4 Stakeholders and their needs

Stakeholders	Phase	Aspect	Needs	ID
Airliner (ARL)	Acquisition	Benefit (achieve)	entry in service before 2035	1.4
	Acquisition	Benefit (achieve)	able to execute desired routes with desired schedule	1.16
	Acquisition	Benefit (achieve)	ability to enter controlled airspace	1.15
	Acquisition	Cost (control)	low acquisition and preparation cost	1.6
	Use	Benefit (achieve)	Transport 19 passengers at a distance of 370 km in 60 minutes	1.1
	Use	Benefit (achieve)	low noise emission and pollution (i.e. anticipate taxes increase)	1.7
	Use	Benefit (achieve)	access small airports	1.2
	Use	Benefit (achieve)	minimal lost in range / passengers (usable load) compared to conventional OBS/prop	1.11
	Use	Benefit (achieve)	low turn around time	1.3
	Use	Benefit (achieve)	High Availability	1.13
	Use	Benefit (achieve)	High dispatch reliability	1.12
	Use	Benefit (achieve)	High availability of spare parts	1.14
	Use	Cost (control)	min operating costs	1.5
	Use	Cost (control)	minimum airport service costs	1.8
	Use	Cost (control)	low pilot training cost	1.9
	Use	Cost (control)	low maintenance cost (including rate, time)	1.10
	Disposal	Benefit (achieve)	max remaining aircraft value	1.17
OEM	Development	Benefit (achieve)	reliable systems architecture (similar safety level as conventional)	2.5
	Development	Benefit (achieve)	low certification time	2.7
	Development	Cost (control)	low certification cost	2.4
	Marketing	Benefit (achieve)	competitive product (low price)	2.1
	Marketing	Benefit (achieve)	comply with airliners mission requirements	2.2
	Marketing	Benefit (achieve)	provide the aircraft according to the entry in service time from airliners	2.9
	Production	Cost (control)	low production cost (ex: less number of parts)	2.3
	Support	Benefit (achieve)	robust systems	2.6
	Support	Benefit (achieve)	Fast and easy maintenance	2.10
	Support	Benefit (achieve)	Exclusiveness of spare parts/monopoly	2.11
	Support	Cost (control)	low maintenance cost	2.8
	Phase out	Benefit (achieve)	good materials recycling capability	2.12
Maintenance organization (MNT)	Preparation	Cost (control)	low maintainers training cost	3.6
	Preparation	Cost (control)	low support equipment and instrument cost	3.7
	Execution	Benefit (achieve)	easy accessibility	3.1
	Execution	Benefit (achieve)	fast and easy maintenance	3.2
	Execution	Benefit (achieve)	low systems complexity	3.3
	Execution	Benefit (achieve)	availability of parts	3.4
	Execution	Benefit (achieve)	availability of support equipment and instruments	3.5
	Execution	Benefit (achieve)	Safe working environment	3.8
	Execution	Benefit (achieve)	Standardization of spare parts and procedures	3.9
	Execution	Benefit (achieve)	Clearly defined maintenance procedure	3.10
politics/society (SCT)	Use	Benefit (achieve)	low noise (external) emission and pollution	4.1
	Use	Benefit (achieve)	competitive product	4.2
	Use	Benefit (achieve)	increase the number of flight connection	4.4
	Disposal	Benefit (achieve)	high recyclability	4.3

passengers (PAX)	Use	Benefit (achieve)	reduce door to door time	5.1
	Use	Benefit (achieve)	high safety level	5.3
	Use	Benefit (achieve)	increase comfort (internal noise, ..)	5.4
	Use	Benefit (achieve)	increase comfort quality of internal air in cabin (air pollution)	5.5
	Use	Benefit (achieve)	Not being disturbed by unscheduled maintenance activities	5.6
	Use	Benefit (achieve)	Departure on time	5.7
	Use	Cost (control)	low ticket price	5.2
Airports authority (ARP)	Preparation	Benefit (achieve)	minimum infrastructure change	6.1
	Preparation	Benefit (achieve)	minimum ground support equipment change	6.2
	Use	Benefit (achieve)	High dispatch reliability	6.3
	Use	Benefit (achieve)	Flight handling should be profitable	6.4
	Use	Benefit (achieve)	High dispatch flights/hour	6.5
Certification authority (CRT)	Initial certification	Benefit (achieve)	commonalities in systems/airframe	7.1
	Initial certification	Benefit (achieve)	clear certification process from OEM	7.2
	Initial certification	Benefit (achieve)	no impact of maintenance process on certification	7.4
	Continuous airworthiness	Benefit (achieve)	The maintenance program development process shall follow certain rules (CFR 14 Part 145 (Repair stations), Part 23 Appendix A (Instructions for continued airworthiness), Part 43 (Maintenance and Alteration), Part 35 (Airworthiness standard: Propellers), Part 135 (Commuter & on demand), ...)	7.3
Pilot (PLT)	Preparation	Cost (control)	low pilot training cost	8.8
	Use	Benefit (achieve)	Receive fast and precise failure report in case of malfunction	8.1
	Use	Benefit (achieve)	Walkaround should be carried out fast and easy	8.2
	Use	Benefit (achieve)	Isolation of malfunctioning system should be possible from cockpit	8.3
	Use	Benefit (achieve)	Failure detection should be possible from cockpit (build in test capability for equipment)	8.4
	Use	Benefit (achieve)	Common aircraft control systems and aircraft handling qualities	8.5
	Use	Benefit (achieve)	Common flight instruments and systems management	8.6
	Use	Benefit (achieve)	Piloting the aircraft should not be stressful	8.7

Tab. 3 AC3 and AC4 mission requirements

ID	Requirement statement	Type	Parent/Source	Stakeholders
MR1	The standard mission shall be performed in 60 minutes	Performance	1.1, 2.2, 4.4, 5.1	ARL, OEM, SCT, PAX
MR2	The standard mission shall provide for the transport of 19 passengers at a distance of 370 km	Performance	1.1, 2.2, 4.4, 5.1	ARL, OEM, SCT, PAX
MR3	The standard mission shall be performed from airports with a minimum runway length of 800m	Performance	1.2, 4.4, 5.1	ARL, SCT, PAX
MR4	The standard mission shall be repeated after 20 minutes	Suitability	1.3, 1.11, 1.12, 1.13, 1.14, 2.10, 3.1, 3.2, 3.4, 3.5, 3.9, 3.10, 5.6, 5.7, 6.3, 6.5, 8.1, 8.2, 8.3, 8.4	ARL,OEM, MNT, PAX, ARP, PLT
MR5	The standard mission shall take place after a maximum delay of 60 minutes	Suitability	1.3, 1.11, 1.12, 1.13, 1.15, 2.10, 3.1, 3.2, 3.4, 3.5, 3.9, 3.10, 5.7, 6.3, 6.5, 8.1, 8.2, 8.3, 8.4	ARL, OEM, MNT, PAX, ARP, PLT
MR6	The standard mission shall be performed from year 2035 (Initial guess)	Design constraint	1.4, 2.7, 2.9, 7.1, 7.2, 7.3, 7.4	ARL, OEM, CRT
MR7	The standard mission shall be performed at a maximum total operating cost between 1800 and 4000 €	Performance	1.5, 1.6, 1.7, 1.8, 1.9, 1.10, 2.1, 2.3, 2.4, 2.8, 2.10, 3.1, 3.2, 3.3,	ARL, OEM, MNT, SCT, PAX, ARP, PLT

			3.4, 3.6, 3.7, 3.9, 4.1, 4.2, 5.2, 6.1, 6.2, 6.3, 6.4, 6.5, 8.5, 8.6	
MR8	The standard mission cruise phase shall be performed at altitude greater than 7500 meters	Performance	1.5, 5.2	ARL, PAX
MR9	The standard mission shall be performed with a probability of catastrophic event not greater than 1/10^9 flight hours	Suitability	2.5, 2.6, 5.3, 7.3, 7.4, 8.1, 8.2, 8.3, 8.4, 8.5, 8.6	OEM, PAX, CRT, PLT
MR10	The standard mission shall be performed from airports provided with the reference hangar dimensions	Performance	1.2	ARL, SCT, PAX
MR11	The standard mission for electric variant of the aircraft shall provide for the transport of 9 passengers at a distance of 555 km	Performance	1.11,2.2, 4.4, 5.1	ARL, OEM, SCT, PAX

The process of requirements derivation is fully traceable, it means that for each requirement the need which generated it as the sub-level requirements derived by its decomposition are always defined. In particular, the hierarchy between requirements is also visualized by means of Papyrus software (see Fig. 7).

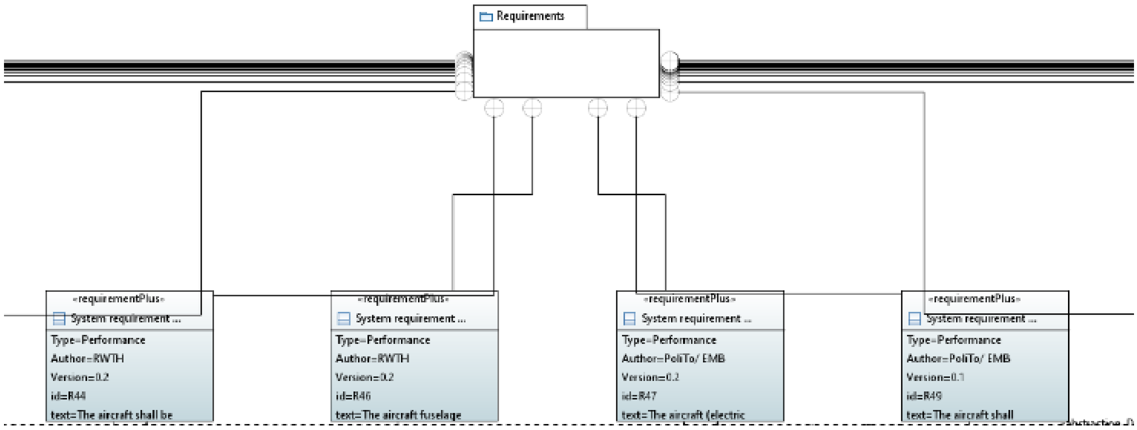


Fig. 7: Requirement list view for some aircraft requirements.

2.3 System Architecting

The third step of the process is related to the formalization of the system architecture (Fig. 16). Considering the main aims of AC3, three Systems of Interest (SoI) are identified: the Pneumatic System (PS), the Flight Control System (FCS) and the Virtual Certification System (VCS). Among the different aircraft systems, the PS and FCS have been identified as SoI because both take an important role in system electrification showing different architectures depending on the technology used. The VCS represents the capabilities of the developed tools in checking the certification requirements acting as a virtual certification process. Depending on the certification (CS23 or CS25), the architecture of the system changes.

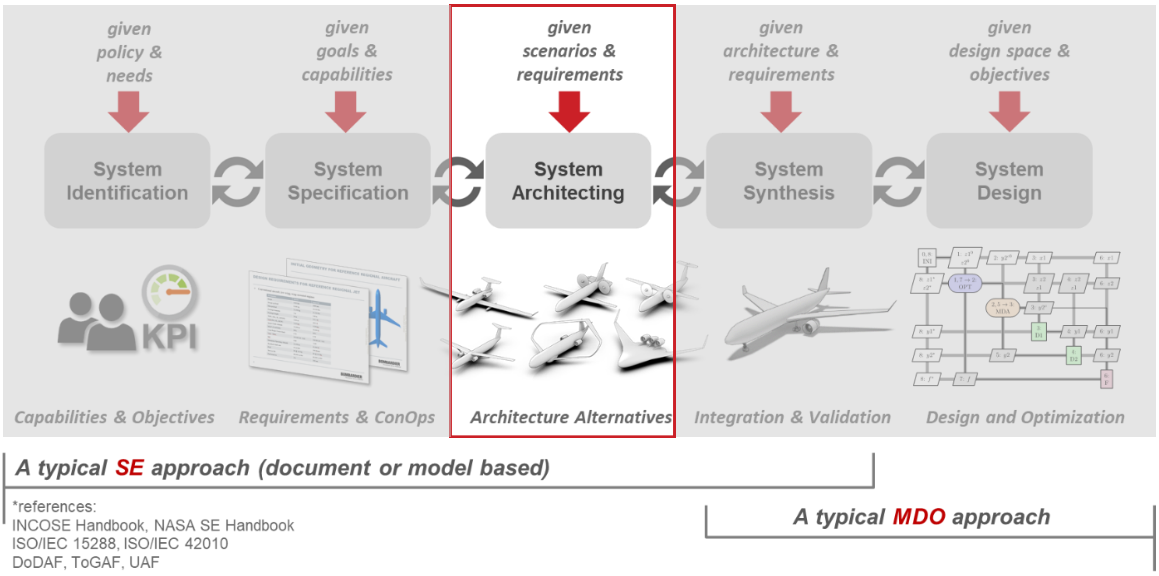


Fig. 8: AGILE 4.0 Step III: System Architecting.

The architecture modelling of the FCS is shown in Fig. 9. For the sake of brevity, the architecture modelling of the PS is not here reported. The architecture of the FCS starts from the main function of the system for the AC3 that is “move secondary surface”. Staring from the requirements and needs formalized in D7.2[4] and D7.3[5], it is possible to trace the origin of this function up to the stakeholders’ needs. Firstly, this function is derived from the following FCS requirement: “The FCS shall permit the control of the aircraft” that in turn is derived from the following aircraft requirement: “The aircraft shall perform the standard mission”. Secondly, this last requirement is derived from the following needs:

- Transport 19 passengers at a distance of 1500 km in 90 minutes (Airliner’s need)
- Comply with airliners mission requirements (Original Equipment Manufacturer’s need)
- Common aircraft control systems and aircraft handling qualities (Pilot’s and Certification Authority’s need)

In the AC3, the primary control surface is mechanically controlled. Two main functionalities branch off from the main function:

- Move the secondary surface in flight
- Move the secondary surface on ground

In this way, different load cases for the AC3 flap are taken into account also identifying the need of creating aerodynamic forces to control the aircraft. Considering this last function and the different loads two main component of the system are identified:

- movable surface
- mechanical actuators

Then a new part of the architecture is dedicated to different technological solutions needed to provide power to the mechanical actuators:

- Gearbox system driven by hydraulic motor
- Gearbox system driven by electric motor
- Direct drive electric motor

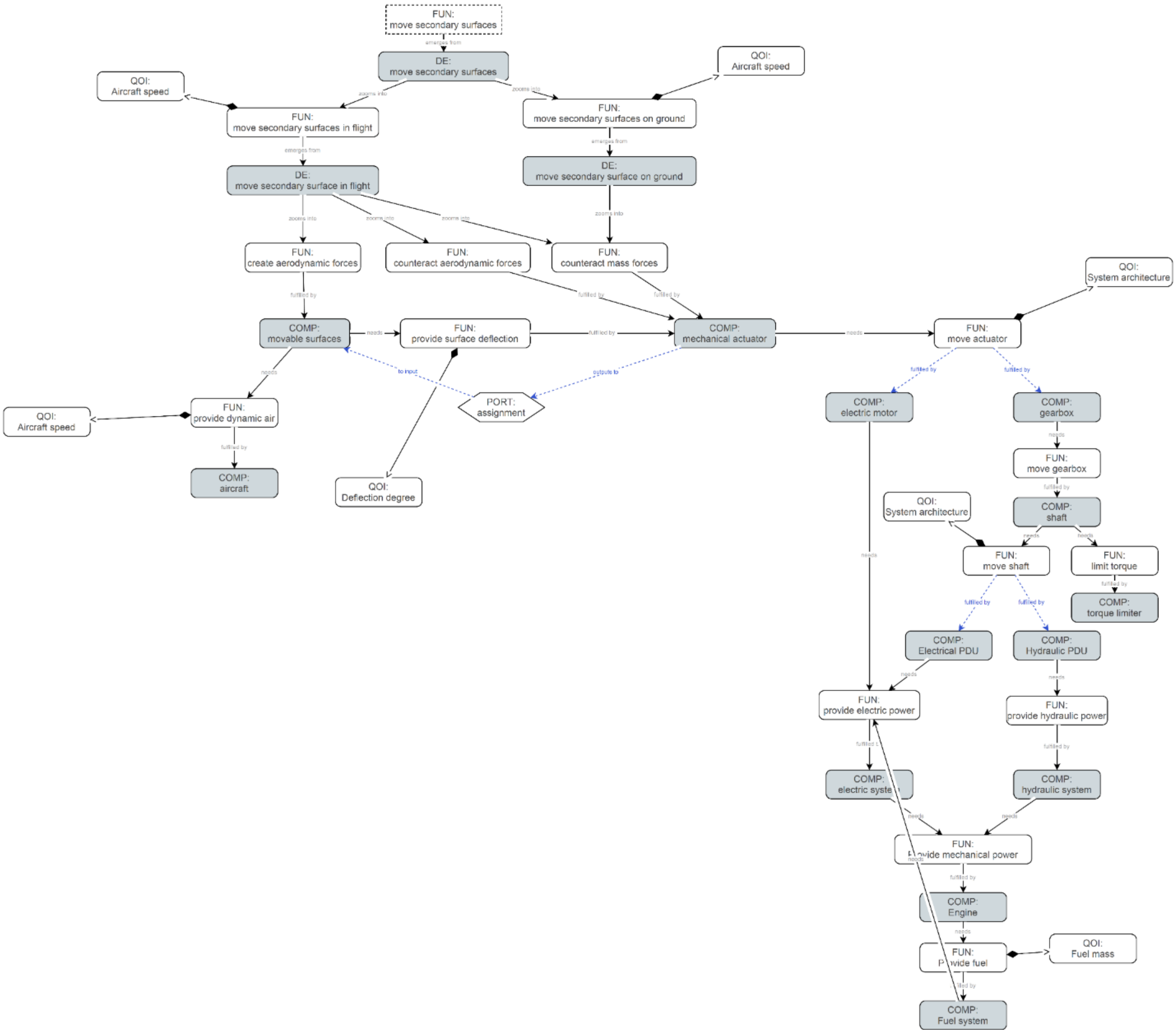


Fig. 9: AC3 Architecture model of the FCS

Another important system architecture to be defined is the architecture of the VCS. The main objective of the AC3 is to integrate certification disciplines within the MDO problem. The VCS architecture represents the integrated architecture of the tools related to certification and implemented in the AC3:

- External noise certification constraints
- Minimum aircraft performance
- Systems safety assessment

There is no intention to be complete including the whole certification process here. The idea is to provide a good example of integration of some parts of the certification process.

The main function “certify the aircraft” is derived from the following alternative system requirements defined in in D7.2[4] and D7.3[5]: “The aircraft shall comply with the CS25” or “The aircraft shall comply with the CS23”. These requirements derive from the following stakeholders’ needs:

- Clear certification process (Certification Authority’s need)
- Entry in service before 2035 (Airliner’s need)
- Low certification time and cost (Original Equipment Manufacturer’s need)

As shown in Fig. 10, the first splitting and decision on the main function “certify the aircraft” is related to the type of certification:

- CS 23
- CS 25

Then, these functions are developed in different ways according to the disciplines involved (i.e. external noise, minimum performance and Safety assessment) and specific regulation. Within the single tool or certification function, several sub-functions are necessary to check the design with regulation constraints.

In particular, for each certification disciplines different sub-functions are needed:

- Safety assessment: provide and then enable safety heuristic. In parallel, information about the architecture of the systems is needed to assess safety parameters
- External noise: in this case, it is necessary to estimate the external noise during takeoff and landing phase (depending on the certification type). An estimation of the noise behaviors of the aircraft is needed as well as the estimation of its performance during those phases.
- Minimum performance: the main function "verify minimum performance" is divided into two sub-functions, verify climb and landing minimum performance. In turn, they are divided into the chapters defined by the regulation.

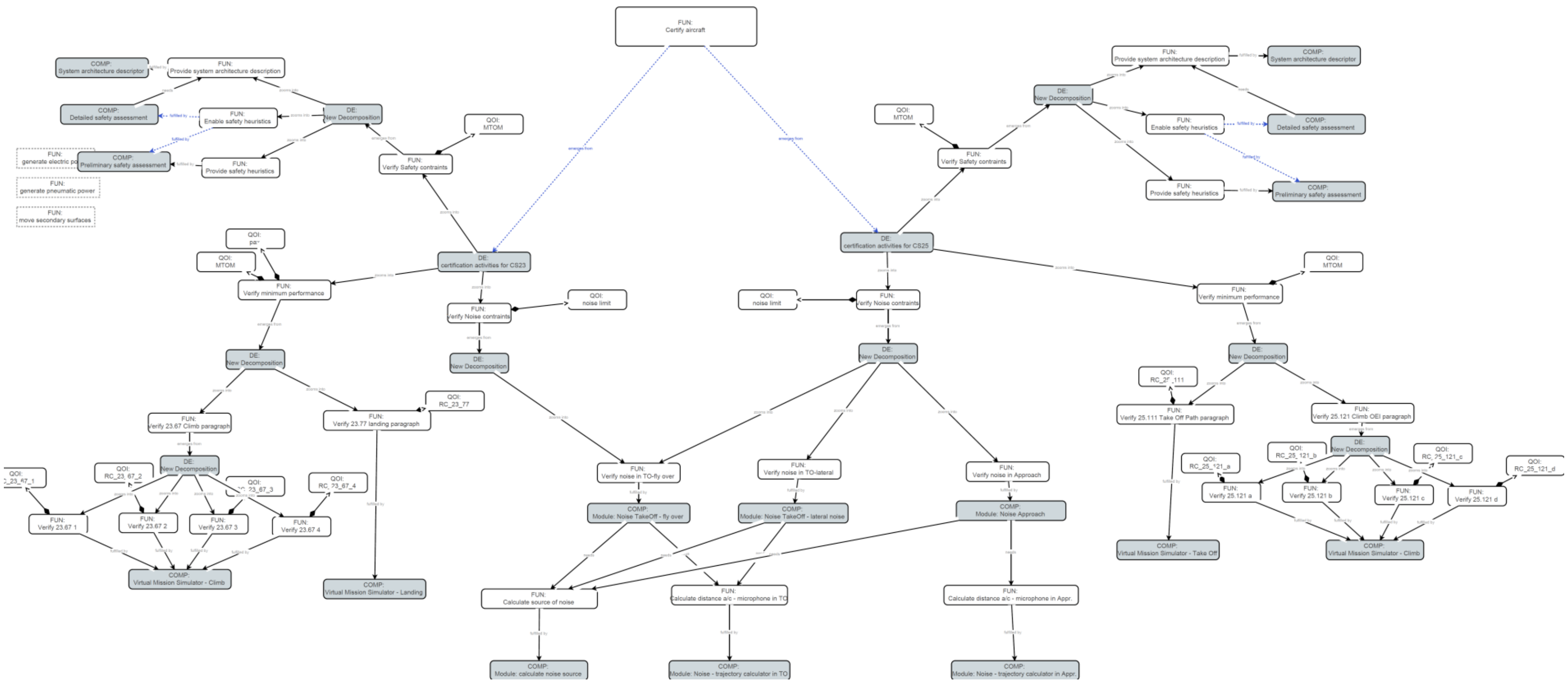


Fig. 10: AC3 Architecture model of the VCS

2.4 System Synthesis

Having defined all the possible architectures of the SoI, it is needed to select one, or more, of them to achieve the system design phase. All the architectural decisions are defined in the fourth step of the process and called system synthesis (Fig. 11).

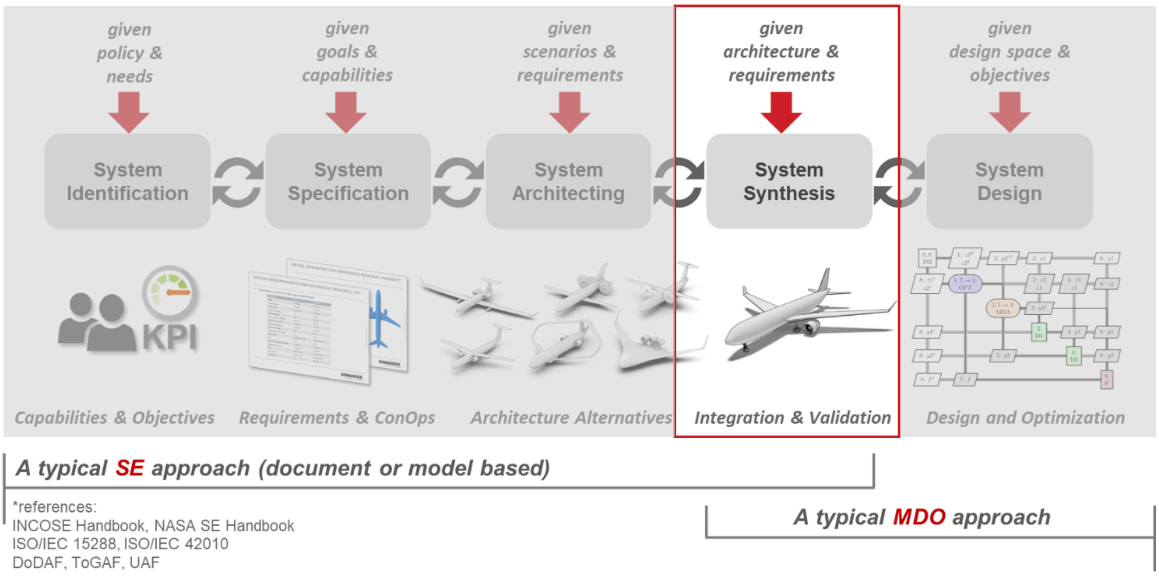
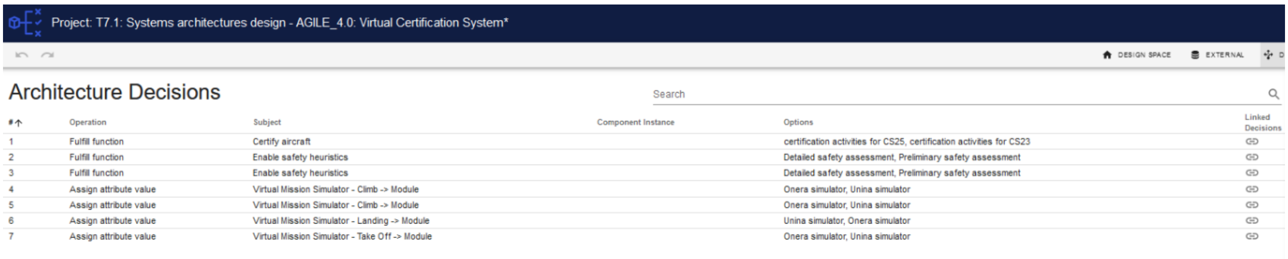


Fig. 11: AGILE 4.0 Step IV: System Synthesis.

All the decision process is supported by the OCE. For the sake of brevity only the VCS decisions are here reported, additional information can be found in D7.4[6]. The architecture decisions panel (shown in Fig. 12) lists all the main decisions concerning the VCS. Beside the regulation type (CS23 or CS25) other decisions are related to:

- Level of detail of system safety assessment (preliminary or detailed)
- Aircraft performance simulation module (provided by ONERA or provided by UNINA)

In Fig. 13 the VCS architecture when only the CS25 is selected.



#	Operation	Subject	Component Instance	Options	Linked Decisions
1	Fulfill function	Certify aircraft		certification activities for CS25, certification activities for CS23	
2	Fulfill function	Enable safety heuristics		Detailed safety assessment, Preliminary safety assessment	
3	Fulfill function	Enable safety heuristics		Detailed safety assessment, Preliminary safety assessment	
4	Assign attribute value	Virtual Mission Simulator - Climb -> Module		Onera simulator, Unina simulator	
5	Assign attribute value	Virtual Mission Simulator - Climb -> Module		Onera simulator, Unina simulator	
6	Assign attribute value	Virtual Mission Simulator - Landing -> Module		Unina simulator, Onera simulator	
7	Assign attribute value	Virtual Mission Simulator - Take Off -> Module		Onera simulator, Unina simulator	

Fig. 12: AC3 OCE Architecture panel (VCS architecture)

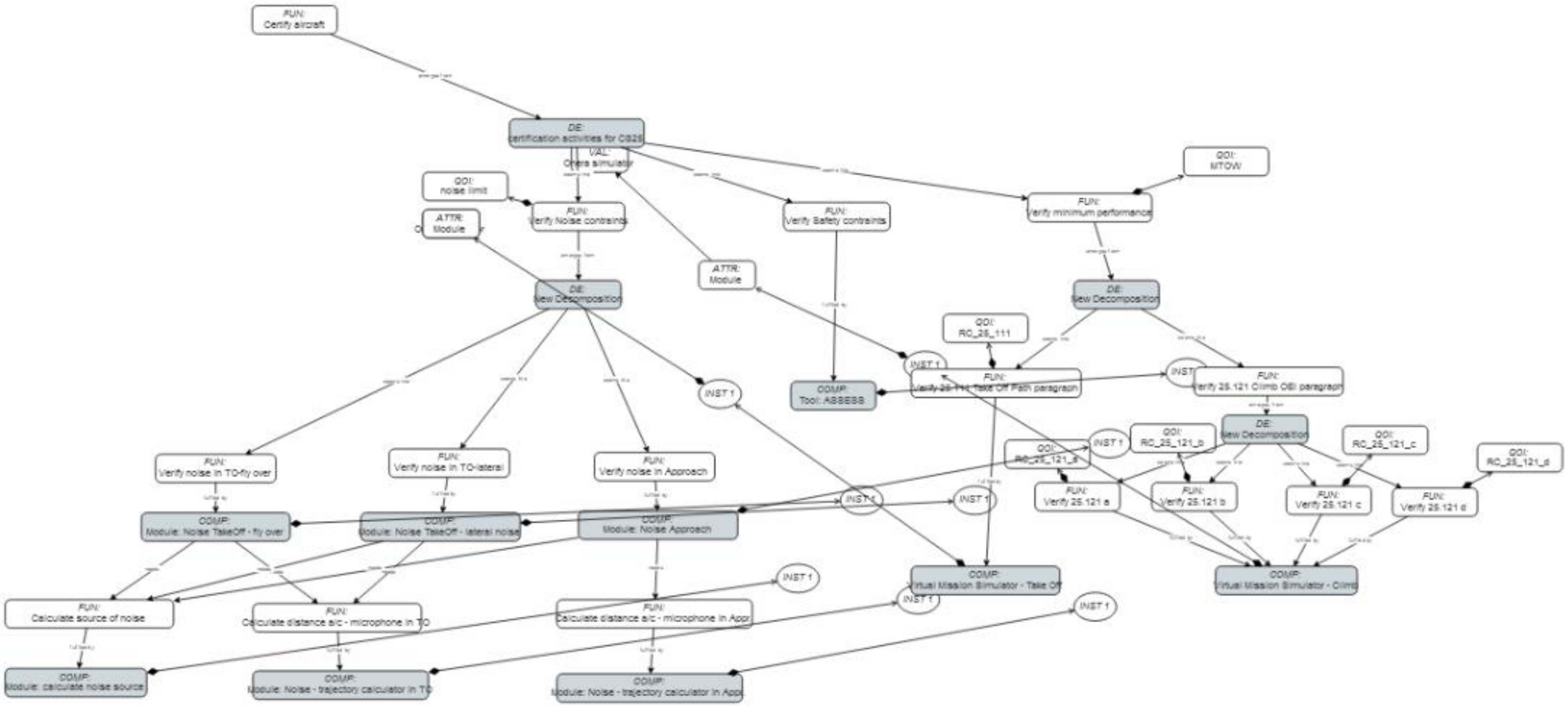


Fig. 13: Specific AC3 architecture of the VCS.

Moreover, some numerical parameters have been added to the architecture as Quantity of Interest (QoI). For the VCS the Maximum Takeoff Mass (MTOM), number of passengers and the noise and performance limits provided by regulation are included in the architecture as QoI. It is then possible to define all these QoI as design variables, objectives, and constraints of the MDO problem.

In this way and as shown in Fig. 14 a MDO problem could be formalized starting from the architecture. However, it may or may not represent the complete MDO problem depending on the completeness of the architecture. In the specific case of the VCS, the cost estimation that provides the life cycle cost (i.e. the objective of the AC3 MDO) and many other parameters cannot be easily connected to the VCS architecture since they belong to a different disciplinary domain.

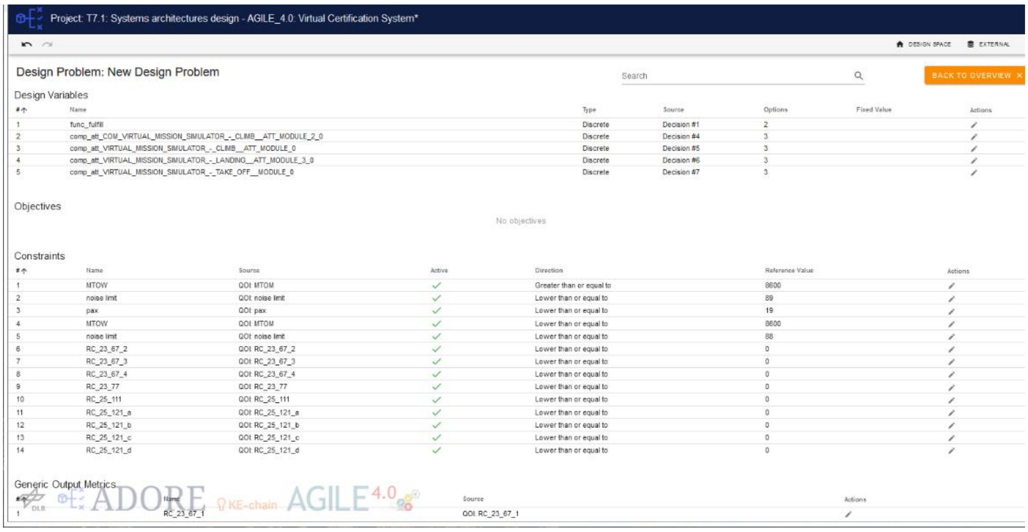


Fig. 14: AC3 OCE Design problem panel

The link between the architecture formulation and the MDO workflow definition is furtherly defined by using the MulitLinQ tool integrated within the OCE. The different QoI defined in the architecture can be linked with tools already defined in the OCE. As shown in Fig. 15, each of the QoI defined in the architecture is listed in the table together with all the tools involved in the main AC3 workflow. As already explained, since the VCS does not represent the architecture of the whole AC3 (aircraft design and LCC estimation are not included) some tools are not linked (red columns).

		Tools									
Components	**QOIs**	ASSESS	ASTRID	Aerosurrogate	Aircraft Synthesis	Cost estimation	EngineDesign and aircraft performance	Ext_Noise	Min_Performance	OpenAD	SFCsensitivity
Virtual Mission Simulator - Climb	RC_25_121_a								✓		
Virtual Mission Simulator - Climb	RC_25_121_b								✓		
Virtual Mission Simulator - Climb	RC_25_121_c								✓		
Virtual Mission Simulator - Climb	RC_25_121_d								✓		
Virtual Mission Simulator - Climb	RC_23_67_1								✓		
Virtual Mission Simulator - Climb	RC_23_67_2								✓		
Virtual Mission Simulator - Climb	RC_23_67_3								✓		
Virtual Mission Simulator - Climb	RC_23_67_4								✓		
Virtual Mission Simulator - Landing	RC_23_77								✓		
Virtual Mission Simulator - Take Off	RC_25_111								✓		
	MTOM		✓		✓		✓			✓	
	MTOM		✓		✓		✓			✓	
	MTOM		✓		✓		✓			✓	
	MTOM		✓		✓		✓			✓	
	noise limit							✓			
	noise limit							✓			
	pax				✓					✓	

Fig. 15: AC3, VCS Mapping matrix view

2.5 System Design

The final step of the overall process is the system design (Fig. 16). The design is based on the Top Level Aircraft Requirements summarized in Tab. 4.

Tab. 4 AC3 and AC4 Top Level Aircraft Requirements

TLARs	Metric	Imperial
MTOW	≤ 8600 KG	≤ 19000 LB
PAX	9	9
Range	≤540 KM	≤300 NM
Speed	0.3 M	0.3 M
Ceiling	7620 m	25000 FT
TOFL	<800 m	< 2600 FT

Considering the aim of the AGILE4.0 project, the design is carried out through a MDO consisting of several distributed tools provided by the different AC3 partners. The MDO problem, the system architectures and specifications are derived by the previous steps of the process (Fig. 16). The main activities behind the system design are:

- Workflow implementation
- Workflow execution
- Optimization
- Trade-off
- Requirements Validation

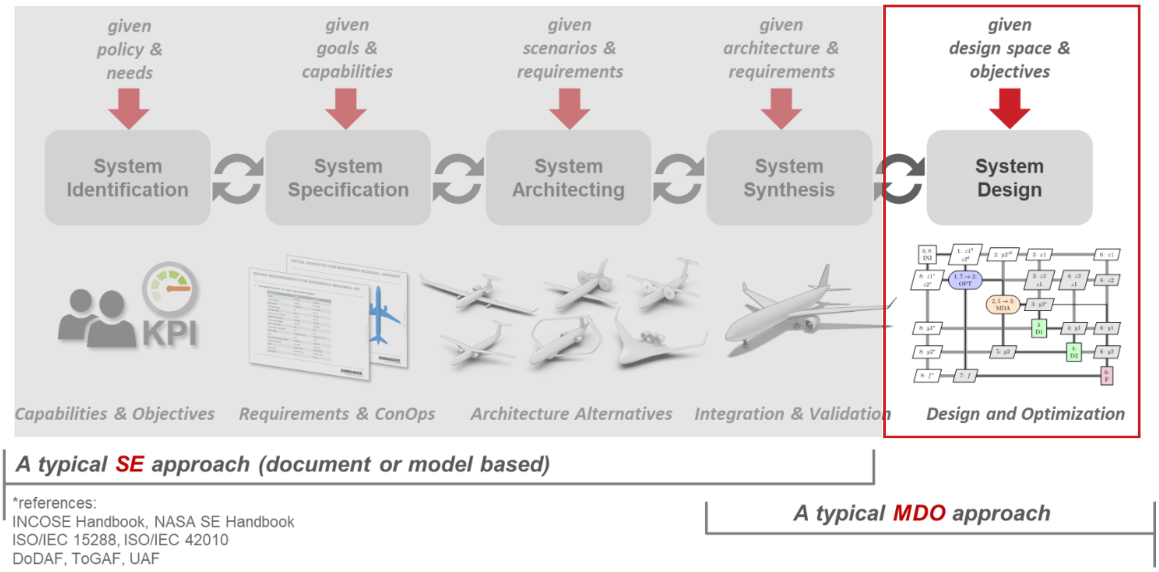


Fig. 16: AGILE 4.0 Step V: System Design.

2.5.1 Workflow implementation

Starting from the stakeholders' needs, the aim of the AC3 is to improve the systems efficiency by their electrification and check their certifiability and affordability. Therefore, the disciplines involved must consider the main aspects of aircraft design, of the certification process and cost estimation. Considering the tools and expertise available and tools developed during the project, the disciplines included in the workflow are summarized in Tab. 5.

Tab. 5 AC3 toolset

Tool / Discipline	Partner	Domain	Main purpose
OpenAD	DLR	Aircraft Design	Aircraft design and aircraft synthesis (mass synthesis and aircraft redesign). Aircraft masses and geometries are the main output.
ASTRID	PoliTo	Aircraft Design	On-board system design. Sensible to electrified architecture. Main output: systems masses, volumes, installation and power required.
Performance	UNINA	Aircraft Design	Aircraft performance calculation. Main output: needed thrust, aircraft drag, mission profile
Engine design	UNINA	Aircraft Design	Engine design. Main output: engine mass, fuel consumption
Aero-surrogate	ONERA-CFSE	Aircraft Design	Wing drag calculation, sensible to wing surface
SFC sensitivity	PoliTo	Aircraft Design	Engine SFC calculation, sensible to systems power offtakes and bleed air requirements
External noise	UNINA	Aircraft Certification	Aircraft external noise calculation to check CS23 and CS25 compliancy
Min. Performance	ONERA	Aircraft Certification	Aircraft minimum performance calculation during take-off and landing

			phases to check CS23 and CS25 compliancy
ASSESS	CONU	Aircraft Certification	Check the systems architecture for minimum safety level required by regulation
Cost	RWTH	Cost estimation	Aircraft life cycle cost estimation. Main output: development, production, and aircraft operating cost
SEGOMOE	ONERA	Optimisation	Multi-objective Bayesian Optimization

To correctly estimate the effect of systems electrification, the aircraft have to be re-design for each system architecture. Therefore, the main aircraft design disciplines are selected for the AC3. Moreover, some key disciplines involved must be sensible to systems electrification. Consequently, to a conceptual design tool (OpenAD) not sensible to systems electrification, the following tools are added:

- ASTRID
- Engine design
- SFC sensitivity

ASTRID is a tool of on-board systems preliminary design and is sensible to system electrification. It provide greater details in system mass estimation, volume allocation and power requirement. The Engine design and SFC sensitivity tools are able to calculate the effect of varying the systems power offtakes and bleed air requirement on engine performance.
The following tools are added to the design loop to respectively increase sensibility on performance calculation and to allow aircraft wing surface variation:

- Performance
- Aero-surrogate

The tools Noise, Min. Performance and ASSESS are added to the present AC to cover some aspects of the certification process. In particular, the aircraft eternal noise, its minimum performance during take-off and landing and the safety of systems architecture are checked by those tools. Finally, as one of the stakeholders' needs is to design an affordable aircraft, the Costs tool is added to estimate the cost of the aircraft designed. In Fig. 17, the concept of the workflow and the partners involved are depicted. The workflow is better described by the eXtended Design Structure Matrix (XDSM) where the connection and the execution order of the tools are described (Fig. 18). It is worth noting the presence of the design loop highlighted by the grey rectangle.

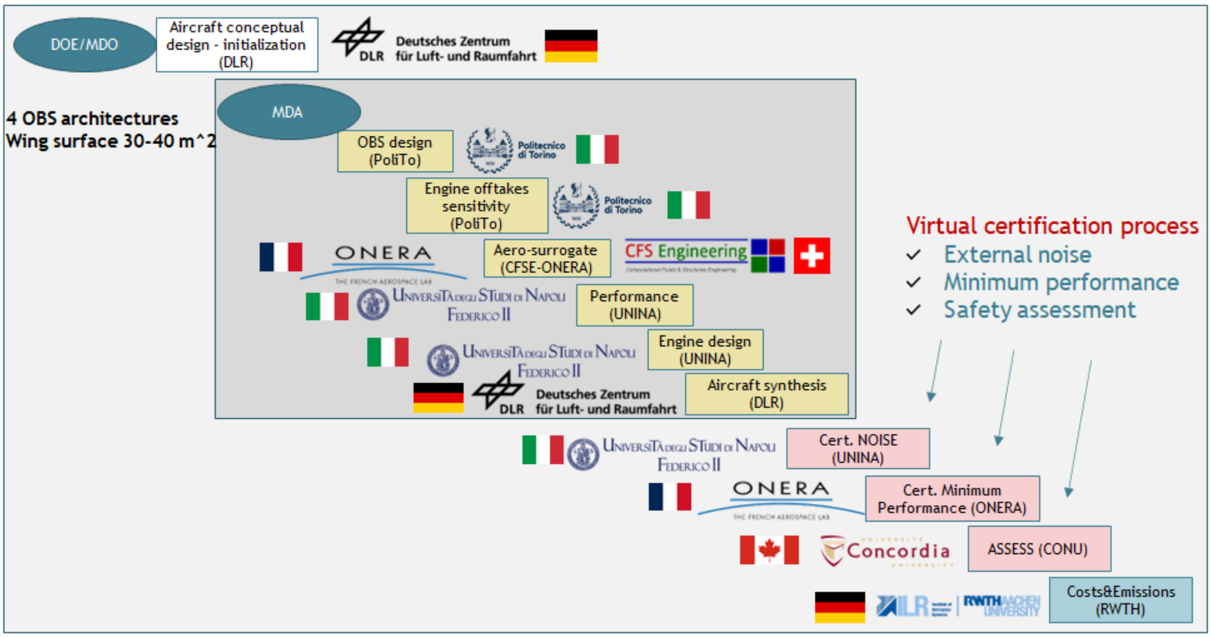


Fig. 17 Pictorial view of the AC3 workflow and partners involved.

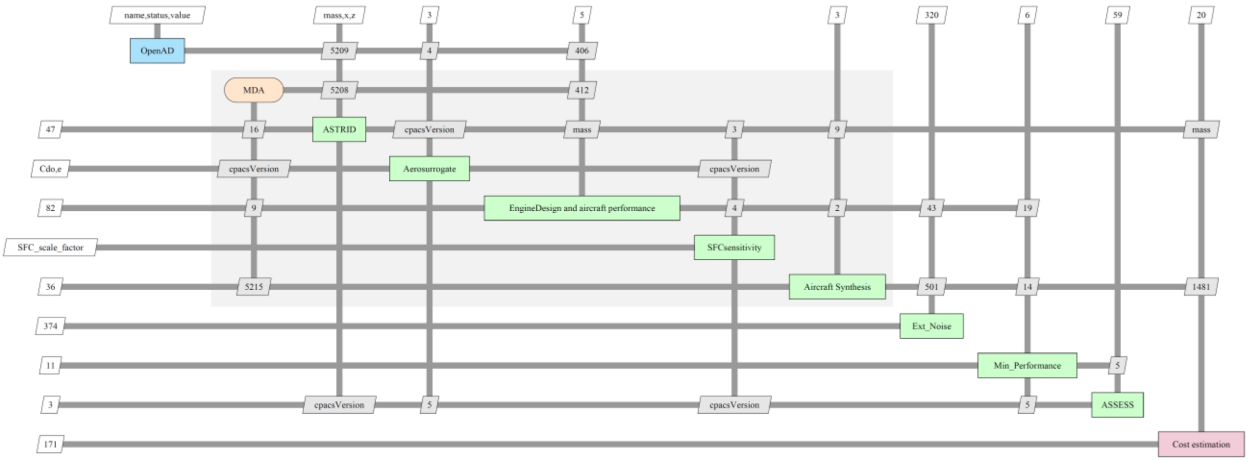


Fig. 18 XDSM of the AC3 workflow creating with Operational Collaborative Environment (OCE)

2.5.2 Workflow execution

The workflow is executed by means of RCE and BRICS. They are respectively the environment where the tools are connected and the internet communication standard allowing a distributed MDAO operation. The workflow is defined to reduce the number of iterations and connections. In particular, the first aircraft design has been remotely executed starting from the top level aircraft requirement to create a first baseline of the aircraft. This baseline is used as starting point for all the calculations within the AC3 and AC4. As can be seen from Fig. 19, inside the design loop, at first the systems are designed starting from the baseline, than the Aero-Surrogate estimate the wing drag coefficient. It was decided to create a surrogate tool for wing drag estimation to avoid slowing down the execution time too much with a real time CFD analysis. The aircraft performance tool is then executed together with the engine design tool being the two tools property of the same partner. This reduced the number of BRICS connections. After that, the SFC sensitivity tool modify the engine SFC according to the system offtakes previously calculated. The design loop is concluded by the aircraft design tool that collects all the new masses (i.e. systems masses, fuel mass, engine mass) and redesigns accordingly the aircraft. In the design loop, the tools are iteratively executed until the convergency on maximum take-off mass is reached.

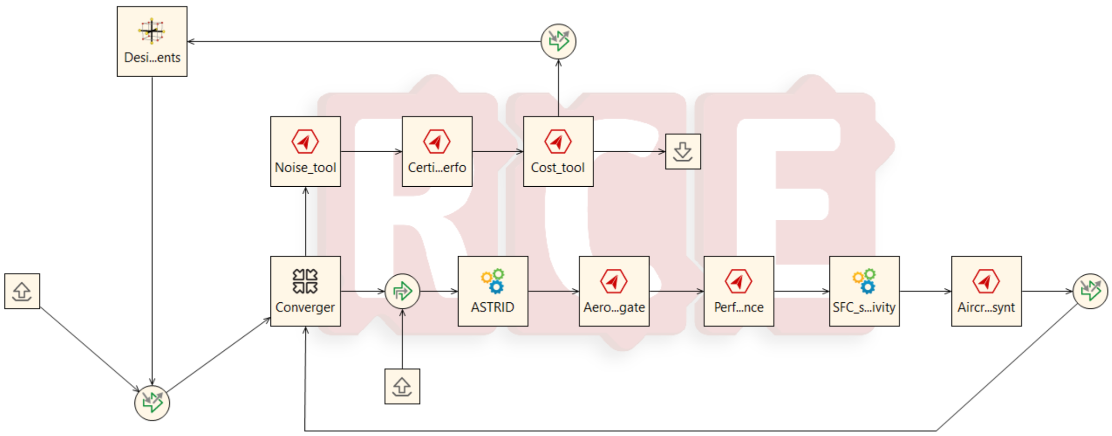


Fig. 19 Workflow execution order (Design of Experiments)

After the end of the design loop, the aircraft designed is checked by the tools belonging to the VCS defined in the previous chapter. The Noise tool acquires the aircraft geometry and performance to define the take-off and landing trajectories and estimate the external noise produced. Then, these values of noise are compared with the noise limits defined by regulations. Two different noise margins are calculated depend on regulation selected (i.e. CS23 or CS25) as defined in 2.3. Some examples of results are depicted in Fig. 20 and Fig. 21.

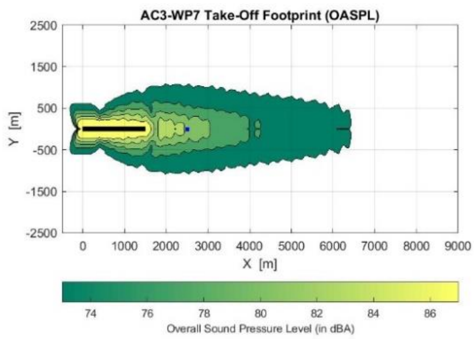


Fig. 20 Noise footprint of AC3 baseline (CS23)

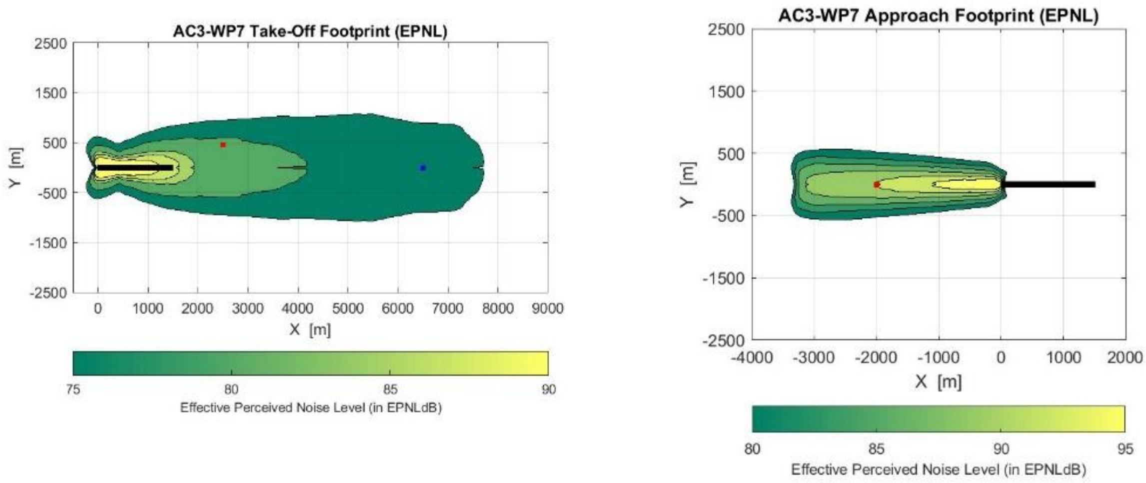


Fig. 21 Noise footprint of AC3 baseline (CS25)

After that, the designed aircraft is checked for minimum performance during take-off and landing phases. The main input of the Min. Performance tool are the aircraft geometry, aircraft mass, and engine performance. The aircraft performance, in all operative conditions (all engine operative, one engine inoperative, take-off, landing, and clean configuration), are calculated in terms of climb gradients. Then, these values are compared with the regulations constraints to evaluate the certification margins. In are depicted the climb gradients for both part 23 and part 25 regulations.

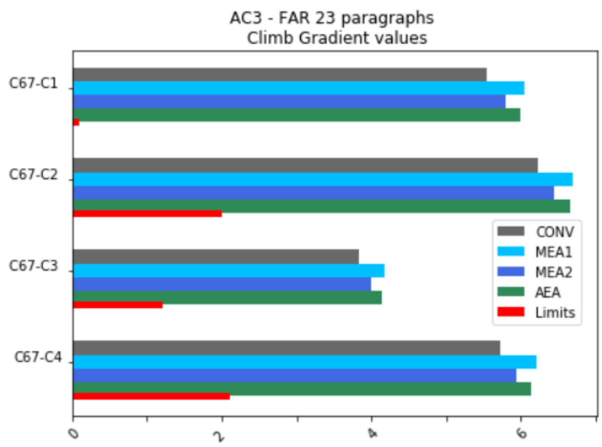


Fig. 22 Minimum performance of AC3 baseline (FAR23)

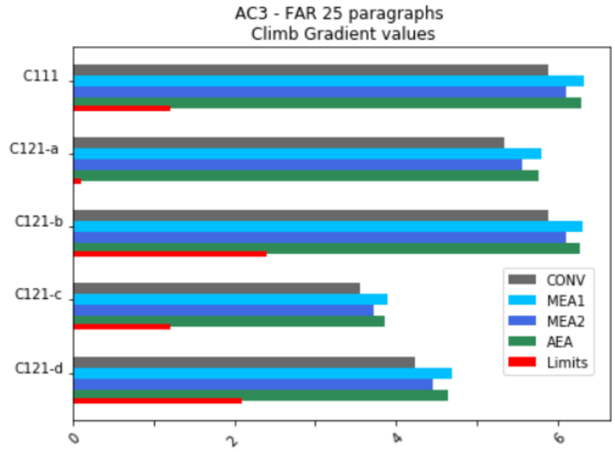


Fig. 23 Minimum performance of AC3 baseline (FAR25)

Finally, to conclude the VCS process, ASSESS tool is employed to check the systems architecture safety. The tool acquires the systems architecture in terms of main components (see Fig. 24) and their connection. A specific branch of the tools interface file is added for the purpose (Fig. 25). ASSESS consists of several modules covering different aspects of the safety assessment process outlined in the SAE ARP4761. In Fig. 26, an example of ASSESS application is depicted. In that case, considering that one of the safety rules requires the landing gear braking unit to be supplied with at least two independent sources of power, the different architectures defined by ASTRID are checked. The last part of the workflow is focused on LCC estimation. The tool has as input the aircraft masses, technologies and main performance and estimate the development, production and operating cost.

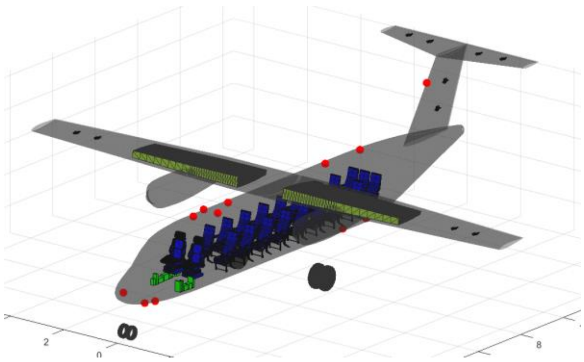


Fig. 24 Visualization of the main components of the aircraft systems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    <Forth_Elect_Line_FCS mapType="vector">0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0;0</Forth_Elect_Line_FCS>
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  </FCS>
```


Fig. 25 New branch of the tool-connection file to describe the component connection.

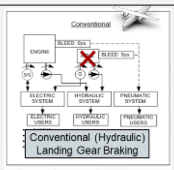
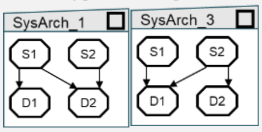
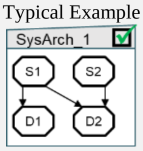
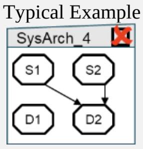
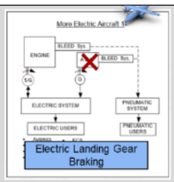
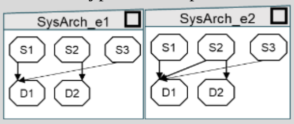
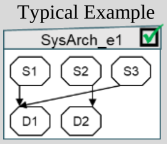
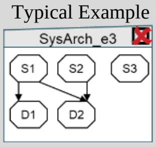
Option	No. of generated architectures	No. of feasible architectures	No. of unfeasible architectures
Conventional (Hydraulic Landing Gear Braking System)	**6**	**4**	**2**
	Typical Examples 	Typical Example 	Typical Example 
More Electric 1 (Fully Electric Landing Gear Braking System)	**5**	**4**	**1**
	Typical Examples 	Typical Example 	Typical Example 

Fig. 26 Example of ASSESS application to the landing gear braking system.

2.5.3 Design of experiments

To better evaluate the potentiality of the workflow and the accuracy of the results, a Design of Experiments (DOE) is carried out. The activity is valuable to evaluate the effect of wing area variation. This is an additional variable indicated by AC Owner (BOM) which has an important effect on the aircraft performance. Therefore, the DOE is carried out considering the range of the following variable:

- OBS level of electrification (4 discrete levels: Conventional, MEA1, MEA2 and AEA)
- Wing surface (11 discrete values from 30 to 40m^2)

The results spanning from the aircraft design, certification, and cost domains. In Fig. 27, the results coming from the design domain are depicted. The general trends are the following:

- The MTOM (Maximum Take-Off Mass) increases with the reduction of wing surface. This trend is mainly driven by the increase of fuel consumption due to a greater thrust required during cruise
- The OEM (Operating Empty Mass) is quite stable, and the minimum value is almost centred to 36m^2
- The engine power tends to increase with the reduction of wing surface.

Considering the systems electrification level, it is worth noting that the best architecture in terms of MTOM reduction is the MEA1 (i.e. the second electrification level). The MEA2 and AEA reach comparable results. The worst one is the conventional. By Fig. 27 it is clear that the results are mainly driven by the reduction of OEM. Whereas the fuel mass would favour the highest electrification levels (MEA2 and AEA), the importance of this parameter, in terms of mass, is negligible compared to the OEM.

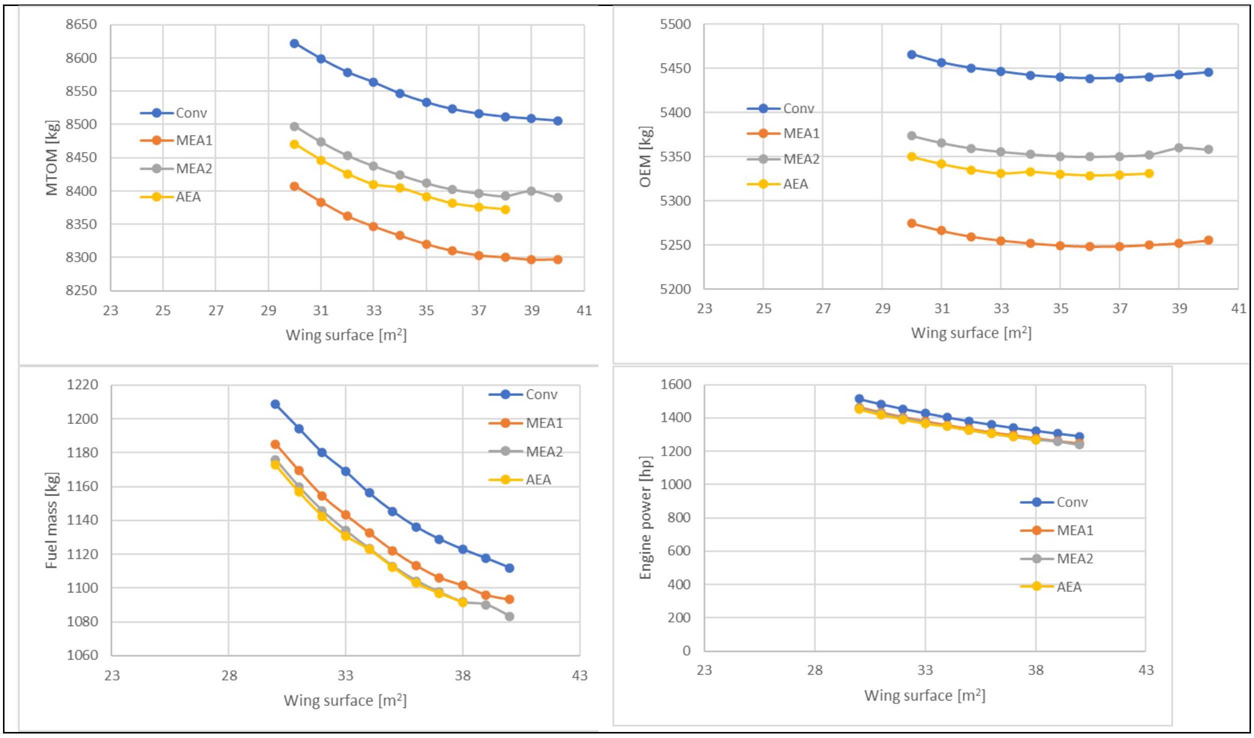


Fig. 27 DOE results. Design domain.

Focusing on the certification domain (see Fig. 28 and Fig. 29) the different OBS architectures perform more similarly. However, the MEA1 achieves greater certification margins for minimum performance constraints compared to the other architectures. It is mainly due to its positive effect on MTOM. In general, all the designed aircraft of the DOE have positive margins compared to both Part23 and Part25 constraints. A part for Part23 Noise margin, a reduction of the certification margins can be noted for aircraft with greater wing surfaces.

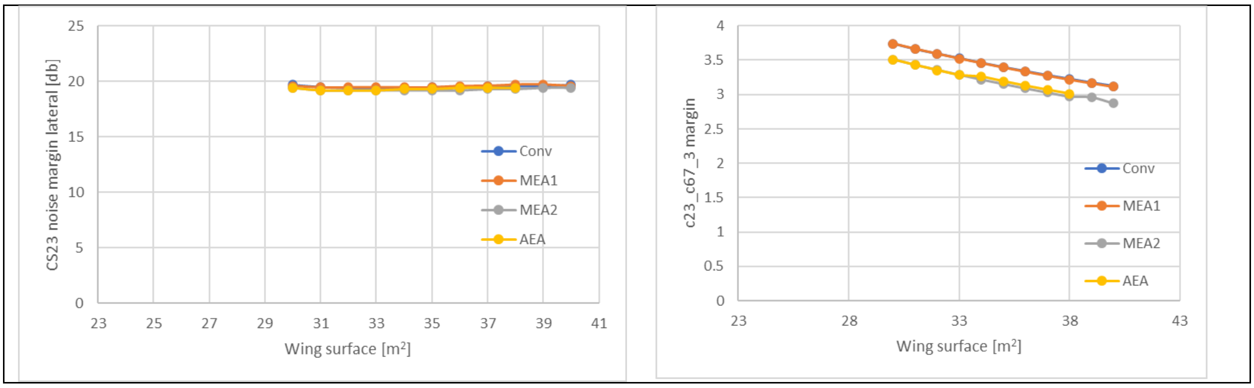


Fig. 28 DOE results. Certification domain - Part23.

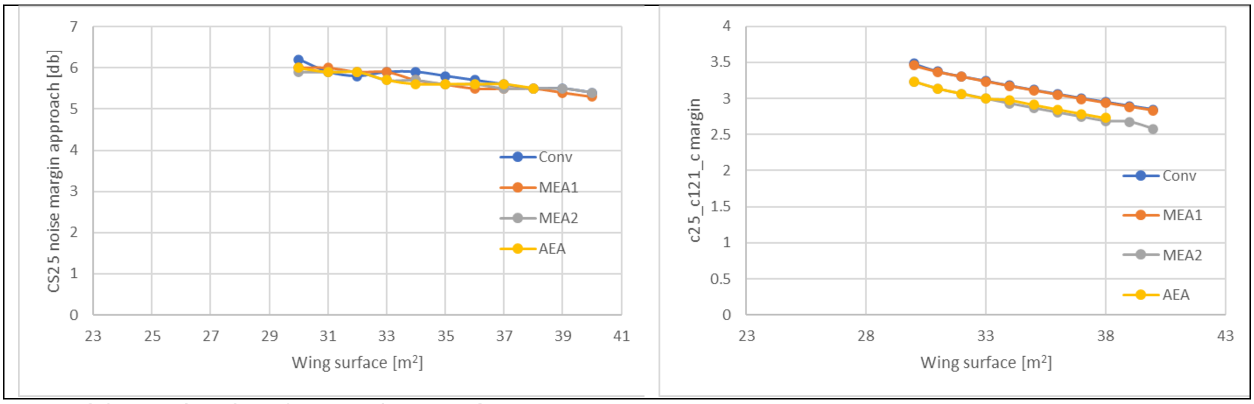


Fig. 29 DOE results. Certification domain - Part25.

Finally, the LCC domain provides the following trends (see Fig. 30):

- The non-recurring costs are stable versus the wing surface, but they are directly proportional to the electrification level
- The aircraft price without NRC component is comparable among the architectures. However, the electrified ones are simpler, and they required less effort to be produced. The aircraft price increase with wing dimensions and mass
- The operating cost considers both maintenance and fuel consumption as main drivers. The minimum values are achieved by AEA and MEA1 with a wing surface of 33m². The removal of the hydraulic system and the reduction of fuel burnt are certainly the reasons for this result.
- The LCC perform similarly to the operating cost since more than the 60% of it is constituted by operating cost. The optimum values are obtained for wing surface close to 35-36m²

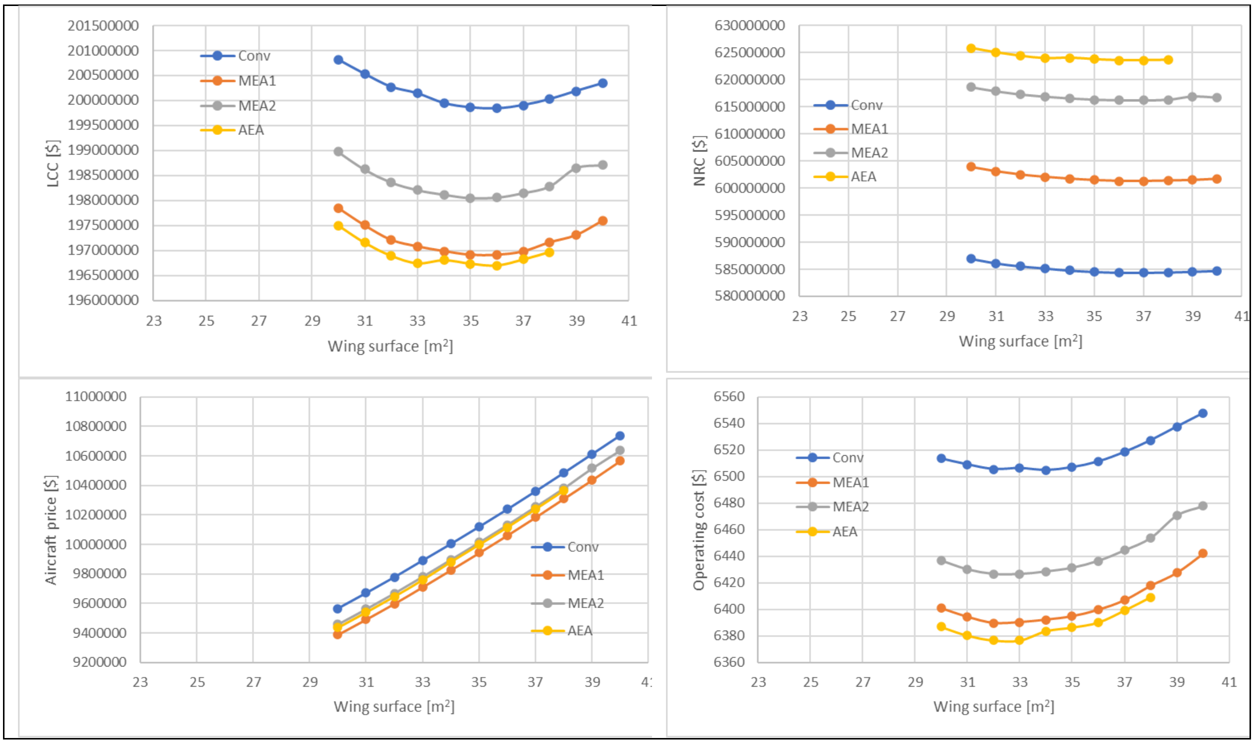


Fig. 30 DOE results. Cost domain.

2.5.4 Optimization

Considering the main aims of the AC3, the stakeholders' needs and the capabilities of the partners involved, the MDO problem is set as follow:

- Objective 1: Lowest LCC
- Objective 2: Highest certification margins
- Variable 1: OBS electrification level (discrete, 4 levels)
- Variable 2: Wing surface (continuous from 30 to 40 m^2)
- Constraint 1: Certification noise margins > 0
- Constraint 2: Certification min. performance margin > 0
- Constraint 3: Acceptable OBS safety level (Boolean)

Therefore, considering the main stakeholders' needs, the optimization should identify the aircraft with the lowest LCC and the highest certification margins. The workflow set up to carried out the optimization should include: the aircraft design loop, the certification margins calculation and the LCC estimation (see Fig. 31(B)). To implement the optimization algorithms (i.e. the multi-objective Bayesian optimization, more information can be found in[7]), another workflow is developed (see Fig. 31(A)) by ONERA and remotely connected to the previous one. To reduce the number of iterations, the optimizator is supplied with the DOE data and additional data calculated by a surrogate model of the DOE workflow (Fig. 31(B)).

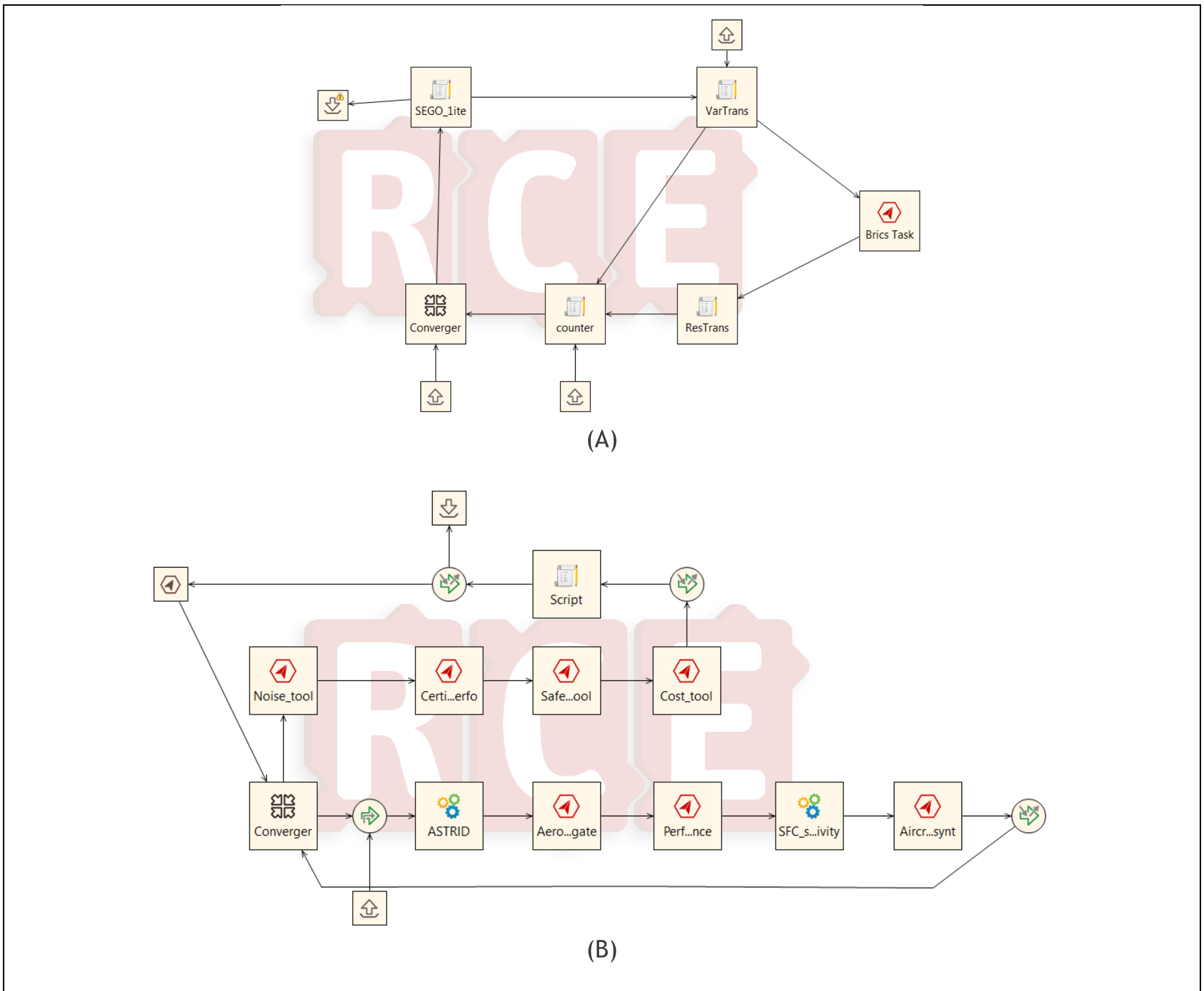


Fig. 31 AC3 optimization workflows

2.5.5 Trade-off

Since the LCC and the mean value of the certification margins tend to be directly proportional and being the final objective to minimize the first one and maximize the second, a pareto front is generated. Therefore, after the analysis, it is possible to quantify the necessary cost effort to increase the certification margins. Fig. 32 and Fig. 33 depict the pareto front and the optimization results for, respectively, Par23 and Part25 certification constraints. It is worth noting, the OBS architectures that mainly compose the pareto front are the AEA and MEA1. Moreover, those points are represented by aircraft with a medium/small wing surface. As shown by the DOE results, the AEA reach the lowest values of LCC especially for aircraft with medium wing surface. When aircraft with small wing surfaces are selected, the MEA1 obtains the lowest LCC values. In terms of certification margins, the highest values are reached by MEA1 (the aircraft with lowest MTOM) with small wing surfaces (with more powerful engines). In only one case the conventional OBS architecture is part of the pareto front with the highest value of margins but with poor cost performance. The MEA2, for this aircraft category, has always lower margins and higher cost then the other architectures. Comparing the results using the 2 regulations (i.e. Part23 and Part25) the trends are quite similar as already noted by the DOE results.

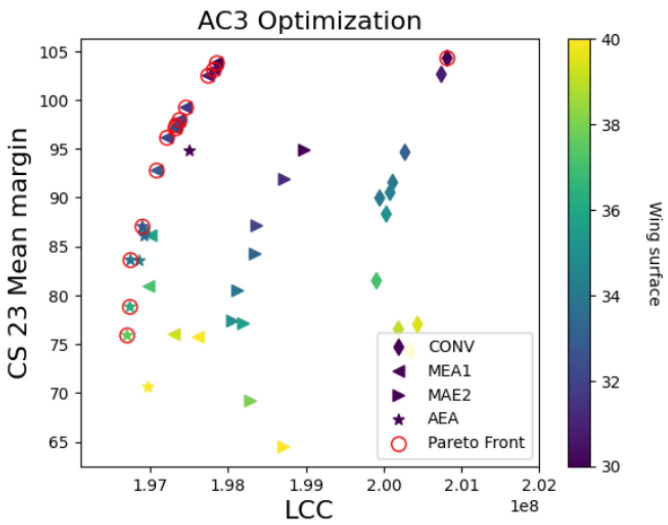


Fig. 32 Pareto front, AC3 optimization, CS 23 regulation

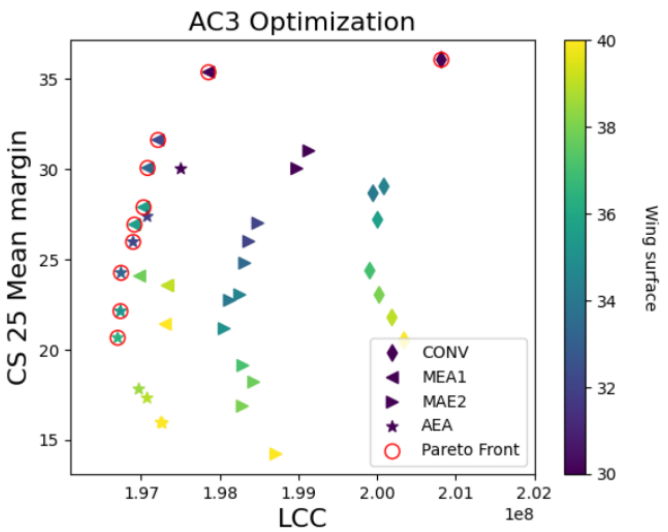


Fig. 33 Pareto front, AC3 optimization, CS 25 regulation

3 Application Case 4

Application Case 4 aims to allocate on-board system components in the aircraft considering maintenance aspects (accessibility, MTTR) and thermal risks during the early aircraft design stage. In particular, the trade-off between the maintainability and the thermal performance of a compartment of the electrical system shall be investigated. The reference aircraft, a 19 PAX CS-23 turboprop is shared with AC3 and shown in Fig. 34. As for AC3 there are four levels of electrification considered for AC4 which both have an impact on the aircraft itself but also the topology of the electrical system and the electrical compartment layout.
To reach the aims of AC4, it was studied the allocation of the components on an electronic bay, as described during this report.

Fig. 34: Application Case 4. On-board systems highlighted.

3.1 System Identification

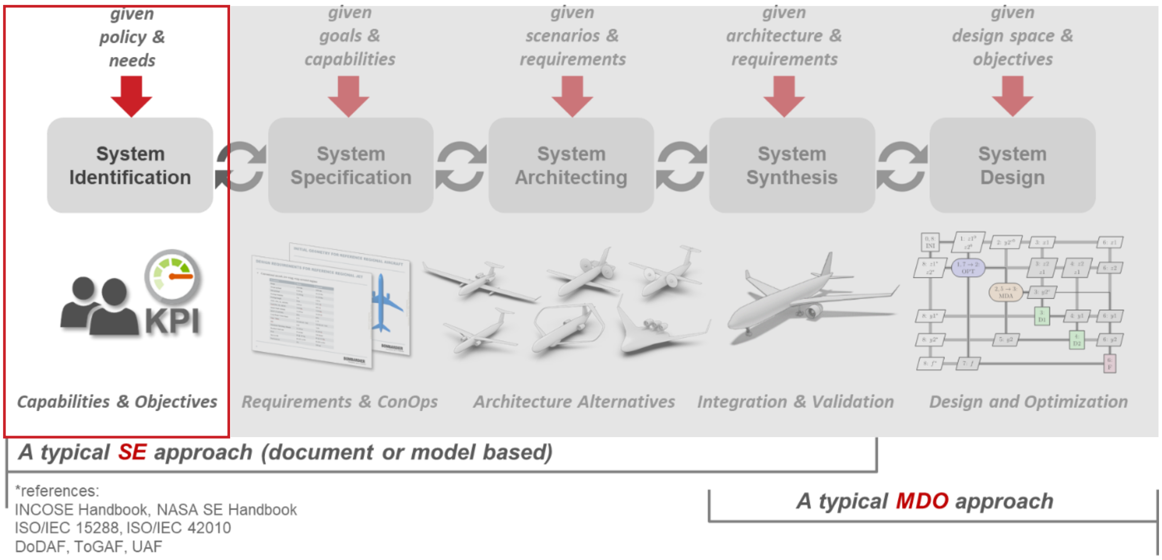


Fig. 35: AGILE 4.0 Step I: System Identification.

According to the AGILE4.0 application case modeling process the first step (system identification) involves the definition of stakeholders, needs and scenarios that are relevant for the respective application case. For AC4 this involves from a stakeholder side primarily the original equipment manufacturer (OEM), the maintenance organization and the airline. The stakeholders relevant for AC4 are listed in Tab. 6 with a subset of their expected needs.

Tab. 6: Stakeholders and subset of stakeholder needs in AC4

Stakeholder	Need
OEM	Low maintenance effort
	Reliable system architecture
	Low certification cost
	Competitive product
Maintenance Organization	Fast and easy maintenance
	High system accessibility
	Clearly defined maintenance procedure
	Low system complexity
	Standardized maintenance procedure
	Safe working environment
Airliner	High system availability
	Low turnaround time
	High system reliability
	Low maintenance cost
	High availability of spare parts
Passengers	High level of safety
	Low disturbance from unscheduled maintenance activities
	Departure on time
	Low ticket price
Airport Authority	High dispatch reliability / high flight dispatch
	No ground handling/infrastructure adaptions

Another part of the system identification phase is the definition of scenarios to validate the needs. For AC4 a representative corrective maintenance task on one of the system components of the electrical systems has been modeled. The activities in general involve: Gaining access to the considered component, replacing the component and reclosing the compartment. Dependent on the installation situation and the individual component the complexity of these tasks and sub-steps may vary. For AC4 the scenario modelling has been carried out on a battery as an example. The implementation of the sub-steps has been carried out in the Operational Collaborative Environment (OCE) followed by an export to the Capella software for displaying the scenario as a sequence diagram. An excerpt of the diagram can be seen in Fig. 36. The modeled scenario shows that the maintenance process involves a lot of interaction with the system and is mostly influenced by the individual installation situation of the component. This scenario thus validates in particular the stakeholder Maintenance Organization’s need for a high component accessibility.

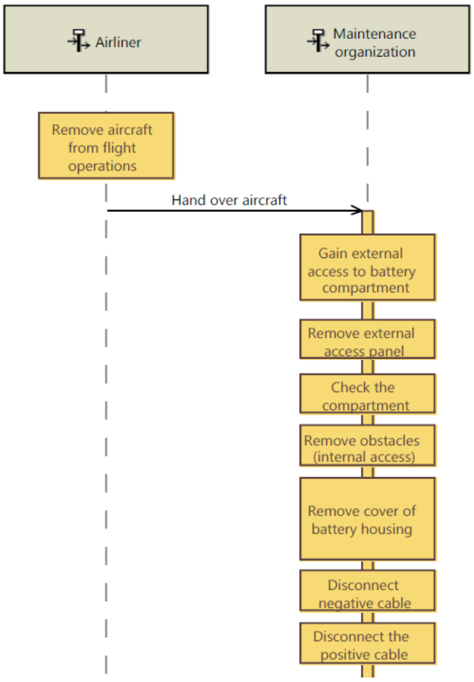


Fig. 36: Part of the sequence diagram for AC4: Unscheduled battery replacement

3.2 System Specifications

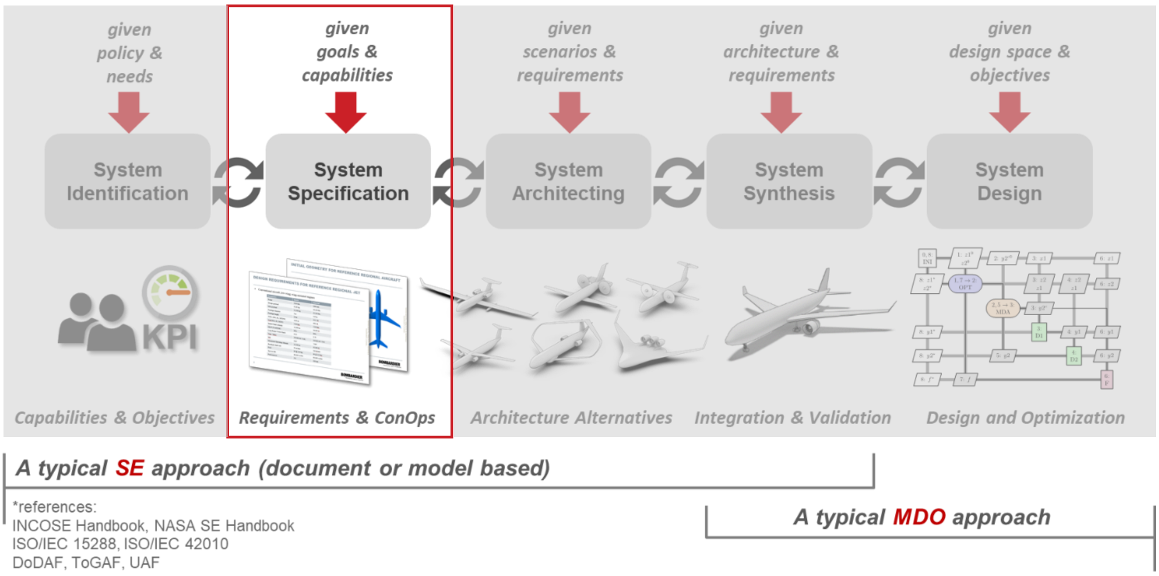


Fig. 37: AGILE 4.0 Step II: System Specification.

The system specification process considers formulation of requirements from the needs of the stakeholders that have been identified in the previous process step. An excerpt of the requirements derived for AC4 can be seen in Tab. 7. Typically there is a large number of requirements emerging from an aircraft as a very complicated product. During the system specification a focus was laid on deriving and refining those requirements that contribute directly to the application case specific problem. A large fraction of the more general and aircraft referencing requirements of AC4 are shared with AC3 as they are referring to the same aircraft. A complete list of requirements can be obtained from the Papyrus MBSE model that is automatically generated from the requirements entered into the OCE. A part of the Papyrus model can be seen in Fig. 38.

The Papyrus model also conveniently displays all connections between requirements, needs and stakeholder which allows easy traceability of these elements. An automated verification of the stated requirements from the optimization results can be obtained from the requirement verification framework (RVF).

Tab. 7: Subset of the requirements defined for AC4

Requirement	Definition	Type
Electrical system maintainability	The electrical system shall be maintainable in a maximum time of 20 min on average.	Performance
Electrical compartment thermal performance	The electrical bay shall have a temperature of less than 50°C.	Performance
Power provision - cruise flight	The electrical system shall provide power to all consumers during cruise flight	Functional
Power provision - emergency operation	The electrical system shall provide electrical power to safety relevant consumers in case of emergency.	Functional
Electrical system availability	The electrical system shall have an availability greater than 90%.	Performance
Component MTTR	The electrical components mean time to repair shall be smaller than 15 min each.	Performance
Dispatch reliability	The aircraft shall operate with a dispatch reliability of 99.5%.	Suitability
Delay	The aircraft shall start its mission with a maximum delay of 60 min.	Suitability
Operating cost	The aircraft shall operate at a maximum cash operating cost of 0.11 US$ per available seat kilometer, for the standard mission and standard utilization scenario over the first 10 years.	Performance
Availability	The aircraft shall operate with an availability of 70%.	Suitability

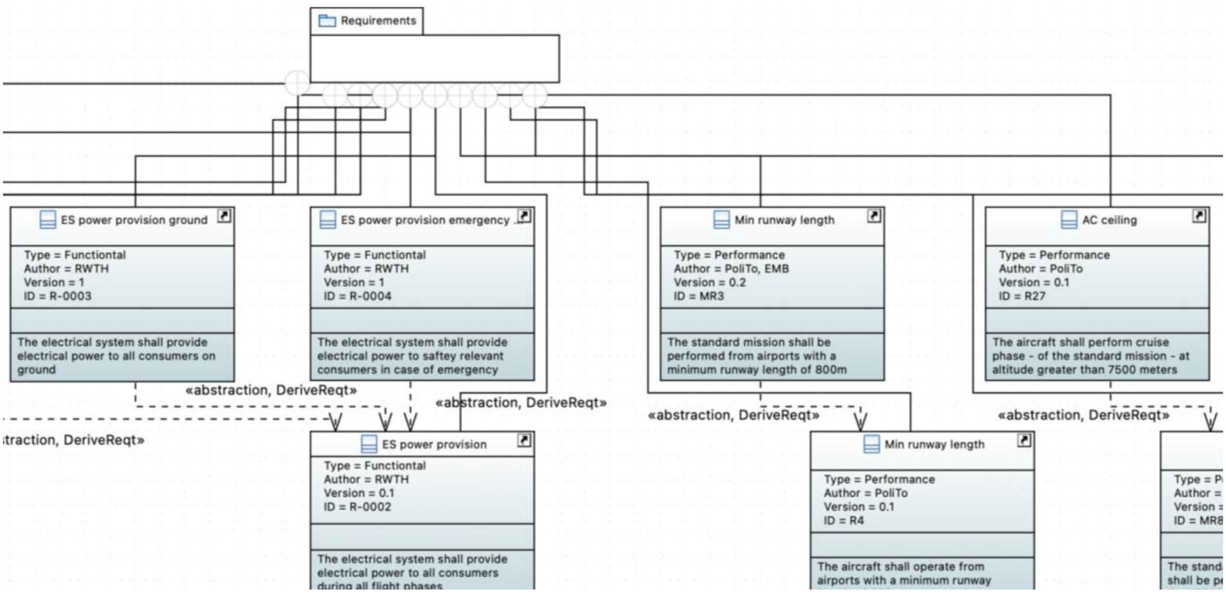


Fig. 38: Excerpt of the Papyrus SysML model of the requirements, needs and stakeholder of AC4

3.3 System Architecting

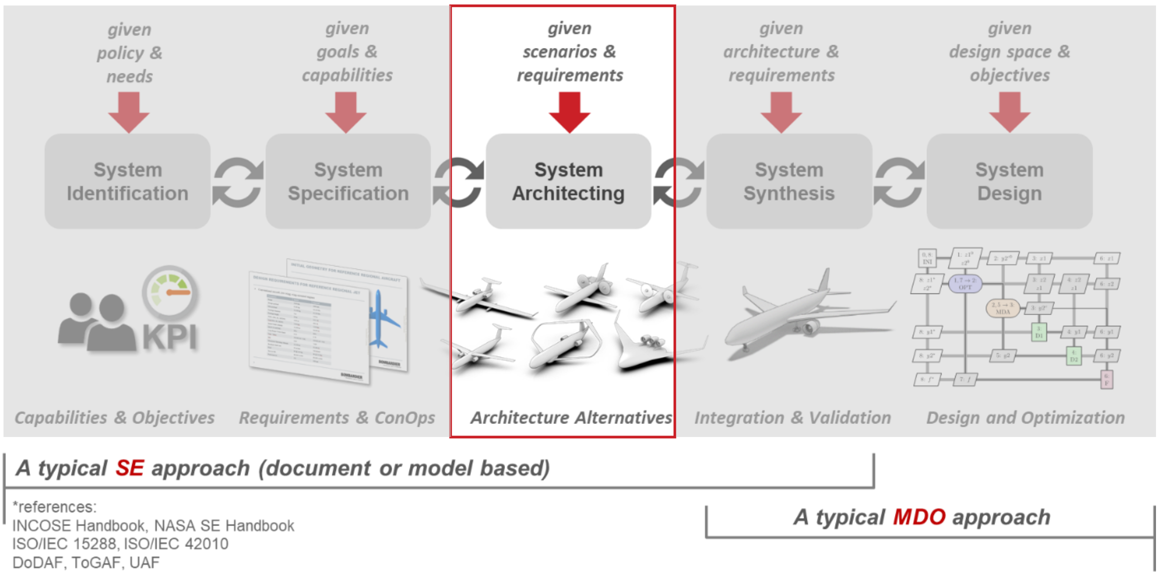


Fig. 39: AGILE 4.0 Step III: System Architecting.

The system architecting step considers the implementation of the systems of interest (SOI) into ADORE. For AC4 the SOI are the electrical system in four different configurations dependent on the degree of electrification considered and the virtual maintenance system.

All functions are derived from boundary functions which emerge from functional requirements defined in the previous AGILE4.0 process step. Boundary functions represent the use cases of the system considered which are: “Provide electrical power to all consumers during normal operation” and “provide electrical power to essential loads in case of emergency”. The functions are successively decomposed and assigned to components for function fulfillment.

From the boundary function “provide electrical power to essential loads in case of emergency” primarily safety related elements of the electrical system could be derived (e.g. fuses, circuit breaker, switches) but also concepts and rules for developing a network topology, e.g. enabling the connection of emergency power providers to essential loads via multiple paths). Since these aspects are safety driven, they hardly can be used to include design decisions and therefore do not affect the system architecture at this design level.

The second focus of the model lies into enabling different architectural options of the electrical system that depend on the composition of power consumers.
A common necessity for the fulfilment of all boundary functions are the elemental functions of an electrical system which can be described as power generation (or provision), power direction/distribution, power conduction and power conversion. These functions are similar to all electrical system regardless the respective architecture.

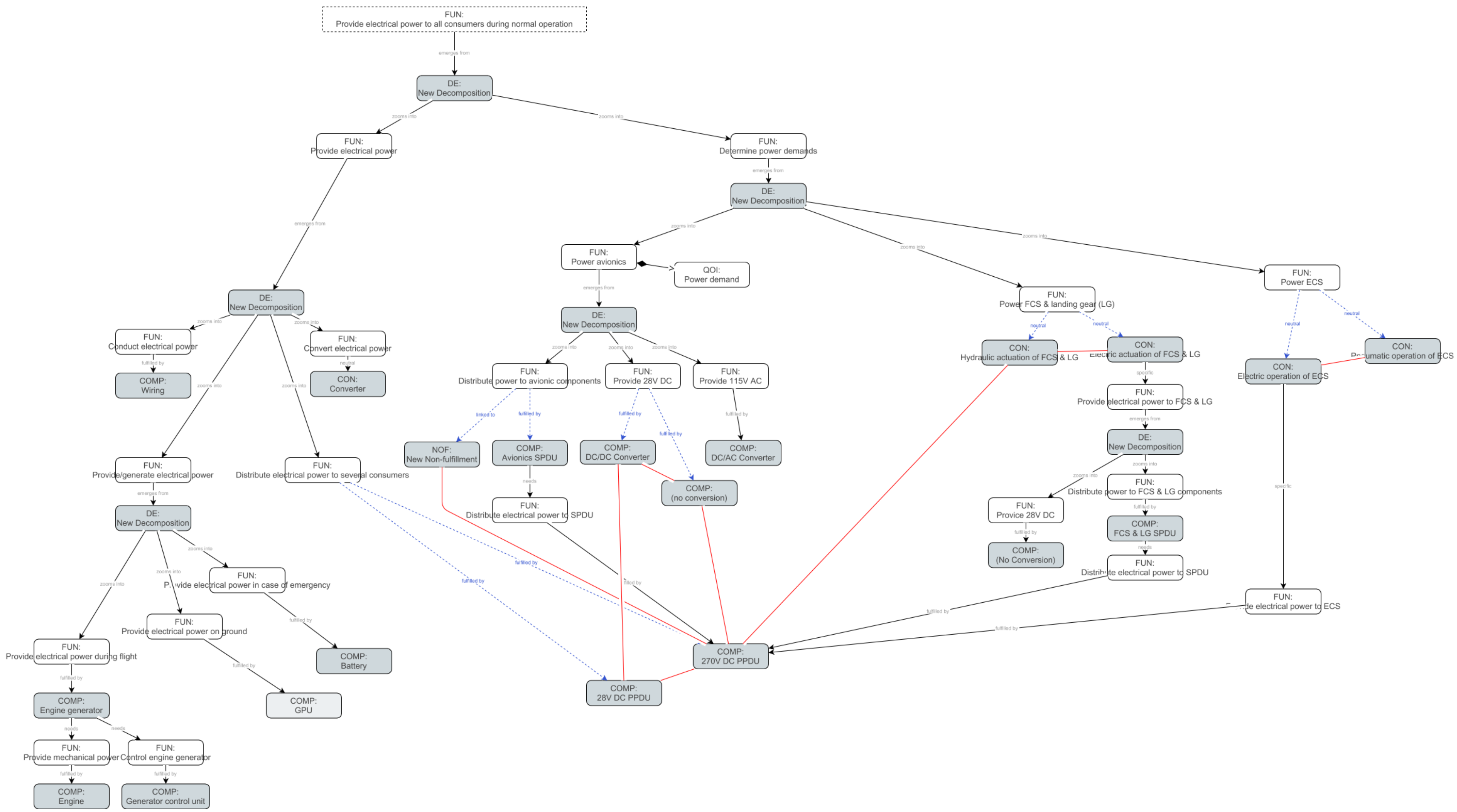
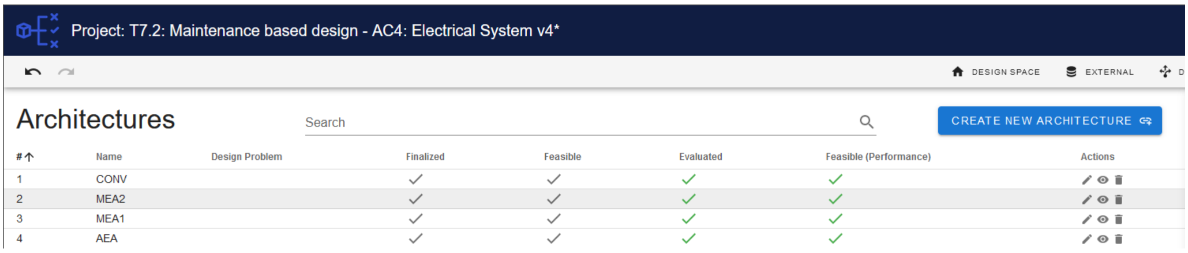


Fig. 40: Detail view of the ADORE model of the primary SOI: The electrical system


Project: T7.2: Maintenance based design - AC4: Electrical System v4*

DESIGN SPACE EXTERNAL

Architectures

Search

CREATE NEW ARCHITECTURE

#	Name	Design Problem	Finalized	Feasible	Evaluated	Feasible (Performance)	Actions
1	CONV		✓	✓	✓	✓	
2	MEA2		✓	✓	✓	✓	
3	MEA1		✓	✓	✓	✓	
4	AEA		✓	✓	✓	✓	

Fig. 41: Architecture decision panel

The architecture decisions panel of the first SOI is shown in Fig. 41. The primary decision available here is related to the power provision of other different aircraft OBS (hydraulic, electric, and pneumatic). These decisions have the most influence on the actual architecture. Dependent on the decisions taken, the resulting architecture will correspond to the CONV, MEA1, MEA2 or AEA architecture as also used in AC3, as shown in Fig. 42. Other architecture decisions are related to design parameters that are relevant for the thermal evaluation of the electrical bay and optimization. An example is given in Fig. 43 for the battery component. The QOIs ‘pos-x’, ‘pos-y’ and ‘pos-z’ are used as optimization variables during the later optimization stage. The QOIs ‘MTTR’ and ‘Temperature’ are used as optimization objectives. Ventilation strategies are selected manually.

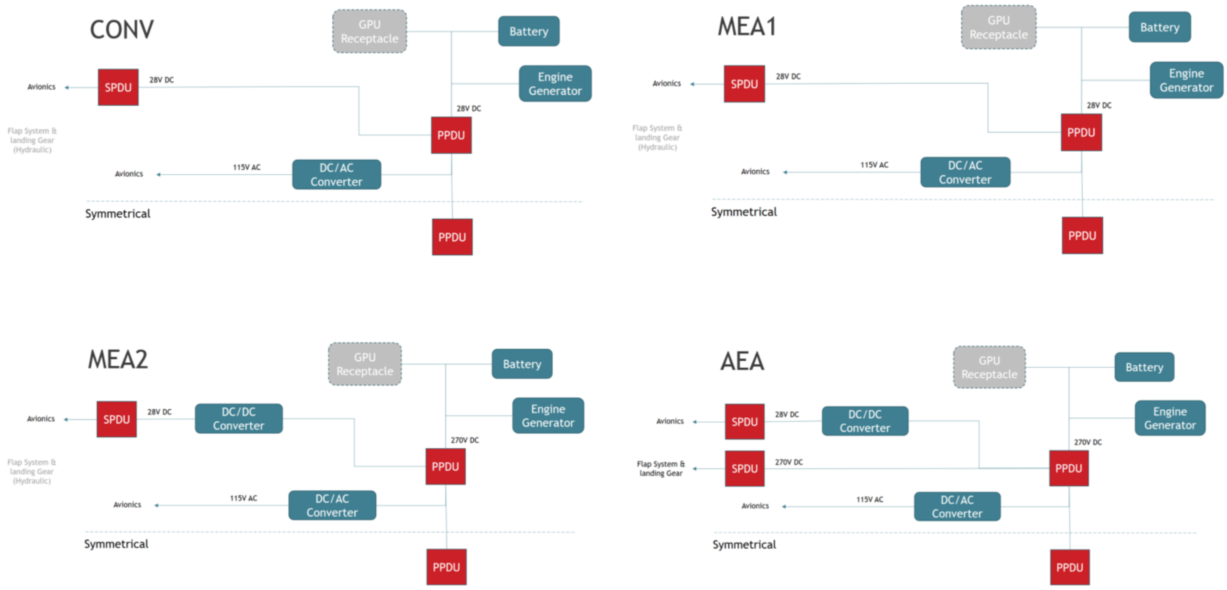


Fig. 42: Considered architectures of the electrical system for AC4 (CONV, MEA1, MEA2, AEA)

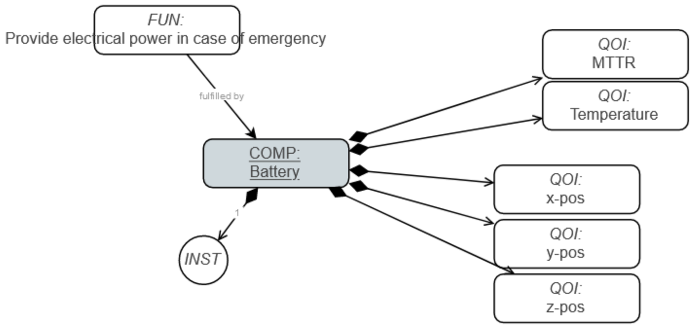


Fig. 43: Detail view of the QOIs allocated to a component of the electrical bay

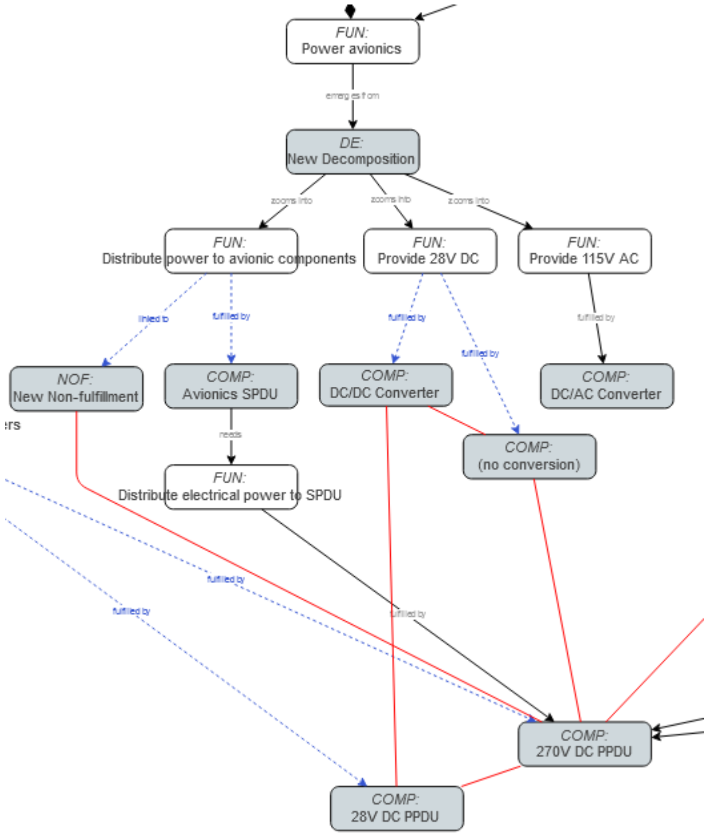


Fig. 44: AC4 SOI architecture – Detail view of avionics power supply

Fig. 44 shows the avionics power supply as a relevant fraction of the first SOI. The board power/voltage level depends on which OBS are powered electrically (e.g. flight control system). This affects which type of primary power distribution unit can be used. E.g. in case of a hydraulic actuation of flight controls, the 270V DC PPDU is incompatible with this decision (indicated by red lines). This decision affects the power distribution to other components and conversion to another current type or voltage level. In this example do the avionics need 28V DC which can be provided by connecting the avionics directly to a 28V DC network (Comp: no conversion) or by employing a DC/DC converter which is only compatible with a 270V DC network.

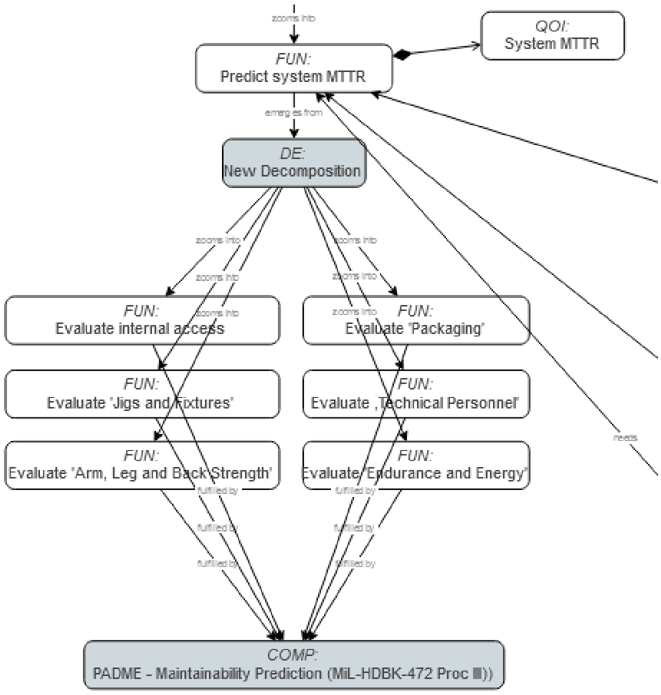


Fig. 45: AC4 Enabling System - Virtual Maintenance System

A detail view on the enabling system, the virtual maintenance system is shown in Fig. 45 comprising the maintainability prediction. To calculate the QOI System Mean Time To Repair an evaluation of different system design parameters has to be performed (e.g. accessibility, packaging…). These functions are fulfilled by the maintainability prediction subroutine of the tool PADME. The two SOIs are linked by the quantity of interest (QOI) 'System MTTR' which is calculated by PADME for the first SOI both for the complete electrical system and also for it's respective system components.

3.4 System Synthesis

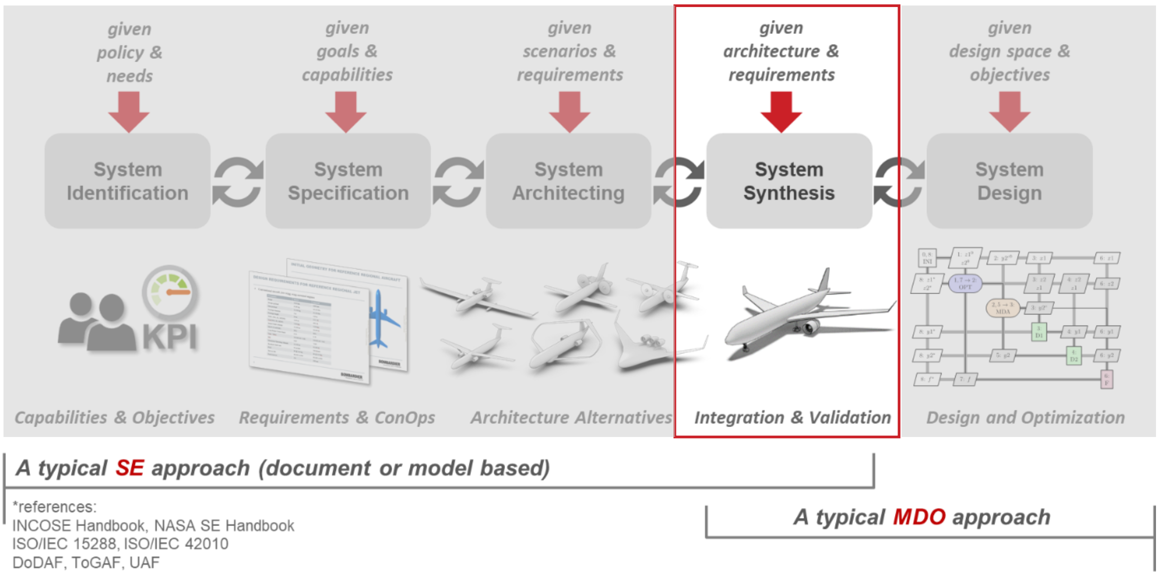
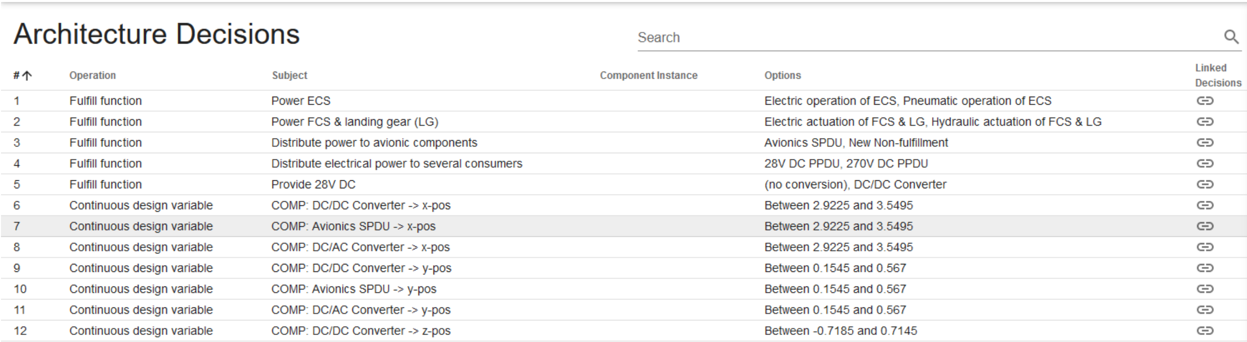


Fig. 46: AGILE 4.0 Step IV: System Synthesis.

The fourth step of the process involves the system synthesis which involves the integration and validation of the modeled architectures from the previous step. As the architecture modeling, this step is done in ADORE in the OCE. Based on the architecture decisions enabled during modeling in the design space panel, all possible decisions can be inspected in the architecture decisions panel as shown in Fig. 42.



Architecture Decisions

Search

#	Operation	Subject	Component Instance	Options	Linked Decisions
1	Fulfill function	Power ECS		Electric operation of ECS, Pneumatic operation of ECS	
2	Fulfill function	Power FCS & landing gear (LG)		Electric actuation of FCS & LG, Hydraulic actuation of FCS & LG	
3	Fulfill function	Distribute power to avionic components		Avionics SPDU, New Non-fulfillment	
4	Fulfill function	Distribute electrical power to several consumers		28V DC PPDU, 270V DC PPDU	
5	Fulfill function	Provide 28V DC		(no conversion), DC/DC Converter	
6	Continuous design variable	COMP: DC/DC Converter -> x-pos		Between 2.9225 and 3.5495	
7	Continuous design variable	COMP: Avionics SPDU -> x-pos		Between 2.9225 and 3.5495	
8	Continuous design variable	COMP: DC/AC Converter -> x-pos		Between 2.9225 and 3.5495	
9	Continuous design variable	COMP: DC/DC Converter -> y-pos		Between 0.1545 and 0.567	
10	Continuous design variable	COMP: Avionics SPDU -> y-pos		Between 0.1545 and 0.567	
11	Continuous design variable	COMP: DC/AC Converter -> y-pos		Between 0.1545 and 0.567	
12	Continuous design variable	COMP: DC/DC Converter -> z-pos		Between -0.7185 and 0.7145	

Fig. 47: Architecture decisions panel of ADORE

In the architecture panel a new architecture can be generated by making the design decisions listed in the architecture panel. For generating the CONV electrical systems architecture one e.g. has to decide on 'Pneumatic operation of ECS' and 'Hydraulic actuation of FCS & LG'. After making the decisions the concrete architecture is obtained as shown in Fig. 48.

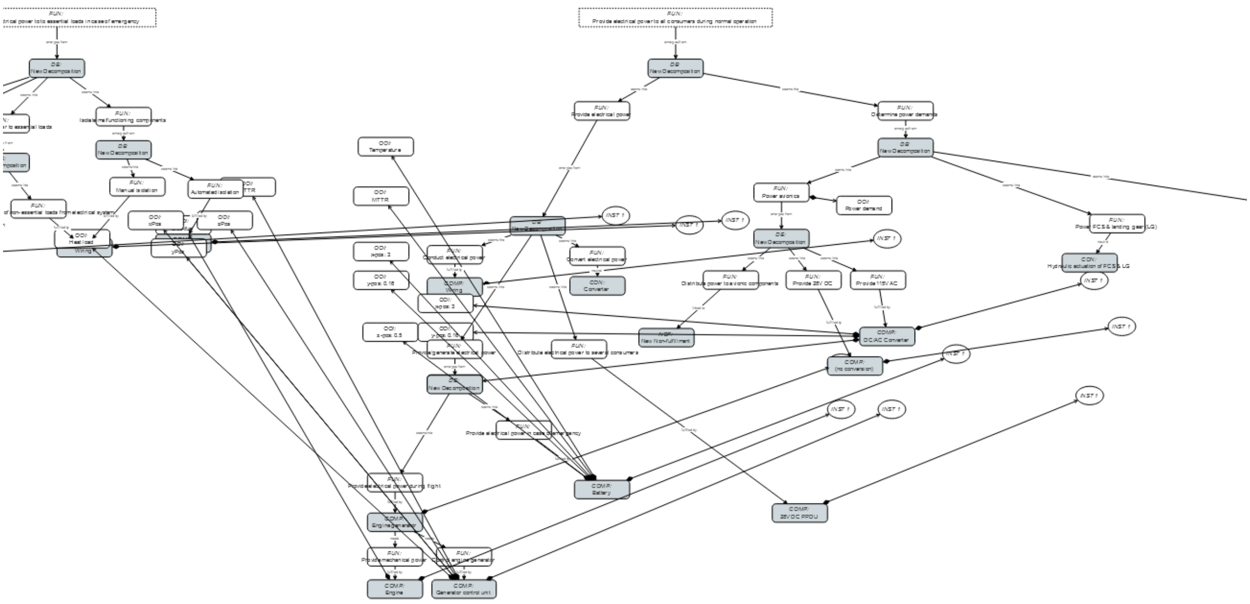


Fig. 48: Detail view of the CONV architecture of the electrical system

It is possible to add quantities of interest (QOI) to the model to enable the formulation of an MDO problem. QOIs can either be a constraint, objective, design variable or metric of an MDO problem. The considered QOIs for AC4 can be inspected in the design problem panel (Fig. 49).

Design Problem: New Design Problem

Search

BACK TO OVERVIEW ✕

Design Variables

#	Name	Type	Source	Options	Fixed Value	Actions
1	func_fulfill	Discrete	Decision #1	2		
2	func_fulfill_2	Discrete	Decision #2	2		
3	QOIS_X-POS_0	Continuous	QOI: x-pos	Between 2.9225 and 3.5495		
4	QOIS_X-POS_2_0	Continuous	QOI: x-pos	Between 2.9225 and 3.5495		
5	QOIS_X-POS_3_0	Continuous	QOI: x-pos	Between 2.9225 and 3.5495		
6	QOIS_Y-POS_0	Continuous	QOI: y-pos	Between 0.1545 and 0.567		
7	QOIS_Y-POS_2_0	Continuous	QOI: y-pos	Between 0.1545 and 0.567		
8	QOIS_Y-POS_3_0	Continuous	QOI: y-pos	Between 0.1545 and 0.567		
9	QOIS_Z-POS_0	Continuous	QOI: z-pos	Between -0.7185 and 0.7145		
10	QOIS_Z-POS_2_0	Continuous	QOI: z-pos	Between -0.7185 and 0.7145		
11	QOIS_Z-POS_3_0	Continuous	QOI: z-pos	Between -0.7185 and 0.7145		
12	X-POS_0	Continuous	QOI: x-pos	Between 2.9225 and 3.5495		
13	Y-POS_0	Continuous	QOI: y-pos	Between 0.1545 and 0.567		
14	Z-POS_0	Continuous	QOI: z-pos	Between -0.7185 and 0.7145		

Objectives

#	Name	Source	Active	Direction	Actions
1	Blockfuel	QOI: Blockfuel	✓	Minimize	
2	Heat load	QOI: Heat load	✓	Minimize	
3	MTTR	QOI: MTTR	✓	Minimize	
4	Power demand	QOI: Power demand	✓	Minimize	
5	MTTR	QOI: MTTR	✓	Minimize	
6	Temperature	QOI: Temperature	✓	Minimize	

Fig. 49: Design problem panel of AC4

3.5 System Design

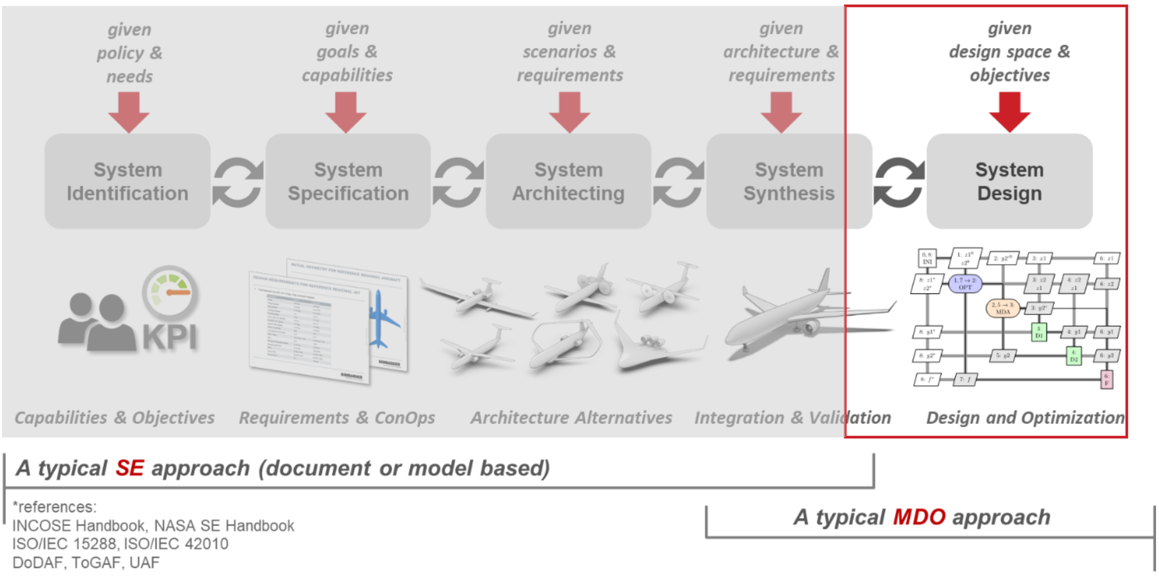


Fig. 50: AGILE 4.0 Step IV: System Synthesis.

3.5.1 Workflow implementation

The last phase of the workflow is the system design which involves the definition and execution of an MDO process to solve the design problem sketched in the previous steps and check if the solution is fulfilling the requirements defined during the second step.
The design problem for AC4 considers the allocation of the components within the compartments of the electrical bay to both minimize the mean time to repair (MTTR) and the compartment average temperature. The design variables considered are the positions of the component within the respective compartment boundaries. Parameters are the degree of electrification of the aircraft and the ventilation strategy that involves the positioning and number of ventilators. The overall intersection volume of different components has been chosen as a constraint. This is necessary because the optimization algorithm considered cannot

distinguish if a certain volume or volume fraction is already occupied by another component. To avoid optimal solutions that consider e.g. all components in the same place to maximize the maintainability, the constraint was added. This ensures that only feasible arrangements are considered.
For the thermal risk there is an additional implicit constraint added that is not applied in the optimization process that limits the compartment thermal risk score to a max value of 9. All values above are considered a high thermal risk and should be avoided. The results from a preliminary investigation on different ventilation strategies (number and position of ventilators, varying mass flow rate) for the starboard compartment can be seen in Fig. 51.

The optimization parameters, objectives and variables originate from the requirements defined in Tab. 7 are shown in Tab. 8.

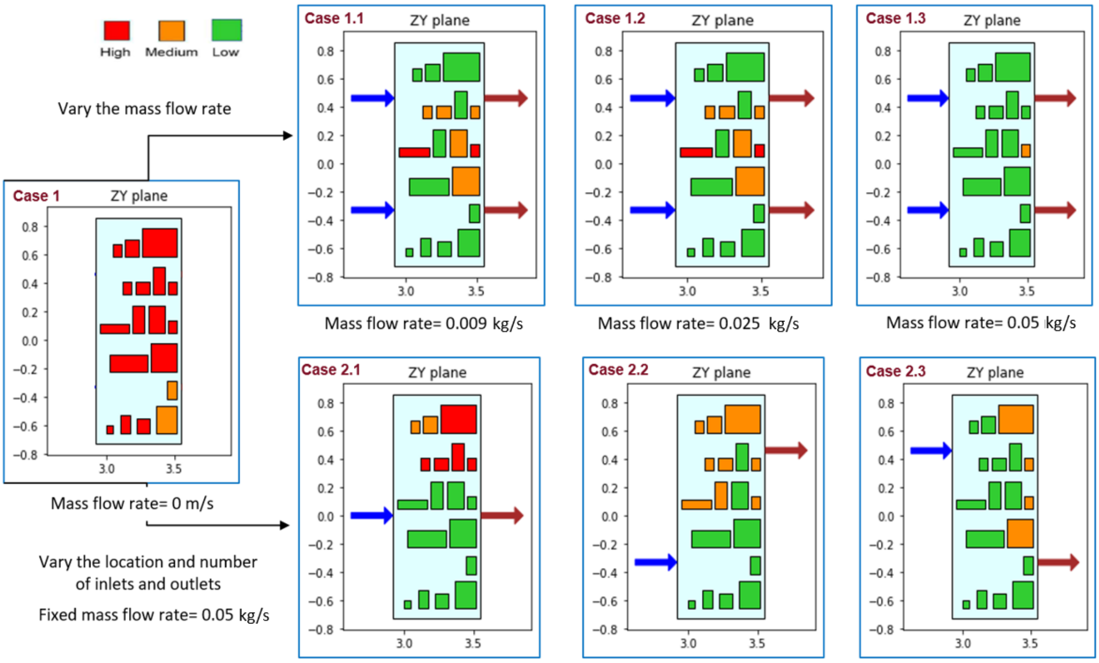


Fig. 51: PySysTher results for the right starboard compartment in CONV configuration for proposed ventilation strategies

Tab. 8: AC4- Optimization variables, parameter, constraints and objectives

Variable	Design variable/parameter	Type	Range
Component positions	Design variable	continuous	2.9225 < x < 3.5495 0.1545 < y < 0.5675 -0.7185 < z < 0.7145
Electrification	Parameter	discrete	CONV (18/21 components) MEA1 (19/25) MEA2 (18/24) AEA (19/25)
Ventilation	Parameter	discrete	(Cf. Fig. 51)
Intersection volume	Constraint	-	= 0
Maintainability (Mean Time To Repair)	Objective	Continuous	Minimize
Thermal Score	Objective	Continuous	Minimize
(Thermal Score)	Constraint	Continuous	< 9

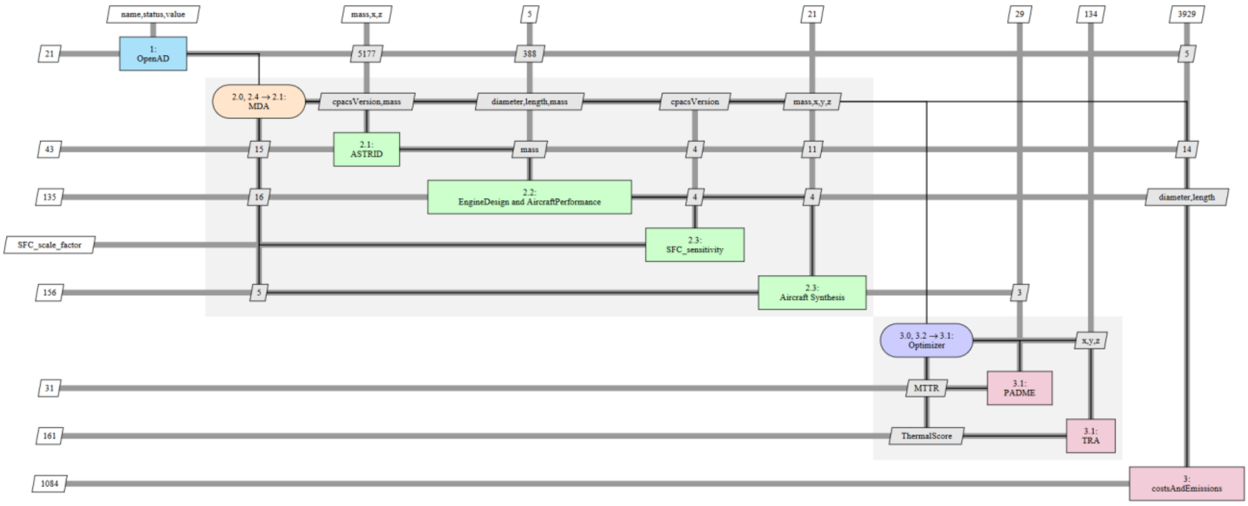


Fig. 52: XDSM of AC4

The XDSM for the optimization problem of AC4 obtained with MDAX is shown in Fig. 52. The following design competences were used:

- OpenAD / AircraftSynthesis – DLR: Overall aircraft design
- ASTRID – PoliTo: Systems design
- EngineDesign – UNINA: Engine design
- AircraftPerformance – UNINA: Aircraft performance evaluation
- AircraftSynthesis/OpenAD – DLR: Mass convergence and redesign
- PADME – RWTH: Maintainability evaluation
- pySysTher / TRA – CONCORDIA: Thermal risk assessment
- costAndEmissions – RWTH: Cost and DOC calculation
- SEGOMOE – ONERA: Surrogate optimization

The workflow can be divided into two parts: The outer mass convergence loop containing the majority of the competences of the overall aircraft design domain including ASTRID, EngineDesign & AircraftPerformance, SFC_sensitivity and the Aircraft Synthesis. In inner optimization loop considering PADME and pySysTher (TRA, ThermalRiskAssessment) addresses the compartment optimization itself.
From the XDSM it can be seen that the compartment optimization part is hardly connected to the overall aircraft design domain. The influence of a shifted center of gravity due to a rearranged compartment was considered to have a negligible influence on the overall aircraft design.

The tools involved in the compartment optimization process shall be briefly described:
PADME (RWTH) estimates the repair time for individual components or several components within a compartment. The estimation uses Procedure III as described in MiL-HDBK-472. Procedure III uses a regression equation to calculate a mean time to repair (MTTR) for individual system components based on a scoring performance evaluated on three different checklists for system design, facility properties and human factors. A majority of the checklist items from the facility checklist and the human factors are outside the scope of the application case and are considered constant. The remaining checklist items can be evaluated based on the component size, mass, installation situation (proximity to other components or the compartment boundary), relative position to the maintenance door and component type (electric, hydraulic, mechanic, pneumatic). The checklist items evaluated are:

- Accessibility: Evaluates visibility and manipulative accessibility
- Fasteners: Estimated number of fasteners to loosen to disassemble/reassemble the component
- Packaging: Calculates if the disassembly path to the maintenance door is clear of other components
- Jigs and fixtures & Required personnel: Jigs, fixtures, lifting hoists or additional personnel are needed if the component mass is exceeding certain thresholds or if the component is not installed within reach from the respective floor level
- Arm-, leg & back strength/Ergonomics: Evaluates how strenuous the posture is that is to be adopted for the maintenance task and the general space around the maintenance technician during performing the task

- Endurance and energy: Considers the component mass

PySysTher (CONCORDIA) is a tool that allows the thermal risk prediction of on-board systems and components [9][10] in a parametric manner. The thermal risk is defined as the potential of non-compliance with thermal requirements (e.g., exceeding the maximum allowable bay temperature). As such, PySysTher adds certification constraints from a thermal perspective to the MDAO workflow.
The tool pySysTher uses a thermal risk assessment approach that consists of two levels of analysis. The first level is the aircraft zone level, including ventilation and temperature stratification predictions of the zone under study. The second part of the approach covers three system-level aspects: The mainstream flow analysis to predict the closeness of a system with regards to the considered ventilation source (discussed in more detail in[10]), the system integration analysis that focuses on the system locations in the bay, the assessment of the thermal interactions between a system and the zone (i.e., heatloads), and the other systems, and the system-level aspects related to the system requirements derived from standards such as RTCA DO-160G or SAE AIR1168/6A.
Finally, a thermal risk score is computed for each system component following a penalty-point approach. A low score (below 5) corresponds to a potentially feasible configuration (low thermal risk) and more points (above 9) to the ones related to non-feasible configurations (high thermal risk). Finally, the system-per-system scores are compiled into a bay-level score that can be used in the optimization loop.
Typically, the thermal risk should be low during conceptual design; medium or high risk might lead to potentially unfeasible configurations in preliminary or detailed design.
For bay configurations requiring ventilation, the required air mass flow rate is translated into additional weight (due to a fan or vapor cycle cooling system) considered in the OBS mass build-up.

3.5.2 Workflow execution

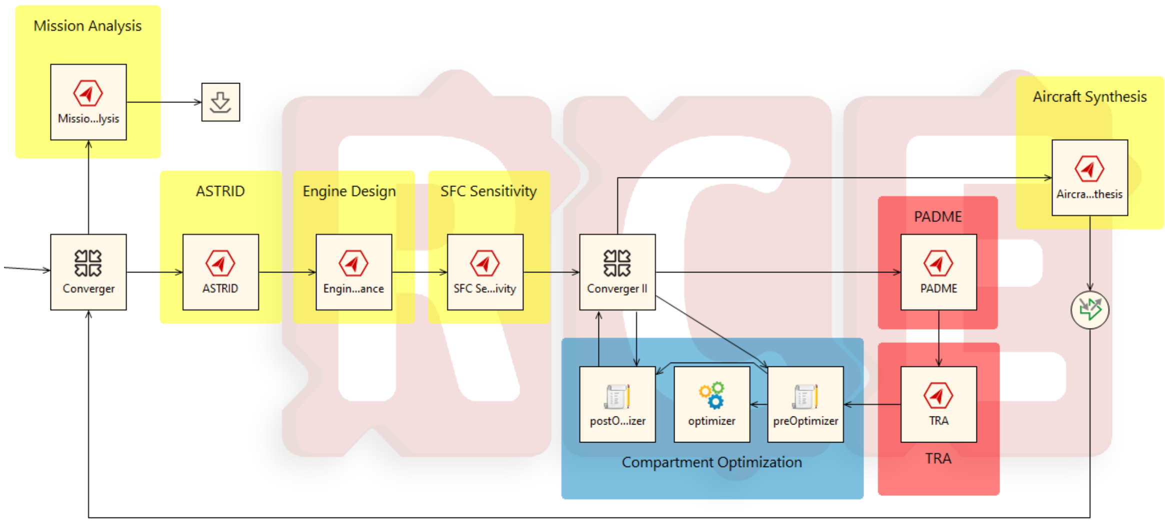


Fig. 53: RCE implementation of the AC4 workflow

Preliminary investigations showed that the interaction between the overall aircraft design domain and the maintainability domain were less pronounced than expected. Meaning that changes in the value of the considered design variables have very little effect on the variables (MTOM, L/D, center of gravity…) of the OAD domain. Therefore the overall aircraft design is hardly subject to changes and the optimization of the compartment can be largely decoupled from the design competences of the overall aircraft design. This has proven to be beneficial as the compartment optimization is a challenging problem in itself.

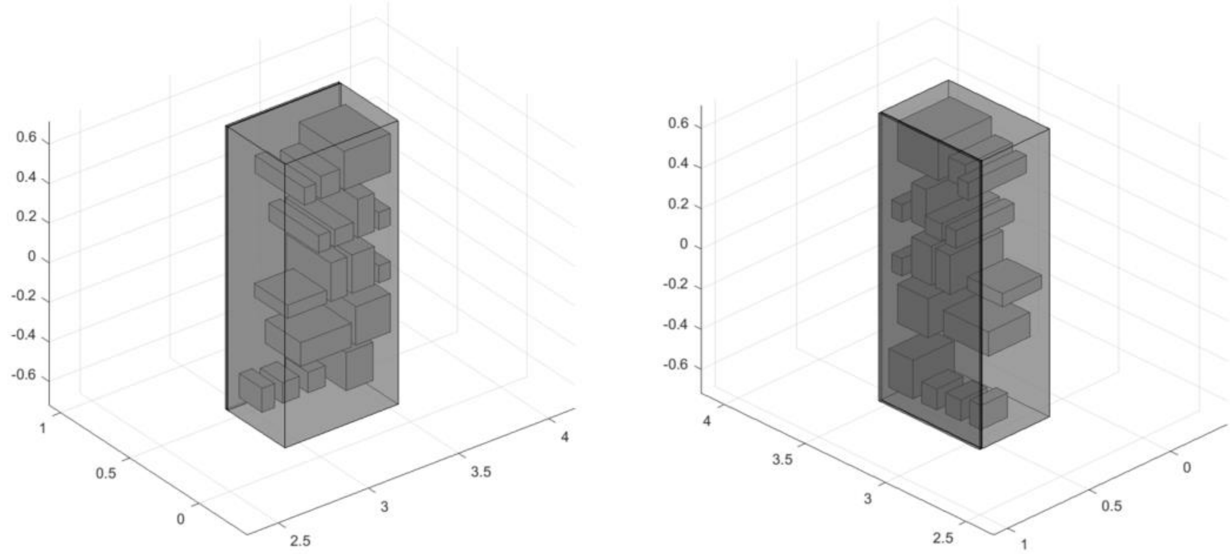


Fig. 54: Starboard electrical bay compartment with CONV electrical system configuration

3.5.3 Optimization

OPT1: Surrogate Optimization using SEGOMOE

For the first optimization approach the SEGOMOE surrogate optimizer by ONERA was used. Subject to the investigation was the starboard electrical bay compartment using the CONV architecture and no means of ventilation. To create a database for the optimizer a DOE was performed that involved 150 points. To obtain a good coverage of the design space, the values of the design variables were obtained by latin hypercube sampling. Based on the DOE the optimizer independently requests the evaluation of additional enrichment points which are added to database. The objective space with the results from the first DOE and additional 53 points obtained from the subsequent optimization are shown in Fig. 55. The initially performed DOE covers a majority of the objective space. As expected from the preliminary investigations, the thermal scores all are exceeding the upper limit of 9 but show a good sensitivity towards different component arrangements. The value range of the maintainability score is with [0.2144 h … 0.2153 h] rather small. This is due to an already very high maintainability of the default compartment configuration. For the maintainability evaluation PADME evaluates several parameter like accessibility, packaging, component/system type, component size & weight etc. It showed that most parameters were maxed out for the unaltered compartment

- since no components are exceeding any size or weight limits that needs them to be handled by a second technician,
- all components are of electrical type and need no additional safety precautions or preparations as it would be the case for e.g. hydraulic systems,
- all components are easily accessible and in direct reach from the maintenance door,
- no components are obstructing the disassembly path of other components.

The major influence on the overall maintainability score is the energy and endurance score which considers the installation height and mass of the component. The best score is awarded when heavy components are located between chest and waist height.

Regarding the optimization results, it was further noted that the intersection volume constraint could not be met by the evaluated solutions. Since the compartment has a high ratio of the total component volumes to the compartment volume, it is very likely to encounter partial or complete intersections by reorganizing the components. A relaxation of the constraint that allows intersection volumes up to 0.021 m^3 did not increase the number of valid solutions. Subsequently the optimizer was provided with five manually arranged collision-free samples to enrich the database with valid solutions. An additional evaluation of 30 points still did not provide any additional valid solutions.
In general the optimizer shows a good behaviour by exploring the Pareto front at minimal thermal score and minimal maintainability score despite having only rather little knowledge with 237 points evaluated for a

problem with 54 dimensions (=18 components × 3 dimensions). All solutions on the Pareto front involve collisions and are violating the intersection volume constraint.

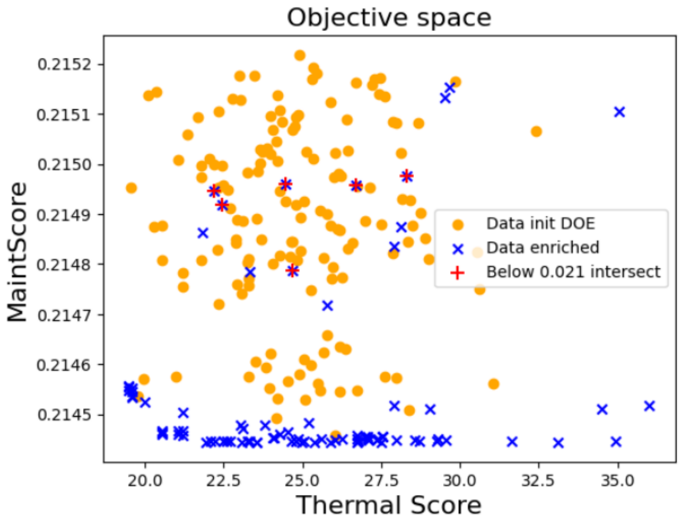


Fig. 55: Objective space obtained with the SEGOMOE surrogate optimizer

Addressing the collision problem usually leads to the need to solve a packaging problem. Since packaging problems belong to a class of problems that are relatively expensive to solve, it was preferred to consider resolving any collisions of invalid solutions in a post processing step. For this, the concept of sequential impulses is used which involves the following steps[11]:

- An intersection vector of two intersecting components or the compartment boundaries is calculated. The intersection vector can be obtained by calculating the intersection depth in the x-, y- and z-direction.
- Half of the intersection vector, but in opposing directions, are applied to the components as a displacement and the resulting component positions are updated. By this, the components are pulled apart and the collision is resolved.
- Since the compartment packaging is relatively high, it is likely that the resolution of one collision leads to a new collision with another component. To resolve also every newly occurring collision the sequential impulses are applied iteratively until there are no more collisions remaining.

An example compartment on which the collision resolution is applied can be seen in Fig. 56. After 15 iterations a majority of the collisions could been resolved and after 27 iterations there are no collisions remaining. The intersection volume equals zero in that case.

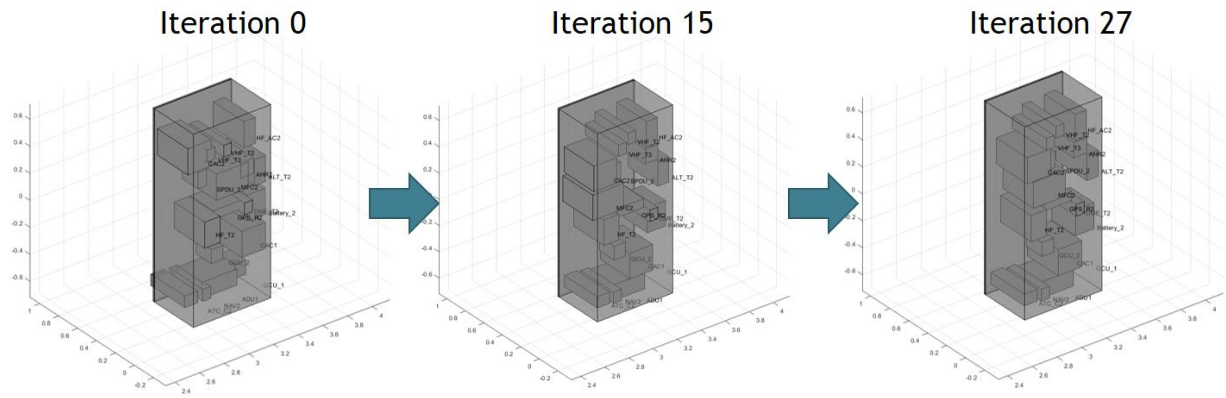


Fig. 56: Application of the collision resolution on a compartment

The collision resolution has been applied to 6 solutions from the Pareto front to evaluate if this method is suitable to both resolve the collisions and also not moving around the components too much in a way that the maintainability and thermal score are worsened. The result is shown in Fig. 57 in red ('PF solved'). After the collision resolution application, the candidate solution are no longer part of the Pareto front but are moved into an area of the objective space where the majority of the solutions previously calculated can be found. All collisions were successfully resolved.

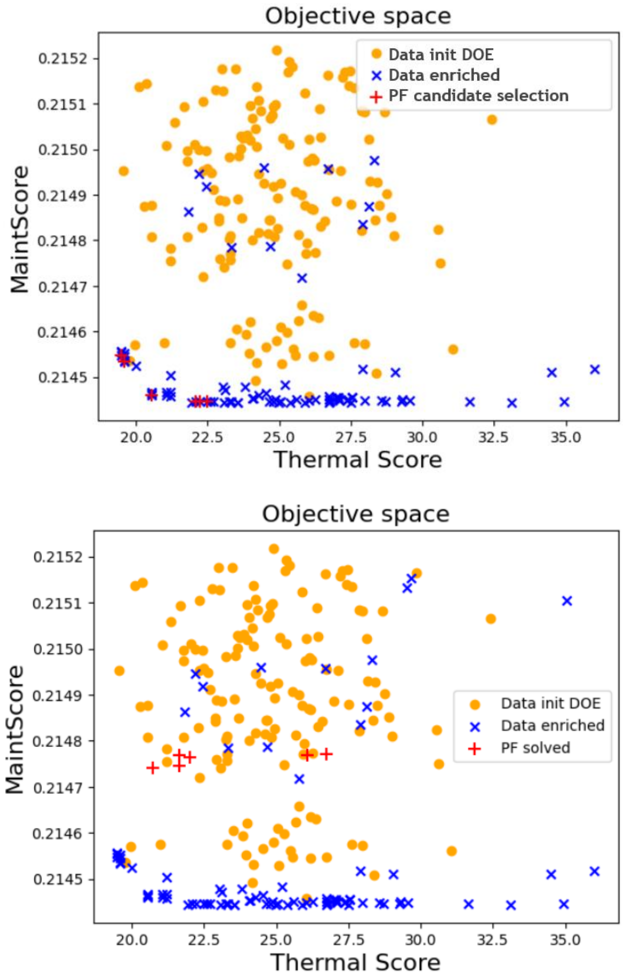


Fig. 57: SEGOMOE optimization results with selection of candidates from the Pareto front (top, red) for collision resolution and after the application of the collision resolution (bottom)

OPT2: Combinatorial Optimization / Genetic Algorithm

To reduce the size of the design space it was considered to only allow swapping components amongst each other. This effectively reduces the design space size to n! permutations where n is the number of components per compartment. Therefore, for the CONV starboard compartment the complexity of the optimization problem can be reduced from 54 continuous dimensions to one dimension with $18! = 6.4 \times 10^{15}$ discrete options. Since there is only one design variable left and the number of values are limited, each option can be unambiguously addressed as a 'permutation index' in the limits of [1 … 18!]. The allocation system of permutation indices to permutation is shown in Fig. 58 for a four-component system which involves 4! = 24 permutations. The respective permutation indices are shown at the bottom. When rearranging the components according to a permutation, the new permutation always refers to the canonical permutation [A B C D] or [1 2 3 4 … 17 18], respectively.

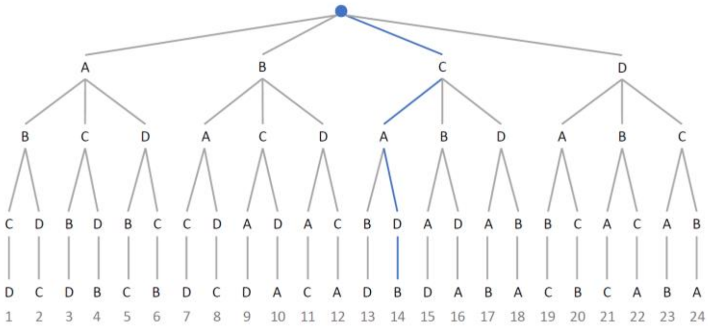


Fig. 58: Allocation of permutation indices to permutations

For testing purposes, a full enumeration of the design space was performed considering only PADME for the objective calculation '1-MaintainabilityScore' and a reduced number of 8 components. The result is shown in Fig. 59. The full enumeration shows that choosing a gradient based optimizer for this combinatorial problem is disadvantageous because the design space consists of several local minima. Instead, it was decided to exploit the tree-like structure of the design space. From the full enumeration it is clear e.g. that keeping the component #1 in their place is always disadvantageous because all possible permutations on the respective branch always result in worse maintainability than putting component #1 in the place of e.g. component #3 or component #4 (cf. Fig. 58). The best solution was found at the permutation index 11821 which corresponds to the permutation [3 4 5 6 7 1 8 2].

In terms of optimization algorithm there were tests performed with simulated annealing (Fig. 60) and branch-and-bound (Fig. 61).
Simulated annealing turned out to be better suited for continuous design spaces because it searches the proximity of the permutation index if a suitable solution is found. However, neighbouring permutation indices might not always lead to similar solutions. Therefore, the design space exploration is rather unstructured most of the time. The best permutation found, [3 4 6 5 7 1 8 2], which is only off by one component swap from the actual best solution identified by the full enumeration, was found by chance as the proximity of the solution was not searched. The solution corresponds to the permutation index 11940. During the design space exploration 1000 function evaluations were performed which covers 2.5% of the permutations of the design space of the eight-component compartment. During this testing procedures, PADME was executed locally, which allowed to perform about 50 function evaluations per second. Transferring this to the larger 18-component system, 2.5% × 18! means that 1.6×10^{14} values have to be evaluated to get the same design space coverage. With 50 function evaluations per seconds that would take up to 102,880 years. Because it's low suitability for the problem, simulated annealing was not considered further.

The Branch-and-Bound algorithm only evaluates a fixed number of candidates per branch and evaluates the results. Branches with the worst score are no longer evaluated in the next evaluation phase. Branch-and-bound turned out to need a similar amount of function evaluations. During the testing up to 10% of the samples per branch were evaluated to achieve a sufficient level of reliability and reproducibility in the results which corresponds to 504 function evaluations per main branch and about 4000 function evaluations in total before the first branch 'cut'. As for simulated annealing the number of necessary function evaluations were stated too high for the branch-and-bound algorithm to be of practical use.

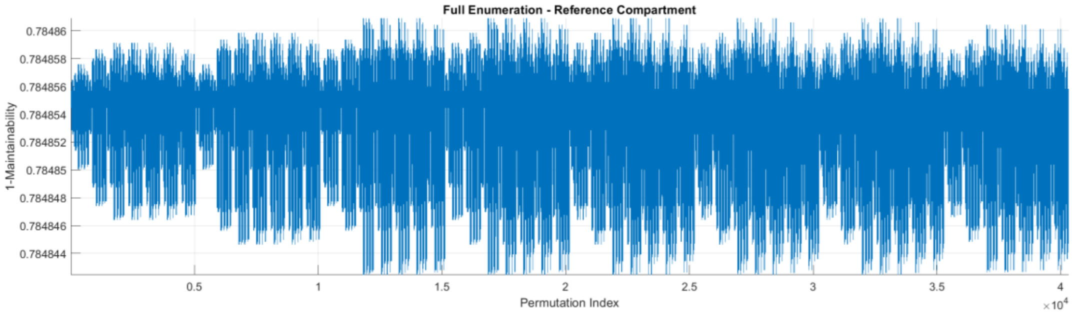


Fig. 59: AC4 - Full Enumeration of the design space

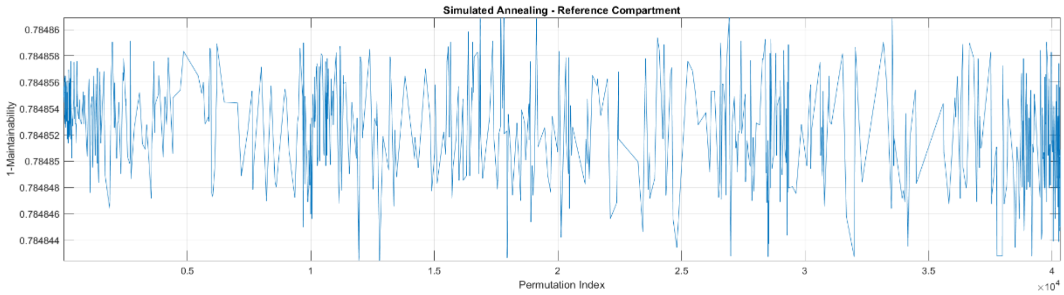


Fig. 60: AC4 - Design space exploration - Simulated Annealing

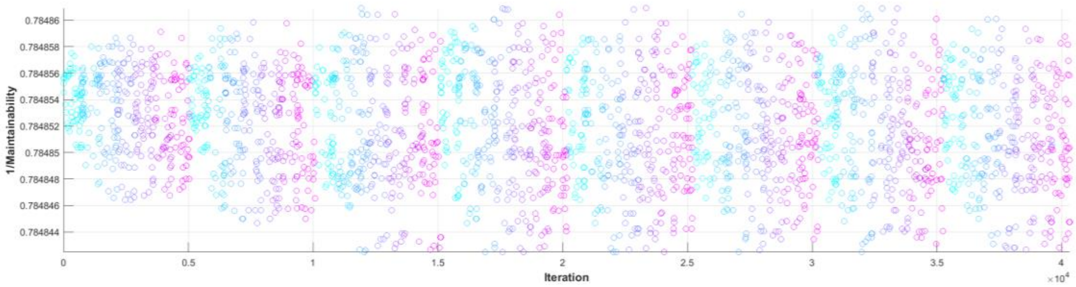


Fig. 61: Design space exploration – Branch-And-Bound algorithm

Most promising results with a combinatorial optimizer were obtained using a genetic algorithm. A permutation can be easily translated into a chromosome that characterizes the individual within a population of the genetic algorithm. The algorithm repeatedly modifies the population and its individuals. The best individuals are used as parents for a new generation. Eventually the population evolves towards an optimal solution. The genetic algorithm was tested using MATLABs *ga* function using a population size of 80 individuals (which corresponds to 80 function evaluations per generation). 200 generations were evaluated. On average the algorithm needed 2 to 3 generations to find the optimal solution which means that the optimum could be found after 160-240 function evaluations which is way faster than the other algorithms evaluated.

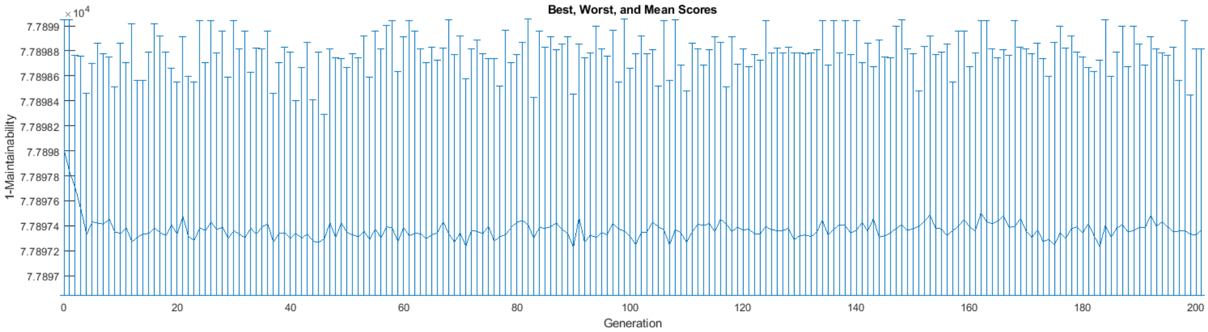


Fig. 62: Performance results of the genetic algorithm (min, max and mean score)

The corresponding multi-objective genetic algorithm was used in a workflow with reduced size that considers PADME for the maintainability evaluation and pySysTher for the thermal risk assessment as shown in Fig. 63. Evaluated was the starboard CONV compartment with the ventilation Case 1.2 (using two ventilation in-/outlets, mass flow rate of 0.025 kg/s, 20°C). Evaluated were 1000 points. To resolve collisions the sequential impulses concept was applied to every by the optimizer requested solution before being forwarded to PADME and pySysTher. The objective space is shown in Fig. 64. Regarding the intersection volume it can be seen that a majority of the collisions could be successfully resolved. Regarding the optimizer performance it can be seen that there is no Pareto front emerging which shows that the optimizer is not converging towards a solution. With regard to the genetic algorithm this means that there is no component-position-combination that is unambiguously superior to other solutions. This is likely due to the collision resolution that is moving the components around too much. The repeated placement of a component in a particular place leads to different results if the other components are placed in a different manner and if collisions are involved. By resolving the collisions also the first component is moved away from their initial position. As a consequence, the results obtained are not predictable by the optimizer and the genetic algorithm is not converging towards a solution.

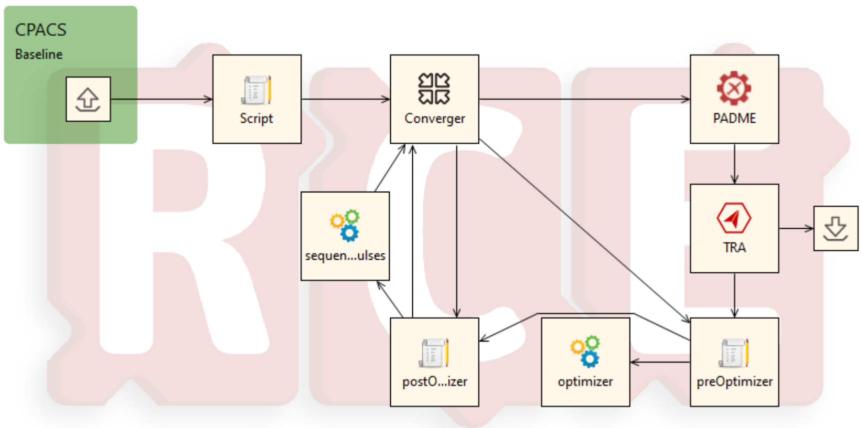


Fig. 63: Custom multi-objective combinatorial optimizer/genetic algorithm implemented in RCE with PADME and pySysTher

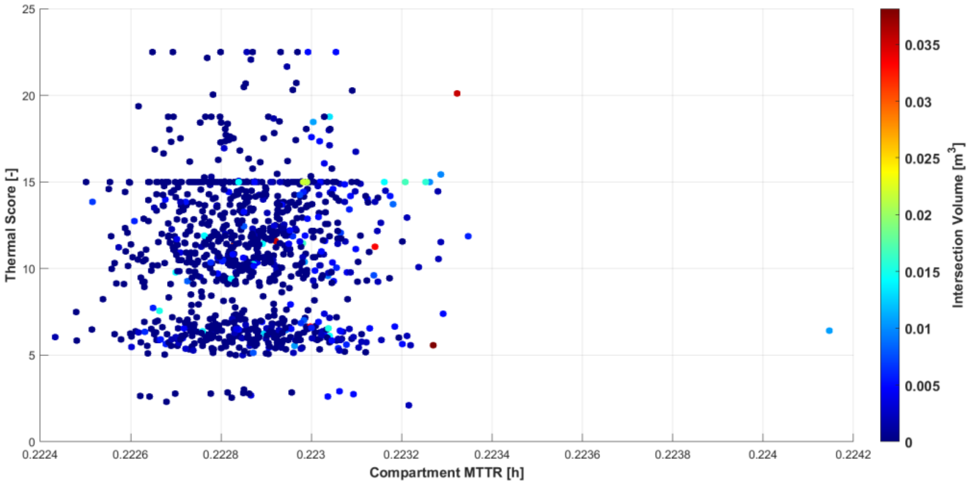


Fig. 64: Objective space from a 1000 point optimization using the genetic algorithm + sequential impulses

OPT3: Gradient Based Optimization by NLR

An alternative to the sequential impulses collision resolution approach was successfully tested by NLR using a gradient based optimization: The objective is based on a weighted sum of the displacement vectors of the components relative to their initial locations; this ensures that the component is not moved too far away from their initial position. The constraints are based on the collision of the components, leading to $\frac{n(n-1)}{2}$ inequality constraints, with n = number of components (153 for the 18 components). The method is explained in detail in[12].
During testing good results could be obtained after a few iterations. The computation time was less than one second. The original compartment with the component displacement is shown in Fig. 65.
Due to time constraints this collision resolution method could not be further incorporated into the workflow.

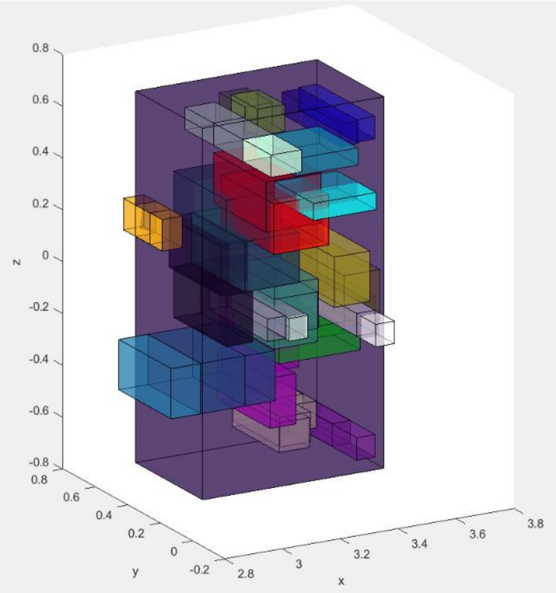


Fig. 65: Compartment with gradient based collision resolution applied

OPT4: SEGOMOE + Sequential Impulses + Input Modification

A forth optimization approach considered the SEGOMOE optimizer and sequential impulses. The previous optimization attempts showed that the optimization process is sensitive towards a subsequent alternation of the optimizer input in form of the collision resolution. To obtain better results from the surrogate optimization the following steps were implemented:

- As a database the 1000 points obtained from the combinatorial optimization are used since it consists of a very high number of valid solutions. The surrogate optimizer calculates a response surface from the database.
- During the optimization the optimizer requests a certain input in the form of x-, y- and z-coordinates for the components.
- The requested compartment is built and the collisions are resolved. The maintainability score and thermal score are evaluated.
- The inputs from the optimizer to the objective function are updated according to the collision free compartment from the previous step. The previously recorded input is replaces by the updated input.
- The new point is added to the database

The results obtained with this procedure are shown in Fig. 66. The ‘init DOE’ points correspond to the previously calculated solutions. The ‘enrichment points’ are all obtained with the described procedure. The score limits for ‘low’, ‘medium’ and ‘high’ thermal risk are marked at the bottom. All newly obtained points are located at both very small maintainability scores and thermal scores and can be considered Pareto efficient. Due to time constraints no additional points could be evaluated.

The solution with a low maintainability score of 0.2224 and a thermal score of 2.4 is shown in Fig. 67 and marked in Fig. 66. All components are located at the compartment bottom; the upper quarter of the compartment contains no components. In terms of maintainability a high score is reached because a majority of the components are located at chest or waist height which awards high ‘endurance & energy’ scores as a part of the overall maintainability score. Regarding the thermal risk it can be seen that the overall thermal risk allows a convenient margin until the overall thermal risk has to be considered ‘medium’. All component individual thermal risk scores are in the ‘low’ zone as well while the maximum achieved score here lies at 4.8. The thermal risk scores of the optimized compartment can be seen in Fig. 68.

The obtained solution is optimized in terms of maintainability and thermal performance but does not seem realistic from a system installation point of view. Future work will need to address the implementation of installation constraints.

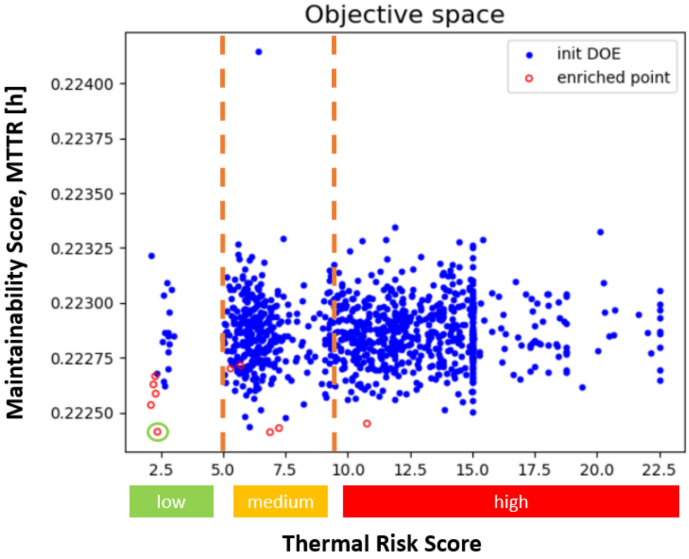


Fig. 66: Optimization results using the SEGOMEO optimizer, collision resolution and modification of the inputs from the optimizer. The selected solution is highlighted

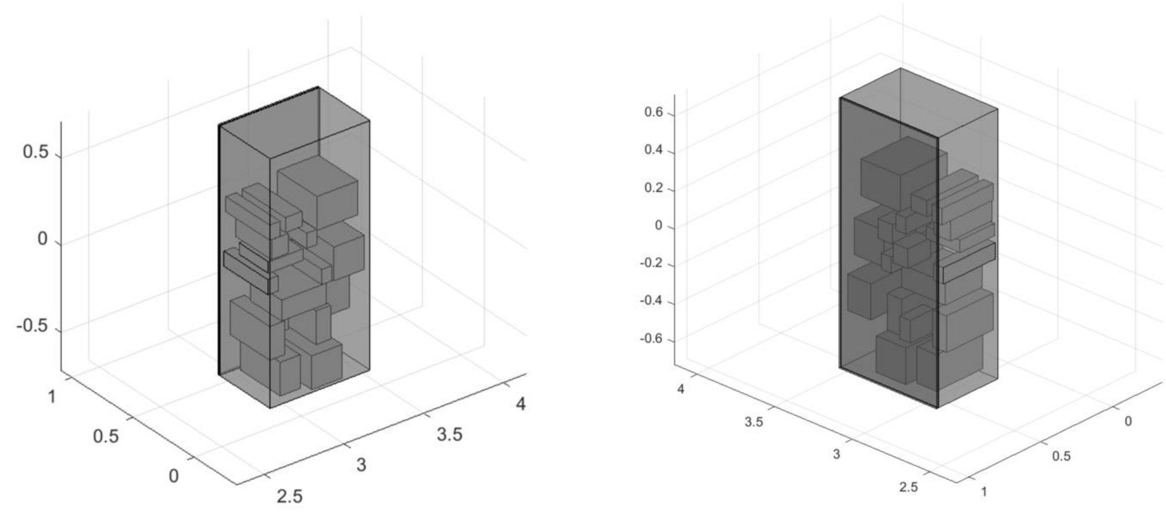


Fig. 67: Selected solution from the Pareto front

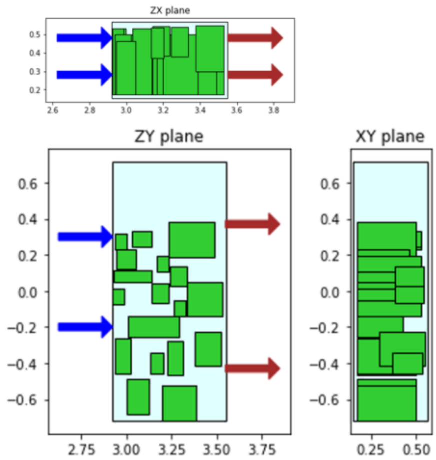


Fig. 68: Thermal risk scores of the optimized compartment

4 Application Case 5

For AC5 the trade-off concerns systems Electro-Magnetic Compatibility (EMC) qualification and the aircraft structural mass. The airframe material type and its width are changed giving different shielding capabilities to systems EMC. A surrogate model of detailed EMC analyses was built to optimize the airframe mass while meeting EMC requirements. Thermal risk analysis is also included in the design process as a final check on the obtained design solution, but not fully integrated in the MDA loop.
A new design optimization paradigm is developing adding the following disciplines:

- EMC calculation (surrogate model)
- Detailed airframe design
- Detailed systems design and positioning
- Thermal risk analysis

Fig. 69: Application Case 5

4.1 System Identification

Considering the main focus of AC5, the following stakeholders have been identified:

- **OEM** (Original Equipment Manufacturer): has to fulfill all the needs coming from the other stakeholders in order to make a market-competitive product. Therefore, all the needs associated to the OEM are connected to the increase of market share: certifiable for civil regulation; or the increase of competitiveness: cost reduction, time to market reduction.
- **Society**: They are also included in the stakeholder list since the vehicle is required to fly also in civil environment.
- **Certification authority:** Considering the aim of WP7, it is important to include the certification authority since specific aspects of the certification process are investigated, and one of the main goals here is to assess the impact of these additional constraints on the preliminary design.
- **Operator:** this is the main user of the product and therefore several needs are connected to this stakeholder.

The following table summarizes stakeholders and needs identified for the AC5.

Tab. 9: AC5 Stakeholders and their needs

Stakeholders	Needs	Aspect	ID
OEM	low certification cost	cost	N1
OEM	low certification time	cost	N2
OEM	aircraft compliant with military regulation	benefit	N3
OEM	aircraft compliant with civil regulation	benefit	N4
OEM	certifiable for severe weather condition	benefit	N5
OEM	have sufficient payload capacity	benefit	N6

OEM	low weight	benefit	N7
OEM	commonalities with other, already certified, platform	benefit	N8
OEM	comply with operator mission requirements	benefit	N23
operators	able to fly the transfer as well as the surveillance mission	benefit	N9
operators	easy to maneuver	benefit	N10
operators	be operable in severe atmospheric condition	benefit	N11
operators	have sufficient volume, mass, and power available for payload	benefit	N12
operators	autonomous flight capability	benefit	N13
operators	beyond line of sight operation	benefit	N14
operators	low acquisition cost	cost	N15
operators	low operating cost	cost	N16
operators	able to take off in high temperature condition	benefit	N17
operators	able to take off and land on short runway	benefit	N18
operators	be operable in civil (and military) environment (e.g. controlled airspace, navigation aids)	benefit	N24
certification authority	clear and simple certification procedure from the OEM	benefit	N19
society	low noise	benefit	N20
society	low emissions	benefit	N21

The SysML diagrams relative to stakeholders and needs have been generated exploited the capability of the OCE, see Fig. 70 and Fig. 71.

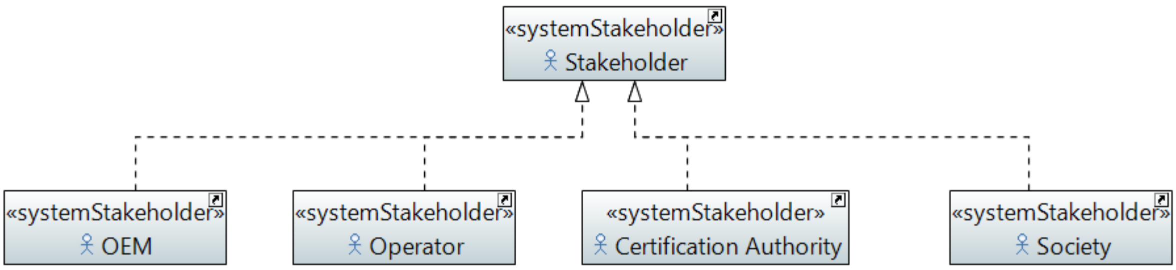


Fig. 70: AC5 Stakeholders Hierarchy view from Papyrus

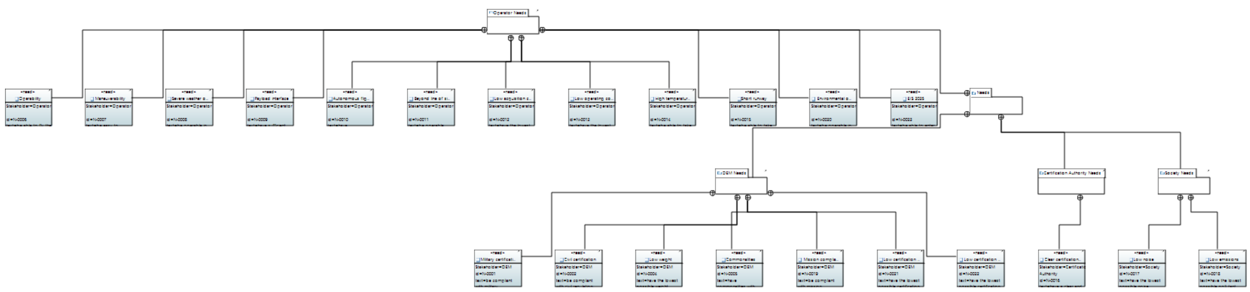


Fig. 71: AC5 needs view

4.1.1 AC5 System Scenario

The AC5 scenario represents the application by the OEM for a new Type Certificate (TC), or a change in an existing TC when the certification basis contains the CS 25.1316 (Protection against the indirect effects of lightning)[1]. The system considered in the scenario is the whole aircraft and the stakeholders involved are the OEM and the certification authority.

The Acceptable Means of Compliance AMC 20-136 is used to demonstrate compliance with the CS 25.1316, and it consists of the following activities:

1. The OEM identifies the sub-systems to be assessed
2. The OEM determines the lightning strikes zones for the aircraft
3. The OEM establishes the lightning environment for each zone
4. The OEM determines the Lightning Transient Environment (LTE) for each sub-systems
5. The OEM establishes the Equipment Transient Design Levels (ETDLs) and the aircraft Actual Transient Level (ATL)
6. The Certification Authority verify compliance with the safety margin defined in the CS
7. If the margin is:
    a. Acceptable: The Certification Authority grants the TC
    b. Not acceptable: The OEM take corrective measures changing either the equipment or the aircraft design, in both cases the process is re-started from activity 4).

the Sequence Diagram, Fig. 72, shows a simplified process that it is still representative of the industrial process and allows an easier inspection.

The AC5 scenario is used to validate the following needs:

1. Civil certification (by OEM): the aircraft shall be compliant with civil regulation
2. Severe weather operability (by Operator): the aircraft shall be operable in severe weather conditions
3. Payload interface (by Operator): the aircraft shall have sufficient volume and mass available for the payload, and shall provide the required power to the payload
4. Clear certification process (by Certification Authority): the aircraft shall have a clear and simple certification process

The scenario represents the process to obtain a Type Certificate that contains the CS 25.1316 and therefore (partially) validates the first one of the above needs. The second one is also validated by the scenario, since the specification: “Protection against the indirect effects of lightning”, is describing one of the most critical aspect for operation in severe weather condition. The payload interface in terms of provided electrical power is indeed analyzed by comparing the ATL and ETL as described in the scenario. Finally, the process described in the scenario strictly follows the AMC 20-136, which is defined by the certification authority itself (EASA in this case), and hence certainly compliant with clarity and conciseness requirements.

[1] CS 25 is for transport category aircraft, however, we use it as reference also for the UAV configuration of this application case, given the absence of a better reference for unmanned vehicle.

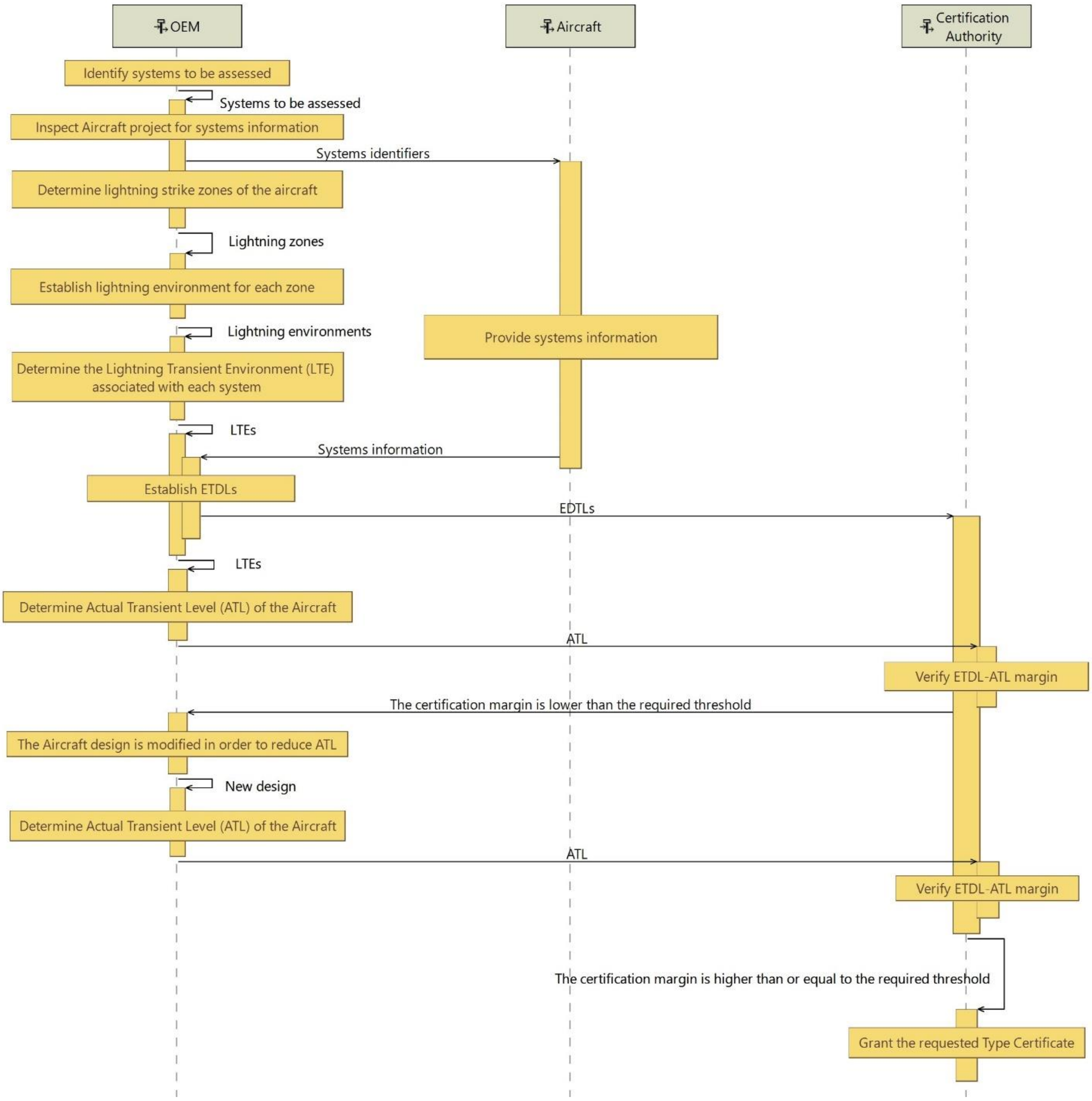


Fig. 72: AC5 Scenario Sequence Diagram

4.2 System Specifications

Starting from the stakeholders' needs listed in Tab. 9, a set of requirements have been derived and organized in a system level: the aircraft, and 2 subsystem levels: the on-board system and the airframe. In this deliverable no distinction has been made between different on-board systems.

Several system requirements come from the operator needs that define the UAV mission. Starting from these several other subsystem requirements are defined. In particular, according to the main focus of the WP 7 dedicated requirements for certification aspects are considered. For the airframe subsystem it is required to be compliant with the CS 25 subpart C and subpart D, whereas concerning the electromagnetic compatibility the vehicle is required to be compliant with Section 22 of DO160. Tab. 10 and Tab. 11 provide a collection of the AC5 requirements at aircraft level and On-board system level respectively.

Tab. 10: collection of AC5 aircraft level requirement

ID	Requirement statement	Type	Parent/Source	Stakeholders
R26	The aircraft shall be compliant with CS 25 Subpart C	Design	N4	regulation authority, OEM
R4	The aircraft shall be compliant with EASA civil regulation CS 23.1306 or CS25.1306 (Electrical and electronic system lightning protection)	Design	N4	regulation authority, OEM
R10	The aircraft shall carry at least 800 kg of payload while flying the survaillance mission	Performance	N9	operators
R11	The aircraft shall carry at least 800 kg of payload while flying the transfer mission	Performance	N9	operators
R12	The aircraft shall roll at a rate higher than 50 deg/sec in case of icing condition	Performance	N10	operators
R13	The aircraft shall sink at a rate of 10 ft/s	Performance	N10	operators
R14	The aircraft shall climb at a rate of 500 ft/min between 1 kft and 55 kft of altitude	Performance	N10	operators
R15	The aircraft shall be maneuverable in case of severe weather condition	Environmental	N11	operators
R16	The aircraft shall fly autonomously the survaillance mission	Function	N13	operators
R17	The aircraft shall fly autonomously the transfer mission	Function	N13	operators
R36	The aircraft shall take off in less than xxx ft at sea level ISA+xx condition	Performance	N17	operators

Tab. 11: collection of AC5 subsystem requirement concerning On-board system

ID	Requirement statement	Type	Parent/Source	Stakeholders
R9	All the on board systems should be commercially available off-the-shelf	Design	N8	OEM
R43	The on board systems shall be tested for conducted susceptibility to lightning induced voltages/currents at connector pins according to test method and to the general requirements of DO-160G Section 22 “Lightning Induced Transient Susceptibility”.	Performance	R4, R42	OEM

4.3 System Architecting

The architecture modelling for the AC5 started with the definition of the OptiMALE UAV system architecture which is the first system of interest for this application case, and then continued with the modeling of the Virtual Certification System (VCS).
Representing the detailed architecture of an entire UAV system or the entire virtual certification process is out of the scope of the current project and therefore we focused on the systems aspects that can be included in the design process given the available design competencies in the AC5 working group.

4.3.1 OptiMALE UAV System Functional Architecture

As preliminary activity before the logical architecture modeling in the OCE, we define the functional architecture for the OptiMALE UAV system. We considered 3 requirements for this activity:

1. The UAV shall fly
2. The UAV shall protect the payload (stakeholder: operator - need: provide a safe payload environment in all condition)
3. The UAV shall provide surveillance capabilities (stakeholder: operator – need: provide surveillance capability)

Tab. 12: AC5 Use Cases and Boundary Functions associated with the requirements: "The UAV shall fly".

Requirements	Use Cases	Boundary Functions	Components
The UAV shall fly	Fly in civil airspace	communicate with ATC and other air vehicles	VHF Radio
		be identifiable by ATC and other air vehicles	TCAS
		monitor vehicle surroundings	TCAS
	Fly with terrestrial navigation aids	determine position relative to ground station	VOR
		determine route to ground station	VOR
		determine distance from ground station	DME/ILS
		determine distance to ground	radar altimeter
	Fly with satellite navigation aids	determine latitude and longitude	GPS
		determine altitude	GPS
		determine time	GPS
	Fly without navigation aids	dead reckoning	INS
		correct drift rate	GPS
	Fly remotely controlled within line of sight	receives flight control commands within line of sight	LOS data link
		transform command signals	FCC
		transmit command signal internally	cables
		actuate control devices	actuator
		generate aero forces	control surfaces
		update status of control settings	FCC
	Fly remotely controlled beyond line of sight	receives flight control commands beyond line of sight	BLOS data link
		as above	
		transmit telemetries	BLOS data link
	Fly autonomously a predefined mission	store mission information	Mission computer
		as above	

Then we associated several use cases to each of the above requirements. Given the use cases, the boundary functions are derived and a component fulfilling this function is linked to them. Tab. 12, Tab. 13 and Tab. 14 represent the functional architecture for the OptiMALE UAV System.

Tab. 13: AC5 Use Cases and Boundary Functions associated with the requirements: "The UAV shall protect the payload".

Requirements	Use Cases	Boundary Functions	Components
The UAV shall protect the payload	Protect in all flight conditions	Withstand flight loads (manoeuvres, gust)	Airframe
		Be stable in all flight conditions	FCS
	Protect during landing	Withstand landing loads	Airframe + Landing Gears
		Be stable in all landing conditions	Airframe + Landing Gears
	Protect against external environment	Control payload environment	ECS
		Protect payload against lightning strikes	Skin

Tab. 14: AC5 Use Cases and Boundary Functions associated with the requirements: "The UAV shall provide surveillance capabilities".

Requirements	Use Cases	Boundary Functions	Components
The UAV shall provide surveillance capabilities	Monitor ground in daylight	Collect optic images	EO/IR
		Transmit images in real time	wide band data link
	Monitor ground at night	Collect radar images	SAR
		Transmit images in real time	wide band data link

The functional architecture definition has been carried out mainly using excel sheet since the OCE organization of the requirements, use cases and boundary functions in different tables (and sometimes in different tabs) was hampering the activity which is inevitably an iterative one.

4.3.2 OptiMALE UAV System Logical/Physical Architecture

Starting from the boundary functions defined in the functional architecture, we defined the components and the associated induced functions which constitute the logical and physical architecture of the OptiMALE UAV System.

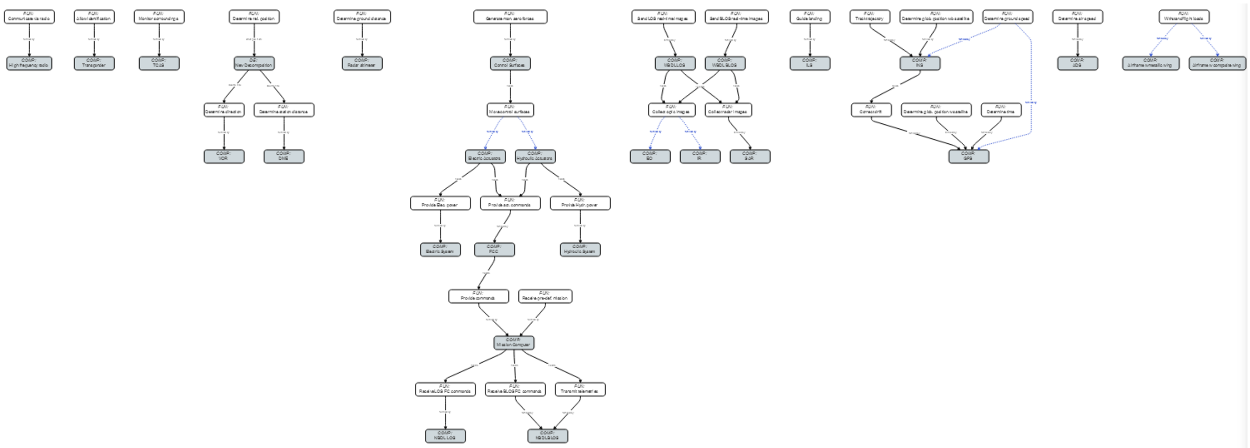


Fig. 73: AC5 Architecture model of the OptiMALE UAV System

All the main avionics items are represented in the architecture model as showed in Fig. 73. The architecture shows only few architectural choices. Several of the choices concern the possibility to use different avionics items to fulfill the same boundary functions. For example, the ground speed can be obtained with the Inertial Navigation System (INS) and also by the GPS, as shown by Fig. 74. Both the items fulfill also several other functions and therefore they will be both included in the physical architecture and, additionally, there are redundancy requirements which force the presence of duplicate component fulfilling the same function (currently it is not possible to represent redundant architecture in the OCE). The other architectural choice concerns the skin material which could be metallic (i.e. aluminum) or composite.

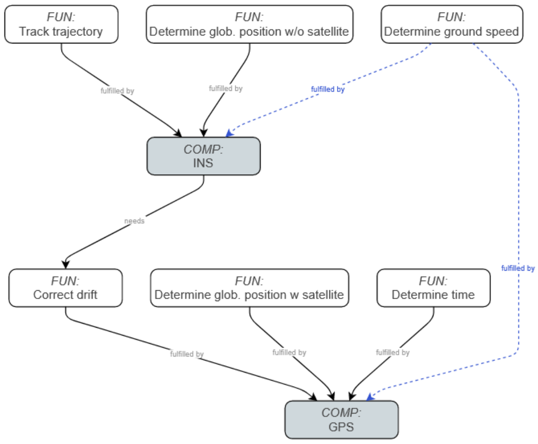


Fig. 74: AC5 Architecture model of the OptiMALE UAV System: zoom on INS and GPS components

4.3.3 OptiMALE Virtual Certification System Logical/Physical Architecture

In the AC5 Virtual Certification System (VCS) the functions represent the different certification aspects (which are all linked to a CS25 paragraph) included in the UAV design process, and the component fulfilling the certification functions are the digital tools, software, simulations or operations integrated in the design workflow.
Similarly to the architecture of the 1st system of interest, also here the architecture scope is limited to the disciplines which are available in the AC5 working group, namely:

- Aero-structural analysis and design
- Lightning Indirect Effects analysis
- On-Board Systems analysis and design
- Thermal Risk analysis

Fig. 75 represents the obtained architecture of the OptiMALE Virtual Certification System. Three main branches can be identified, stemming from the following functions:

- Certify Structure: which include the main paragraph of the subpart C of the CS25
- Certify OBS against Thermal Risk: connected to the CS25.1431
- Certify OBS for Electro-Magnetic Compatibility (EMC): although there are many EMC aspects that must be included in a certification system, here we included only the Lightning Indirect Effects (LIE) protection (CS25.1316) since this is the competence available in the AC5 working group

The architecture model highlights the connections among the different certification aspects. Both the thermal risk assessment and the LIE assessment depends on the OBS design specifications and on the OBS layout. For the LIE assessment, the qualification level of all the equipment items need to be defined in order to obtain the Equipment Transient Design Levels (ETDL), whereas the Actual Transient Level (ATL) depends on the OBS layout. The thermal risk levels of the OBS can be computed only given the operational temperature ranges and the position of each items in the compartment.
The OBS layout definition affects three different certification aspects. The LIE simulations need the OBS items position and the relative cable network as input. The position of the OBS in the compartment is also necessary for the environmental thermal analysis. Finally, the structural analysis uses the OBS position and connection to the structural elements to introduce the concentrated inertia loads due to the OBS masses.
Another component linking two different certification aspects is the structural design, since this is a necessary operation before the structural and the lightning indirect effect analysis.

4.4 System Design

Last step of the development process is the system design which is carried out starting from the architecture defined in Section 4.3, and fulfilling requirement defined in Section 4.2.
As explained, in the following Subsections the design space is mainly limited by the computational resources available for the Lightening Indirect Effects (LIE) simulations done by LEONARDO. However, excluding LIE, the workflow is capable of dealing with an extended design space, including geometrical modification, when defined according to the CPACS parametrization.

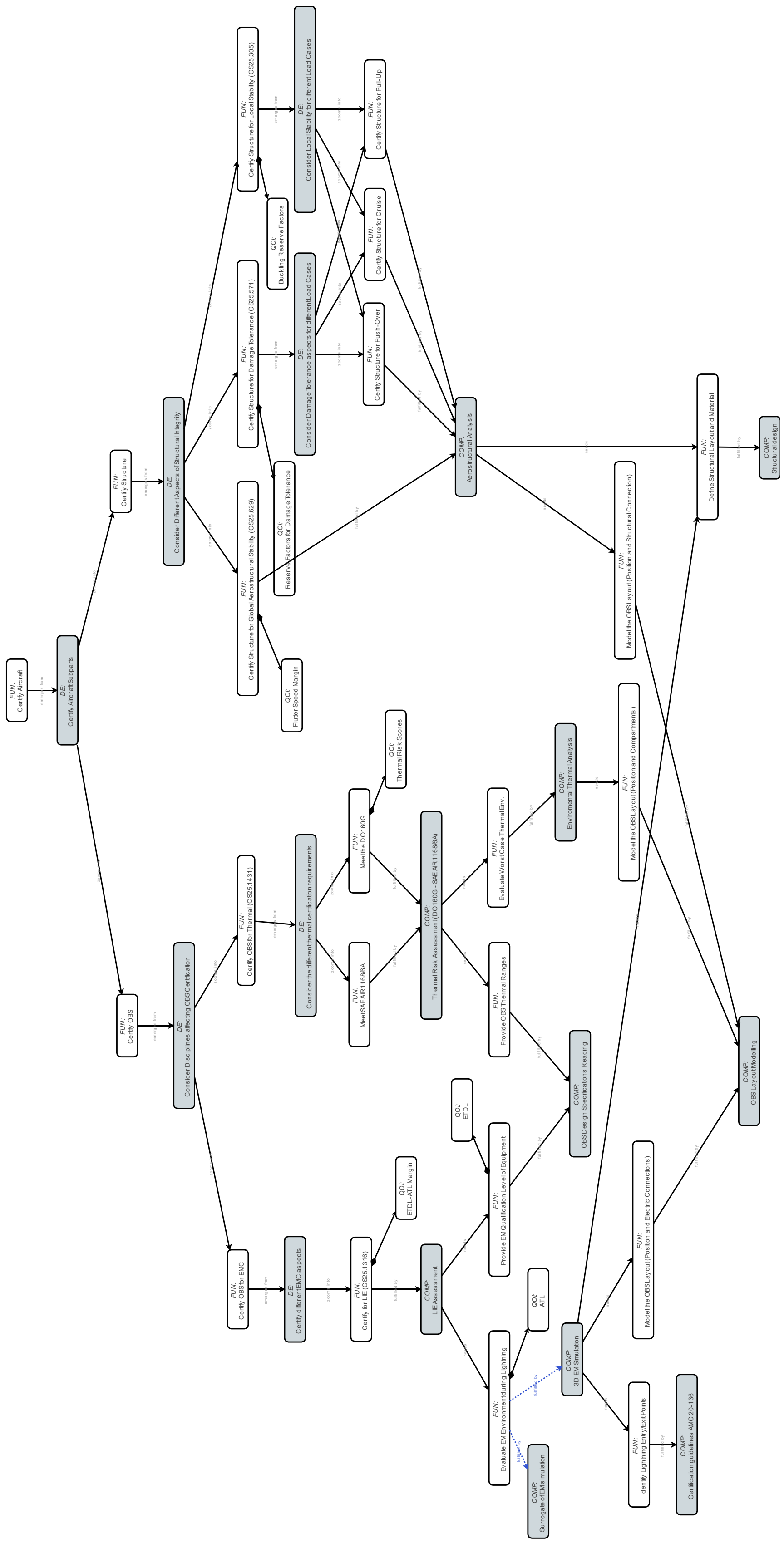


Fig. 75: AC5 Architecture model of the OptiMALE Virtual Certification System

Two different materials have been considered for the wing upper and lower skin: aluminum 7075, or 8-layers symmetrical CFRP. However, between aluminum and the CFRP configurations there is also a difference in terms of electric cable routing. LEONARDO did the computation of the aluminum configuration first, at that point LEONARDO realized that a cable routing modification was necessary for the CFRP case (which more prone to be LIE critical than any metallic configuration). Due to the computational resource limitations, it was not possible to perform the LIE analyses for the aluminum configuration with the same cable routing modification implemented in the CFRP configuration. Therefore, a comparison between the aluminum and CFRP configurations is not possible; in the following subsections only the results relative to the CFRP configuration are presented.

4.4.1 Disciplinary Capabilities

Following the application case owner guidelines, the main objective of the design activity is to design both the airframe and the on-board systems without changing the external vehicle geometry and according to the requirements presented in previous sections. In the AGILE 4.0 framework, the design process is also model-based: the product (the unmanned vehicle), as well as the design workflow itself, have both an associated model which allows the automatic definition and reconfiguration of the design process in case of changes in the tools' repository or in the design requirements.
All the tools integrated into the design workflow use CPACS as the common language for interdisciplinary communications, which results in increased consistency and reliability of the design process and a reduction of connections among the different modules. The following disciplinary modules are available in the AGILE 4.0 for the design of the OptiMALE configuration. The interested reader can find more information about the specific tool in the reference paper [13].

Descartes (Airbus DS) is a parametric aircraft geometry tool developed in-house at Airbus Defence and Space. It is based on the open-source tools/libraries CPACS, TiGLViewer, TiGL and Tixi (developed by the DLR). Using a CPACS aircraft definition Descartes allows generation and visualization of the aircraft's geometry as well as interaction and modification of this geometry through the parametric basis defined in CPACS. Descartes also supports analysis model generation (e.g. structural FEM, aerodynamic vortex lattice etc.) based on this geometry and the CPACS configuration. For the analysis model generation, Descartes uses the additional metadata stored in the CPACS configuration (e.g. component hierarchy, materials, structural dimensions etc.) to enrich the automatically generated analysis model after the meshing process. This way, it enables highly automated analysis model generation with minimal manual interaction required which is employed in this workflow.

Lagrange (Airbus DS) is an in-house MDO structural sizing tool including a FEM solver and a selection of gradient-based optimization algorithms developed at Airbus Defence and Space. Lagrange supports structural shape, sizing and fiber angle optimization based on static, aeroelastic, modal and transient analysis loads. Based on these analyses, Lagrange can consider a large number of constraints taking into account strength, stability, damage tolerance, manufacturing, aeroelastic and dynamic requirements during an optimization. In this workflow, Lagrange is used twice: first for the structural analysis in order to obtain the displacements for the different load cases; additionally, for the structural sizing optimizing the thickness distribution of the complete configuration.

CESIOMpy (CFSE) can perform aerodynamics calculations with two levels of fidelity: low and medium. Low fidelity calculations can be performed by the vortex lattice method (VLM) code PyTornado. The medium level of fidelity is used here to compute the rigid polars. In this level, the calculations are performed with the Stanford open-source CFD code SU2, using Euler equation, which is a special case of Navier-Stokes equation, without viscosity and thermal conductivity. To use this solver, other tools are used to create automatically a mesh from a CPACS file geometry. With both medium- and low-fidelity methods, skin friction is added afterwards, it is calculated from an empirical method based on Reynolds number and wetted area, it allows to consider viscous drag, which is neglected by VLM and Euler equations.

MUST (DLR) is a 3D panel method library for steady and unsteady frequency domain aerodynamic analysis developed by DLR. It consists of two sub-modules that can also be used as standalone. In the first sub-module the 3D panel model is generated starting from the outer mold line definition in CPACS, and it consists of flat quadrilateral panels with a straight fixed wake detaching from the trailing edge of the lifting bodies. The second sub-module assembles the aerodynamic influence coefficients matrix considering a constant distribution of aerodynamic potential over the panels. The matrix is provided for different values of the Mach number and different values of reduced frequency in case of unsteady analysis. The theoretical foundation is the boundary element method proposed by Morino that solves the aerodynamic small perturbation equation for generic 3D lifting or non-lifting surfaces. The compressibility effects are included by means of the Prandtl-Glauert theory.

FAEDO (DLR) is a framework for steady and steady aeroelastic stability analysis developed by DLR and, in the OptiMALE design workflow, it is used to compute the aerodynamic loads. Two approaches are available within FAEDO: a linear direct method and a non-linear iterative one. Here, the first one is used since the aerodynamic term is provided by the linear aerodynamic method implemented in MUST. In the linear approach, given the structural stiffness matrix (from Lagrange) and the aerodynamic influence coefficient matrix (from MUST), FAEDO solves the aeroelastic linear systems, including the flight mechanics longitudinal stability conditions for different values of altitudes, speed and mass layouts. The mapping between the aerodynamic and the structural grid is obtained with the implementation of the infinite plate splining (IPS).

ASTRID (POLITO): the OBS design process is carried out with ASTRID tool developed by Politecnico di Torino. The OBS module uses both physics-based and semi-empirical algorithms to calculate the OBS masses, the power required by each OBS and the volume of each main equipment. The OBS masses are defined at subsystem (e.g. electric, hydraulic, flight control systems etc.) and at the main equipment level (e.g. electric generator, hydraulic pump, actuator etc.). The data required to run the module are at aircraft and OBS level. At the aircraft level, ASTRID requires the main aircraft masses, dimensions (e.g. wing and fuselage geometries) and the aircraft mission profile in terms of altitude, speed and duration of each mission phase. At the OBS level, the systems technology (e.g. conventional, more-electric, all-electric) should be selected as well as the voltage and hydraulic pressure level. The module is able to assess the main OBS users such as Flight Control System (FCS), landing gear actuation and structure, avionics, Ice Protection System (IPS), Environmental Control System (ECS) and fuel system. After assessing the power required by the users for each phase of the mission profile, ASTRID is able to design the power generation and distribution systems such as electric, hydraulic and pneumatic systems. Then, the volume and main dimensions are estimated for each main equipment starting from their mass and power. Another module of ASTRID is capable of providing a simplified installation layout using the aircraft geometry and systems compartments definition.

PySysTher (CONCORDIA) is a tool that allows the thermal risk prediction of on-board systems and components. The thermal risk is defined as the potential of non-compliance with thermal requirements (e.g., exceeding the maximum allowable bay temperature).
The tool pySysTher uses a thermal risk assessment approach that consists of two levels of analysis. The first level is the aircraft zone level, including ventilation and temperature stratification predictions of the zone under study. The second part of the approach covers three system-level aspects: The mainstream flow analysis to predict the closeness of a system with regards to the considered ventilation source, the system integration analysis that focuses on the system locations in the bay, the assessment of the thermal interactions between a system and the zone, and the other systems, and the system-level aspects related to the system requirements, derived from standards such as RTCA DO-160G or SAE AIR1168/6A.
Finally, the tool uses a penalty-point approach to convert all these analyses into a thermal risk score for each studied system. It consists of associating points to every output of the analyses by giving fewer points to the ones related to favorable configurations (low thermal risk) and more points to the ones related to non-favorable configurations (high thermal risk). A thermal risk score is computed for each component and for the bay as a whole. In case ventilation is needed, as mass estimate for the additional cooling and ventilation equipment is added to the OBS systems mass.

LIO-OBS (LEONARDO) using the Dassault Systems CST Studio Suite commercial tool the capabilities of a 3D and 2D Electro-Magnetic analyses were combined. The simulation campaign was carried out by using a finite difference time domain (FDTD) solver; the platform was discretized by using an hexaedrical mesh (about 80 million cells), and finally, the effect of the strike on the structure was obtained by the Transmission Line Matrix (TLM) method. According to the procedure defined by the scenario in Subsection 4.1.1, for each avionic sub-system the actual transient level (ATL) is computed in terms of total bundle current and maximum pin current. The simulation campaign was executed by injecting the lightning waveform (double-exponential with 200kA amplitude and 100μs as defined in EUROCAE ED-105) on three different lightning entry/exit points; following the worst-case condition is chosen for each sub-system.
The equipment transient design levels (ETDL) are defined considering two testing methodologies: bundle injection and pin injection, and following the relative categories presented in the DO-160G, which is the international standard for avionics environmental test conditions and applicable test procedures. The ETDL

depends on the qualification levels of the considered equipment: the higher the qualification level, the higher the ETDL.

The CS 25.1316 prescribed a margin of 6dB between ETDL and ATL. If the between ETDL and ATL is below the required margin, the designer needs to either choose a higher qualification level for the critical equipment (if available) or given the original qualification level re-design the aircraft in order to lower the ATL. Considering that the use of a copper mesh (or similar) is already prescribed to mitigate the direct effects of lightning (e.g. burning, dielectric breakdown) on CFRP structures, it was considered to use a commercial copper mesh layer on top of the composite skin fuselage panels in order to decrease the ATL of the critical avionics' components.

4.4.2 Workflow formulation

Once all the CPACS tool's interfaces are defined, the AGILE 4.0 framework offers the capability to automatically establish the connections among the disciplines and then directly export the workflow in the designated PIDO environment. This capability reduces the integrator's burden to establish the connections manually and allows the easy reconfiguration of the workflow according to a specific strategy (e.g. minimizing the feedback connections) or necessary to include new tools in the design chain. The XDSM graph in Fig. 76 represents the collaborative multidisciplinary workflow deployed for the design of the OptiMALE configuration.

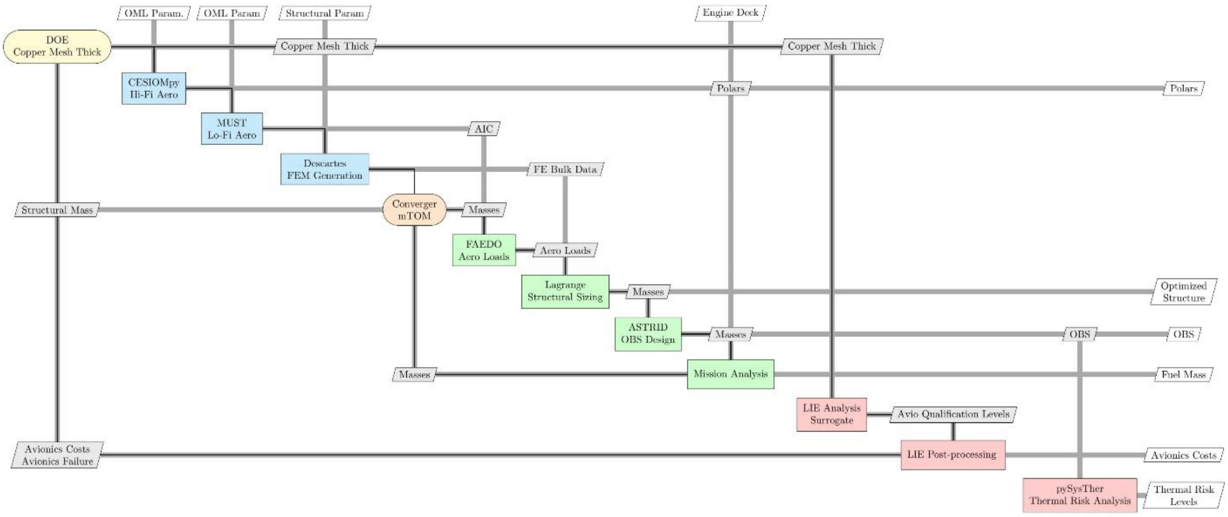


Fig. 76: OptiMALE design workflow

As shown in Fig. 76, the workflow can be divided into three blocks: the pre-coupling, the coupling and the post-coupling block. The pre-coupling blocks mainly consist of model generation operations, in particular the structural and the aerodynamic model are here generated starting from the CPACS definition. In addition, the high-fidelity aerodynamic performance analysis is also outside the coupling block since the outer mold line is kept fix and we are not currently considering flexibility for the aero-performances computations. The coupled disciplines are aerodynamic load analysis, structural sizing, on-board system design and mission analysis, which are all either updating or using some items of the mass breakdown. The thermal risk analysis is performed after the mass iteration is converged, and therefore the characteristics of the on-board system are consistently defined. LIE analysis and post-processing do share the same input variable, the copper mesh thickness, with the rest of the workflow, but except for that they constitute a separated branch of the workflow.

4.4.3 Workflow execution

The design workflow is first executed with a DOE driver, populating the database with different values of copper mesh thickness. Then, a surrogate of the whole workflow is built on the DOE results and the optimization is performed on the surrogate.

Pre- and Post-coupling disciplines are executed as standalone hosted by the respective partners, since the DOE setup allows for decoupled execution of the different disciplines. The only part of the workflow integrated in RCE and execute collaboratively using BRICS is the converging MDA loop, involving aero-structural sizing hosted by DLR, OBS design hosted by POLITO and Mission analysis hosted again by DLR. The master workflow, represented by Fig. 77, is also hosted by DLR.

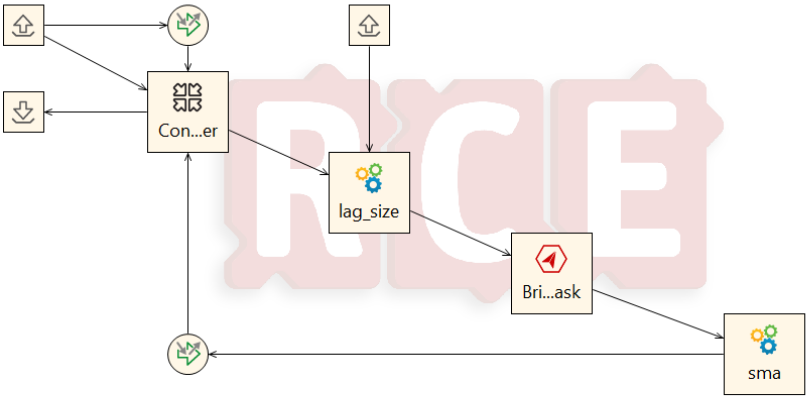


Fig. 77: AC5 master workflow in RCE. The Brics component calls the OBS design competence hosted at POLITO

4.4.4 Optimization and Surrogates

The computational time for a single LIE simulation resulted to be 90h, therefore the use of a surrogate for the integration of the disciplines was the only viable solution. As explained in the previous paragraph, another surrogate is built for the entire workflow, which is then used to actually run the optimization.
The high-level optimization problem is defined in the following table, Tab. 15.

Tab. 15: Optimization problem definition for AC5

Design Variable	Copper Mesh Thickness [mm]
Design Objective	Airframe Structural Mass [kg]
	Avionics' Relative Cost [-]
Design Constraint	Avionics LIE Failure [-]

The structural sizing is a nested optimization loop within the overall workflow, which has the thickness of all the primary structures as design variables, the structural mass as objective, buckling and stress reserve factor as constraint.

4.4.5 DOE Results

Results of the DOE for the main disciplines involved in the design workflow are presented in the following paragraph.

4.4.5.1 Structural Sizing Results

Structural Sizing results consist of optimal thickness distribution in the wing primary structure for each value of the copper mesh thickness. Only four static load cases are considered for the structural sizing procedure: the pull-up manoeuvre with 2.5 load factor, the pull-down manoeuvre with -1.5 load factor and the two maximum aileron deflections (an angle of ±25° is used). After the loads are computed with FAEDO, the wing-box structure is optimized by Lagrange using the wing mass as the objective function, stress constraints for all the structural elements and buckling constraints for spars, upper and lower wing-box skin. For the CFRP configuration, the internal wing structure (spars, ribs, spar caps, stringers) is aluminium and the skin is the only composite structural element. A symmetrical 8-layers stacking sequence is used for all composite structural elements with the following orientation: [45°, -45°, 90°, 0°].

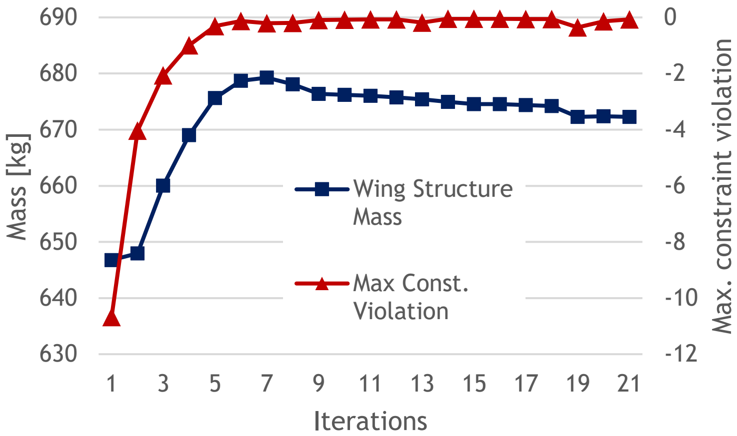


Fig. 78: Objective and maximum constraint violation for structural optimization with null copper mesh thickness

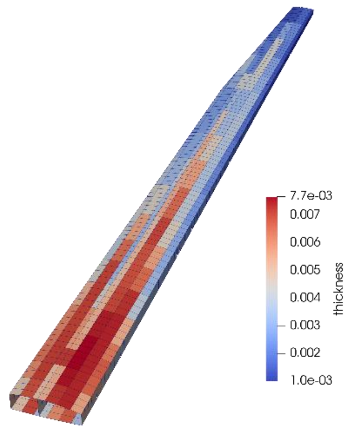


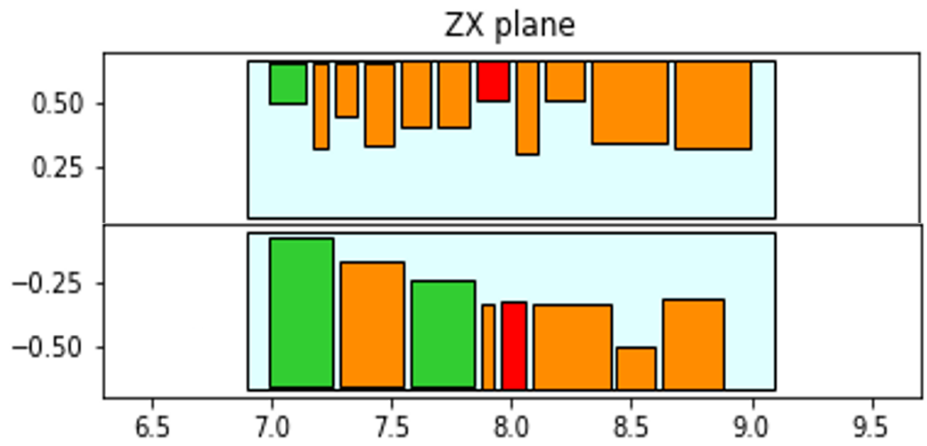
Fig. 79: Optimized wing-box for null copper mesh thickness

As shown in Fig. 78: Objective and maximum constraint violation for structural optimization with null copper mesh thickness, the initial thickness values are not compliant with the structural integrity requirements (a Lagrange negative constraint values represents a non-feasible solution), and therefore the optimized and feasible solution has an increased mass with respect to the initial one. The final optimized wing structural mass is 672 kg, which accounts for 32% of the total airframe mass.

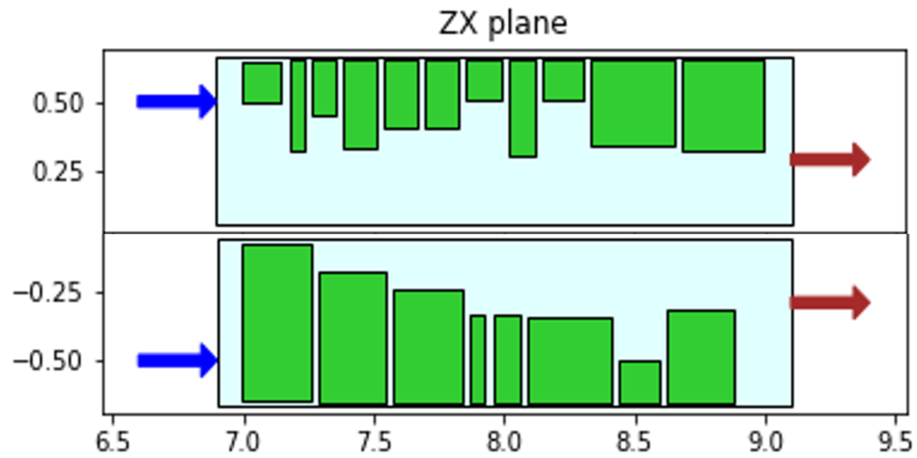
4.4.5.2 Thermal Risk Analysis Results

The thermal risk of the OBS depends on the cooling architecture defined for the avionics and electric compartments. The vapor-cycle machine of the ECS can deliver enough ventilation flow rate to cool down the OBS located in the avionics compartment. The authors estimated the required mass flow rate to extract the heat loads dissipated by the avionics while keeping the avionics environment below 60 degrees Celsius. Since the locations of the ventilation sources depend on the airframe definition and the OBS layout, the authors used the pySyTher tool to evaluate the influence of the location of the ventilation sources on the avionics thermal risk. Therefore, the preliminary thermal risk analyses enabled finding the optimal location of the inlet and outlet flow sources to minimize OBS thermal risks. The thermal risk analysis shows that the ventilation flow rate associated with the considered ventilation configuration provides a safe thermal environment for the studied OBS layout in the avionics compartment, Fig. 80.

For the defined design space (see sub-section 4.4.4), the copper mesh thickness does not affect the thermal risk analysis. This is expected since avionics mainly depends on functional requirements and less on overall aircraft parameters, like maximum take-off mass. The variation of the maximum take-off mass associated with the maximum copper mesh thickness is around 1%. Therefore, avionics parameters, like the heat load used in the thermal risk analysis, are constant for all the DOE points.



a. No Ventilation



b. Optimized Ventilation

Fig. 80: Initial (a.) and optimized (b.) thermal risk score of the avionics bay

4.4.5.3 Lightning Indirect Effects Analysis and Post-Processing

Following the process described in the scenario, subsection 4.1.1, the qualification level for each avionics item and for the different values of the copper mesh thickness is obtained, Fig. 81. For null copper mesh thickness there are several items that fail the test prescribed by the certification specification on lightening indirect effects. Only for a copper mesh thickness of 0.1 mm, all the avionics items pass the certification test. In a post-processing procedure, the qualification level is then correlated to the avionics cost: the higher the qualification level, the higher the cost of the item. In order to not disclose sensitive data of industrial partners, in AC5 design study the avionics relative cost is used instead of the real absolute value. However, the procedure is fully parametrized and ready to deal with real data once shared by the industry partners.

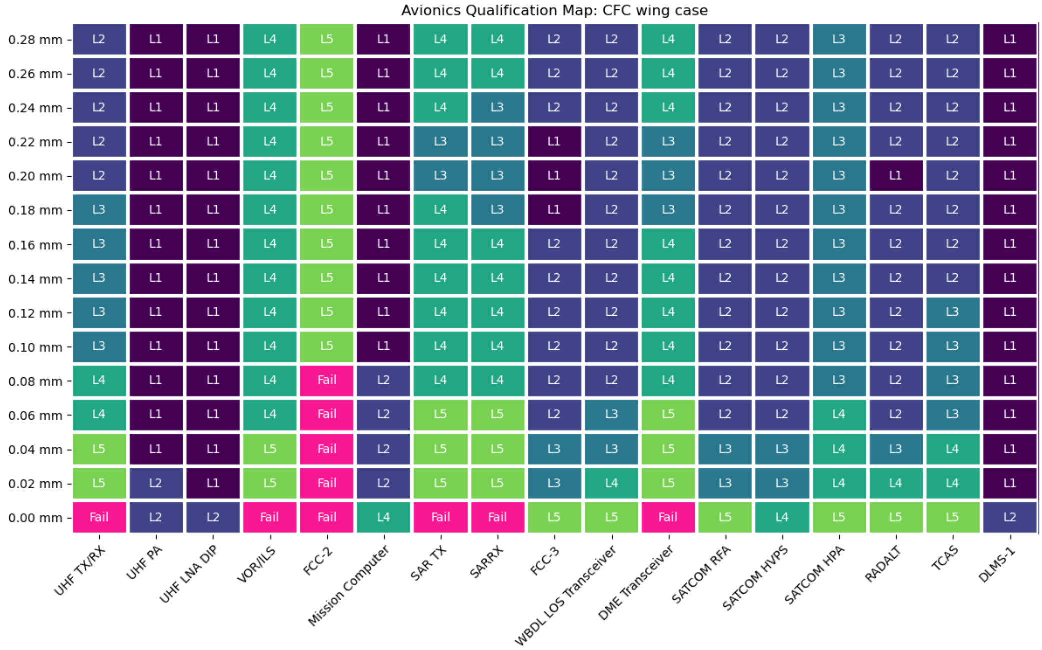


Fig. 81: AC5 avionics qualification level heatmap

4.4.6 Trade-off

Given the DOE results, a trade-off is sought between the wing structural mass and the avionics relative cost due to LIE qualification level. This is done by means of a multi-objective optimization.

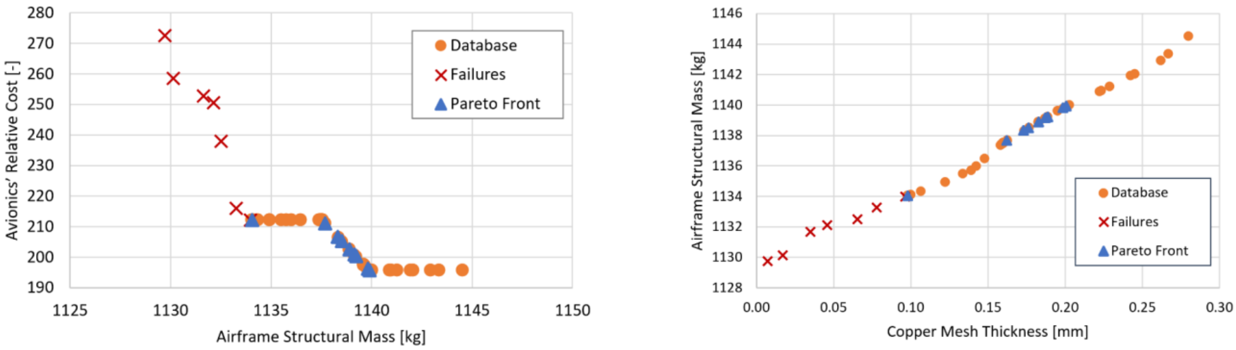


Fig. 82: AC5 Pareto Front between Avionics Cost and Wing Structural Mass with Copper Mesh Thickness

The pareto front is split in two zones due to the step-like trend of the objective functions. Points belonging to the first zone are the one with the lowest value of wing structural mass and lowest value of copper mesh thickness. The points of the second zone have higher wing mass but lowest avionics cost.
The minimum wing mass point is close to the unfeasible zone, which means it is associated with the minimum value of copper mesh thickness necessary to pass the LIE certification requirement. When looking for the minimum cost point, it is observed that there is no need to go for the heaviest structure and the highest value of the copper mesh thickness, since all the point with a copper mesh thickness greater than 0.22 mm have the same cost, but higher structural weight.

4.4.6.1 Design Scenarios

The post-processing of LIE analysis results is fully parametrized, allowing for investigation of the impact of different avionics reference cost. As said in the previous sections, the avionics relative cost is computed starting from a reference cost which is different for the different avionics' items. Then the cost is increased or decreased proportionally depending on the required qualification level and a qualification level factor. We defined 3 different design scenarios varying the reference cost of some items and also varying the qualification factors of same of the items:

- Design Scenario 0: here the baseline values of the avionics reference costs and a uniform qualification level for all the items are used. From L3 to L4 the factor is 1.2, from L3 to L5 the factor is 1.6
- Design Scenario 1: the Flight Control Computer (FCC) becomes more expensive
- Design Scenario 2: the Synthetic Aperture Radar (SAR) becomes more expensive and the FCC less expensive

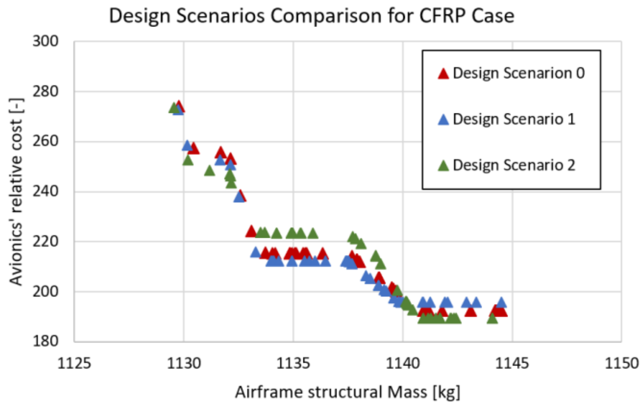


Fig. 83: Comparison of the 3 Design Scenarios for AC5.

The same multi-objective optimization described in the previous section is carried out here for the 3 different scenarios. As can be observed in Fig. 84, the design scenario affects the minimum cost point. In particular, the increase of FCC cost in Design Scenario 1 (DS1) increase the value of the minimum avionics cost, whereas in Design Scenario 2 (DS2) the minimum cost is lower than the one in the initial Design Scenario (DS0) even if is obtained for the same value of the copper mesh thickness.

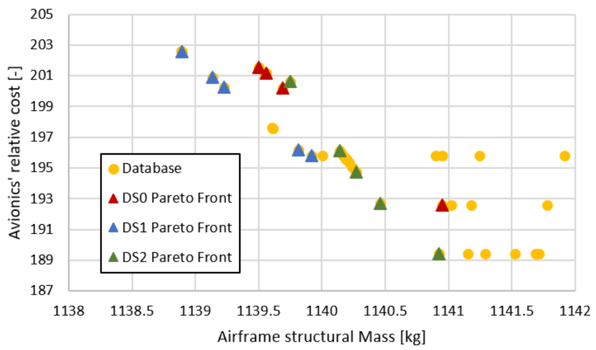


Fig. 84: Comparison of Pareto front obtained for the 3 Design Scenarios – Zoom on the lowest cost points

5 CONCLUSION AND OUTLOOK

The need of integrating a virtual certification process in the aircraft conceptual and preliminary design phases led the whole research activities within the WP7. The obvious advantage is the reduction of development cost and time reducing the re-design effort and the overall project risk. However, considering the remarkable complexity of the real certification process, only a small part of it has been modelled in this WP with the main aim to prove that the implementation of a virtual certification processes was possible, and the technologies developed within the AGILE4.0 project were suitable for the purpose.

In particular, the AC3 has demonstrated that the systems electrification and their different architectures performs differently in terms of safety level, aircraft minimum performance and external noise. Therefore, using the models here developed some electrification levels/systems architectures should be discarded since their detrimental effect on the certification margin and aircraft total cost.
Conversely, the AC4 having the same reference aircraft and systems architectures of AC3, was focused on another part of the certification process, the demonstration of the continuous airworthiness. This implies that the aircraft must be maintainable, and its airworthiness must be maintained during all the aircraft life. Considering the inherent complexity of the maintenance process the investigation has been focused on one electric bay identifying the best equipment installation to increase the maintainability avoiding or reducing the thermal risk.
Finally, the AC5 has been focused on other aspects of the certification process: the wing loadings and the indirect effect of lighting strike. Therefore, on one hand the AC5 demonstrated how the wing aero-structural design can be optimized following the loading certification constraints. On the other hand, the same wing has been equipped with a copper mesh with variable thickness satisfying the EMC certification constraints and balancing the equipment qualification level (and cost) with the wing mass.

Beyond the scope of the WP7, to further improve the integration of the certification process on aircraft design, a more comprehensive virtual certification should be applied. Many analyses usually performed after the detailed design phase to demonstrate the fulfillment of the certification constraints should be simplified to be used from the beginning of the design process.

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