POLITECNICO DI TORINO
Repository ISTITUZIONALE

MBSE Certification-Driven Design of a UAV MALE Configuration in the AGILE 4.0 Design Environment

Original
MBSE Certification-Driven Design of a UAV MALE Configuration in the AGILE 4.0 Design Environment / Torrigiani, F.; Ciampa, P. D.; Nagel, B.; Deinert, S.; Fioriti, M.; Di Fede, F.; Pisu, L.; Gatti, S.; Sanchez, F.; Liscouet-Hanke, S.; Jungo, A.. - ELETTRONICO. - (2021). (Intervento presentato al convegno AIAA AVIATION 2021 Forum tenutosi a Virtual nel August 2-6, 2021) [10.2514/6.2021-3080].

Availability:
This version is available at: 11583/2977258 since: 2023-03-20T17:02:11Z

Publisher:
AIAA

Published
DOI:10.2514/6.2021-3080

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright
ACM postprint/Author's Accepted Manuscript, con Copyr. autore

(Article begins on next page)

12 October 2024

AIAA AVIATION Forum
August 2-6, 2021, VIRTUAL EVENT
AIAA AVIATION 2021 FORUM

10.2514/6.2021-3080

MBSE Certification-Driven Design of a UAV MALE Configuration in the AGILE 4.0 Design Environment

Francesco Torrigiani[1], Pier Davide Ciampa[2], Björn Nagel[3]
DLR, German Aerospace Center, Institute of System Architectures in Aeronautics, Hamburg, Germany

Sebastian Deinert[4]
Airbus Defence and Space, Manching, Germany

Marco Fioriti[5], Flavio Di Fede[6]
Politecnico di Torino, Department of Mechanical and Aerospace Engineering, Turin, Italy

Luigi Pisu[7], Serena Gatti[8]
Leonardo S.p.A., Aircraft Division, Turin, Italy

Florian Sanchez[9], Susan Liscouët-Hanke[10]
Concordia University, Department of Mechanical, Industrial and Aerospace Engineering, Montreal, Canada

Aidan Jungo[11]
CFS Engineering, Lausanne, Switzerland

This paper presents a certification-driven design process for an Unmanned Medium-Altitude-Long-Endurance (UAV MALE) air vehicle, including on-board system design and placements, electro-magnetic compatibility analysis, and thermal risk assessments. In literature, the preliminary aircraft design phase is mainly driven by mission performances and structural integrity aspects. However, the inclusion of other disciplines, like on-board system design or electro-magnetic compatibility, or thermal analysis, can lead to more efficient and cost-effective solutions and becomes paramount for non-conventional configurations like unmanned vehicles or highly electrified platforms. In the EC-funded AGILE 4.0 project (2019-2022), the traditional scope of the preliminary aircraft design is extended by including domains that are usually considered only in later design phases, such as certification, production and maintenance. In this paper, the AGILE 4.0 design environment supports the definition and execution of a certification-driven design process of a UAV MALE configuration, using a Model-Based Systems Engineering (MBSE) approach.

[1] Research Engineer, Aircraft Design & System Integration, AIAA Member
[2] Head of MDO Group, Institute of System Architectures in Aeronautics, Aircraft Design & System Integration, AIAA MDO TC Member
[3] Founding director, Institute of System Architectures in Aeronautics
[4] Multidisciplinary Analysis and Optimization Engineer, Stress Methods & Optimization
[5] Assistant Professor, Mechanical and Aerospace Engineering Department, AIAA Member
[6] Researcher, Mechanical and Aerospace Engineering Department
[7] E3 (Electro-magnetic Environmental Effects) Engineer
[8] E3 (Electro-magnetic Environmental Effects) Engineer
[9] Post-Doctoral Researcher, AIAA Member
[10] Associate Professor, AIAA Member
[11] Research Scientist

Downloaded by Marco Fioriti on March 20, 2023 | http://arc.aiaa.org | DOI: 10.2514/6.2021-3080

Copyright © 2021 by Francesco Torrigiani, Pier Davide Ciampa, Björn Nagel, Sebastian Deinert, Marco Fioriti, Flavio Di Fede, Luigi Pisu, Serena Gatti, Aidan Jungo.
Published by the American Institute of Aeronautics and Astronautics, Inc., with permission.

Downloaded by Marco Fioriti on March 20, 2023 | http://arc.aiaa.org | DOI: 10.2514/6.2021-3080

I. Nomenclature

MDAO	=	Multi-Disciplinary Analysis and Optimization
SE	=	System Engineering
MBSE	=	Model-Based System Engineering
MALE	=	Medium Altitude Long Endurance
UAV	=	Unmanned Aerial Vehicle
OAD	=	Overall Aircraft Design
OBS	=	On-Board Systems
EMC	=	Electro-Magnetic Compatibility
CPACS	=	Common Parametric Aircraft Configuration Schema
XDSM	=	Extended Design Structure Matrix
PIDO	=	Process Integration and Design Optimization
EASA	=	European Aviation Safety Agency
CS	=	Certification Specification
EC	=	European Commission
BLOS	=	Beyond Line Of Sight
CFD	=	Computational Fluid Dynamics
RANS	=	Raynolds-Averaged Navier-Stokes equations
FEM	=	Finite Element Method

II. Introduction

The aircraft design process is inherently a multidisciplinary and multi-fidelity process with numerous requirements and conflicting objectives. A classic example is the trade-off between performances, cost and development time. The latest on-board system (OBS) technology, like a full electric OBS architecture, can improve the overall aircraft efficiency but can be more expensive and might need a different certification procedure with respect to a conventional OBS architecture.

Leveraging the experience of the AGILE project [1] in building multidisciplinary design analysis and optimization (MDAO) systems [2], one of the goals of the EC funded AGILE 4.0 project (2019-2022) is to formalize and model the design process using System Engineering (SE) practices in order to accelerate the development of complex systems [3]. The well-proven capability of SE approaches to manage complexity allows extending the traditional scope of the aircraft design process, including disciplines from the entire aircraft life-cycle, like certification, production and maintenance. The developed SE approach is tested on eight different application-cases; in this paper, the AGILE 4.0 design environment supports the definition and execution of a certification-driven design process for a UAV MALE configuration: the OptiMALE [4].

Certification constraints are at the core of the aircraft design process and are considered in any phase of the latter. Traditionally aircraft design is divided into three stages: conceptual, preliminary and detailed. In the conceptual phase, the given requirements are used to obtain a rough estimation of the aircraft mass, size, aerodynamic and performances. Several tools can be found in the literature for the aircraft conceptual design, including OpenAD [5], SUAVE [6] and FLOPS [7]. All of them strongly rely on statistical data and can be used for quick and extensive parametric design exploration as well as for uncertainties quantification studies. At this stage, certification constraints are implicitly considered in the statistical data based on certified vehicles.

In the preliminary design phase, aircraft designers start to use mostly physics-based tools, and certification requirements are directly used to define the set of analyses to be performed. Cavagna [8] developed the NeoCASS framework for preliminary aero-structural sizing of the complete aircraft configuration. Doublet-lattice method, as well as a RANS-based reduced order model, are available for the aerodynamic analysis. Both fuselage and wing structure are modelled with a stick finite element model, in which all the parameter of the section, like skin, frames and spar, are used to define the section stiffness characteristics. The framework allows the user to perform structural optimization using a gradient-based algorithm. OpenAeroStruct [9] is an open-source low-fidelity aero-structural analysis and optimization tool based on NASA's OpenMDAO framework by the MDOLab at the University of Michigan. OpenAeroStruct couples the VLM method with a circular section Euler-Bernoulli beam for static aeroelastic optimization. The MDOLab also developed a framework for high-fidelity aero-structural optimization [10]. The CFD solver ADFlow is used for aerodynamics, whereas the structural modelling and analysis are carried out using the TACS software [11], a FEM solver specialized for thin-walled composite structures. The framework [12] developed by the Aircraft Systems Design Laboratory at the Georgia Institute of Technology, in addition to the

classical aero-structural sizing procedure, includes sub-system sizing and dynamic maneuvers constraints coming from Subpart B of the Certification Specification.

Considering the tools and frameworks already available in the literature for preliminary aircraft design, the authors identify few possible areas of improvement. First, a fixed monolithic framework can be difficult to extend or update. For example, the design requirements can be updated or extended during the project leading to a complete restructuring of the design process, including change in the disciplines which need to be integrated. Moreover, in a large collaborative project, such as AGILE 4.0, some of the design modules might not be available at the beginning of the project, and an easily reconfigurable design and optimization framework helps in the transition to the final development phases, still allowing to obtain preliminary results in the initial phase.

In this paper, AGILE 4.0 digital engineering technologies are leveraged for the OptiMALE aircraft, and the design workflow is assembled starting from the given set of requirements, the defined objectives of the study and the available disciplinary modules. Second, most of the preliminary design platforms focus on structural integrity requirements, and in literature, few works address disciplines beyond the aero-structural domain, notably the aforementioned [12]. Here, together with the classical aeroelastic disciplines, on-board system (OBS) design, electro-magnetic compatibility (EMC) and thermal risk analysis are included in the design process.

Finally, the most investigated configurations are the typical civil commercial vehicles, with few frameworks tested on non-conventional vehicles. Here, the OptiMALE configuration in an unmanned vehicle with a very slender wing, a prescribed cruise altitude above commercial airliners routes and a required endurance greater than 20 hours. Moreover, in UAV design, the role performed by the OBS and their interaction with other disciplines is even more important than in civil commercial vehicles. For UAV, the OBS mass is usually a greater fraction of the maximum take-off mass, and more importantly, the OBS requirements are often driving the entire design process, as shown in this design study.

The paper presents the design studies on the OptiMALE UAV configuration carried out in the AGILE 4.0 project at the current point in time. In Section III, we introduce the vehicle characteristics as well as the associated mission profiles. After presenting the requirements and their modeling procedure in Section IV, the derived design process is described in Section V together with the obtained results. Several analyses and design activities are not yet integrated into the design workflow of Section V, and are currently executed off-line. These off-line studies focus on the interactions among OBS design, aero-structural sizing and electro-magnetic compatibility (EMC) aspects, and they are presented in Section VI. The final section summarizes the main achievements of the design activity and presents the future developments of this application case within the project framework.

III. The OptiMALE Configuration

The baseline for the collaborative multidisciplinary design task at hand is the OptiMALE configuration developed during the German AeroStruct research project [4]. A representation of the vehicle in the Common Parametric Aircraft Configuration Schema, CPACS [13], has been provided to the AGILE 4.0 consortium by Airbus Defence and Space (ADS) and the visualization of the model using the ADS tool Descartes [14] is shown in Fig. 1.

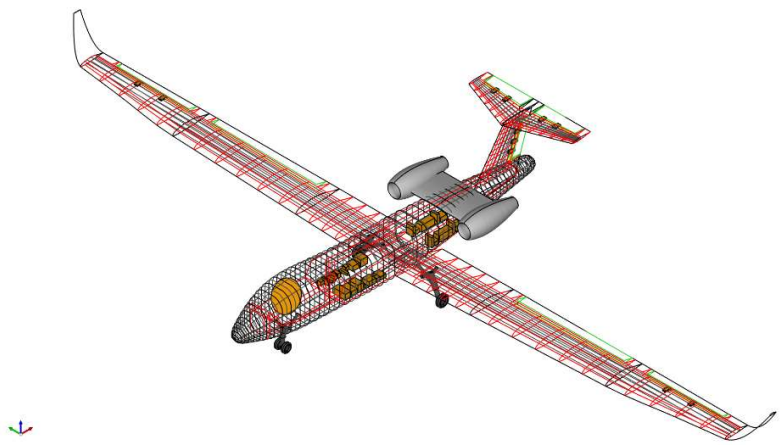

Fig. 1: OptiMALE visualization in Descartes

Downloaded by Marco Fioriti on March 20, 2023 | http://arc.aiaa.org | DOI: 10.2514/6.2021-3080

As can be seen, the OptiMALE is a low wing configuration with a T-tail and two rear fuselage-mounted turbofan engines. The wingspan is 32.4 m (winglet included) with a reference area of 55.209 m, resulting in an aspect ratio of 19. The mean aerodynamic chord is 1.801 m, and the wing has a small positive sweep angle coherently with the low cruise Mach number.

The CPACS schema allows a detailed definition of the outer geometry as well as the internal structures. The fuselage structure consists of frames and stringers as well as pressure bulkheads, walls to separate the different compartments and floors for payload and equipment installation. Two spars run through the entire wing-box span for the wing, and they are parallel to the leading and trailing edge, respectively. The third middle spar stops at two-thirds of the wing, where the taper ratio increases significantly. The low value of the wing sweep angle allows all the wing ribs to be parallel to the vehicle symmetry plane. T-profile stringers extend from root to tip of the wing box on the upper and lower side of the latter, and they are parallel to the rear spar. The fuel tank occupies the entire main wing box, including the central fuselage segment; additionally, two underwing pods can extend the fuel capacity by 400 kg each. For the tail lifting surfaces, a classic two-spar layout of the wing-box is chosen.

As shown in Fig. 1, the configuration definition in CPACS includes the trailing edge devices and the landing gears position and geometry. Finally, an extension of the CPACS schema definition allowing a detailed description of the on-board systems is currently under development. In the proposed definition, the geometry, the position and the attachment to structural elements are included as well as the equipment performance parameters such as mass, volume, required power and allowed heat load. The actual definition of all the OBS parameters is one of the design activity results and is presented in Section V.

The mission parameters are given in Tab. 1. Two reference missions have been defined for the OptiMALE: one is the transfer mission where the aircraft is relocated between two bases, and the other is the surveillance mission. The first mission consists of a take-off, climb, constant altitude cruise, descent, and landing segments. Whereas, in the second mission a loitering segment is added to the cruise segment, in which the aircraft loiters at a lower altitude to gather surveillance data.

Requirements	Values
Cruise altitude	> 15000 m
Loitering altitude	7500 m -13500 m
Endurance	> 20 h
Range	> 12000 km
Cruise speed	150 m/s
Dive speed	180 m/s

Tab. 1: Selected TLARs of the OptiMALE configuration

IV. Requirements Modeling

A complete requirements model for a UAV MALE configuration is out of the scope of the AGILE 4.0 project. As defined by the application case owner Airbus Defence and Space, the focus of this application case is on the interaction between airframe sizing and on-board systems design; therefore, the requirements definition activity is limited to this area of interest[12].

This approach implies an iterative procedure since some of the requirements might be missing initially or might need to be modified during the design campaign. The system engineering (SE) method followed in the AGILE 4.0 project [15] together with the technologies implementing it, provide the sought flexibility and consistency to cope with this. According to the followed SE approach, the requirements are derived from the needs which are addressed by the different system stakeholders. The scenario clarifies the needs definition describing the interactions between the product and the stakeholders in a specific situation. Another purpose of the scenario is to show how the needs are validated and who are the stakeholders involved in the validation process.

A. Stakeholders and Needs

The first step in the requirements modeling procedure is the identification of the stakeholders. For the given OptiMALE design scope, we identify the following stakeholders:

[12] This approach, justified by the available project resources, is also common in real industrial cases. Very rarely the requirements definition activity starts from a blank sheet, usually, there is an initial database coming from an old version or a similar configuration, which needs to be updated and extended according to the specific purpose of the configuration at hand.

Downloaded by Marco Fioriti on March 20, 2023 | http://arc.aiaa.org | DOI: 10.2514/6.2021-3080

- The **OEM** (original equipment manufacturer) is one of the main stakeholders, and although several needs are associated with it, its main role is to consider all the needs coming from the other stakeholders in order to manufacture a market-competitive product. All the needs associated to the OEM are connected with the increase of market share (like being certifiable for civil and/or military regulations), or the increase in market competitiveness (cost reduction, time to market reduction).
- Each of the needs associated with the **certification authority** results in one or more constraints to be included in the design process. As a reference for the needs associated with the certification authority, the authors considered the EASA Certification Specification 25.
- The **operator** is the end-user of the product and provides all the needs associated with the vehicle's performance. In particular, the choice of several OBS elements is directly driven by the operator's needs.
- The environmental impact of the system's production and deployment plays an increasingly important role in the design process nowadays . Therefore, the requirements modeling considers needs associated with the **society**.

For each of the stakeholders, several needs are identified. Although the authors define the main needs affecting all the on-board systems and the airframe, only the needs driving the avionics design are discussed in this paper. As can be seen from Tab. 2, the avionics design is mainly driven by the operator's needs. Many of these needs arise directly from the operator's use, like surveillance, transmit images, transmit data in real-time, or communicate beyond the line of sight. Other operator's needs are connected to the way the vehicle is used, like flying in civil airspace, flying without navigation aids, flying autonomously or flying remote-controlled. The avionics design is also affected by some performance constraints addressed by the OEM, which are the prescribed upper limit for the system mass, volume, required power, and the minimum number of redundancies.

ID	Name	Needs	Values
N0020	Civil airspace	The UAV shall operate in civil airspace	operator
N0003	Surveillance	The UAV shall provide surveillance/monitoring capability	operator
N0024	No navigation aids	The UAV shall fly without external navigation aids	operator
N0010	Autonomous flight	The UAV shall fly autonomously	operator
N0011	Beyond line of sight	The operator shall be able to control the UAV beyond the line of sight	operator
N0025	Remote control	The UAV shall be remote controlled	operator
N0026	Real-time image trans.	The UAV shall transmit radar and optic image data in real-time	operator
N0014	High temp. take-off	The UAV shall take-off in high temperature condition	operator
N0027	Avionics max mass	The avionics shall have a maximum mass of 60 kg	OEM
N0028	Avionics max volume	The avionics shall have a maximum volume of 0.1 m3	OEM
N0029	Avionics max power	The avionics shall have a maximum power consumption of 3 kW	OEM
N0030	Avionics redundancy	The avionics shall have a three-fold redundancy	OEM

Tab. 2: OptiMALE needs driving avionics design

Once the stakeholders and needs are defined either in a table like Tab. 2, or directly in the dedicated interface, the AGILE 4.0 framework allows the automatic generation of the respective models and the definition of the model connections. Models are then exported in Papyrus [16] for visualization, review and further modifications.For example, Fig. 2 shows a view of the operator's needs model.

Downloaded by Marco Fioriti on March 20, 2023 | http://arc.aiaa.org | DOI: 10.2514/6.2021-3080

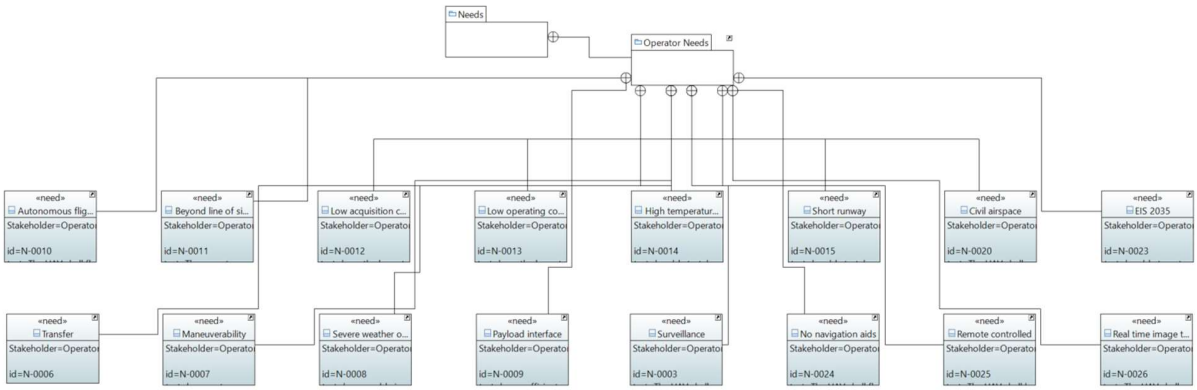

Fig. 2: Visualization of the operator's needs model in Papyrus

B. Scenario Definition

The OptiMALE scenario is chosen to highlight the interaction between the on-board systems and the airframe, and it represents the following situation.

The OEM applies for a new type certificate (TC), or for a change in an existing TC when the certification basis contains the certification specification CS 25.1316 [17]*: "Protection against the indirect effects of lightning".*

The system considered in the scenario is the whole aircraft, whereas the stakeholders involved are the OEM and the certification authority. The tasks performed during the scenario are directly taken from the acceptable means of compliance, AMC 20-136 [17], since this is the procedure suggested by the certification authority to demonstrate compliance with the CS 25.1316.

1) The OEM identifies the subsystems to be assessed.
2) The OEM determines the lightning strikes zones of the aircraft.
3) The OEM establishes the lightning environment for each zone.
4) The OEM determines the lightning transient environment (LTE) for each subsystem.
5) The OEM establishes the equipment transient design levels (ETDLs) and the aircraft actual transient levels (ATLs).
6) The certification authority verifies the compliance with the safety margin
7) If the margin is:
    a) Acceptable: The certification authority grants the TC
    b) Not acceptable: The OEM takes corrective measures changing either the equipment or the aircraft design, in both cases the process is re-started from activity 4).

Concerning step 4, the OEM has to agree with the certification authority on the means to establish the ATLs. There are several possibilities, numerical and experimental, that can be accepted by the certification authority, here we choose the electro-magnetic finite-difference time-domain (FDTD) 3D full wave simulation, since this is the same method we are using in the implemented design process, see Section VI.

Downloaded by Marco Fioriti on March 20, 2023 | http://arc.aiaa.org | DOI: 10.2514/6.2021-3080

Downloaded by Marco Fioriti on March 20, 2023 | http://arc.aiaa.org | DOI: 10.2514/6.2021-3080

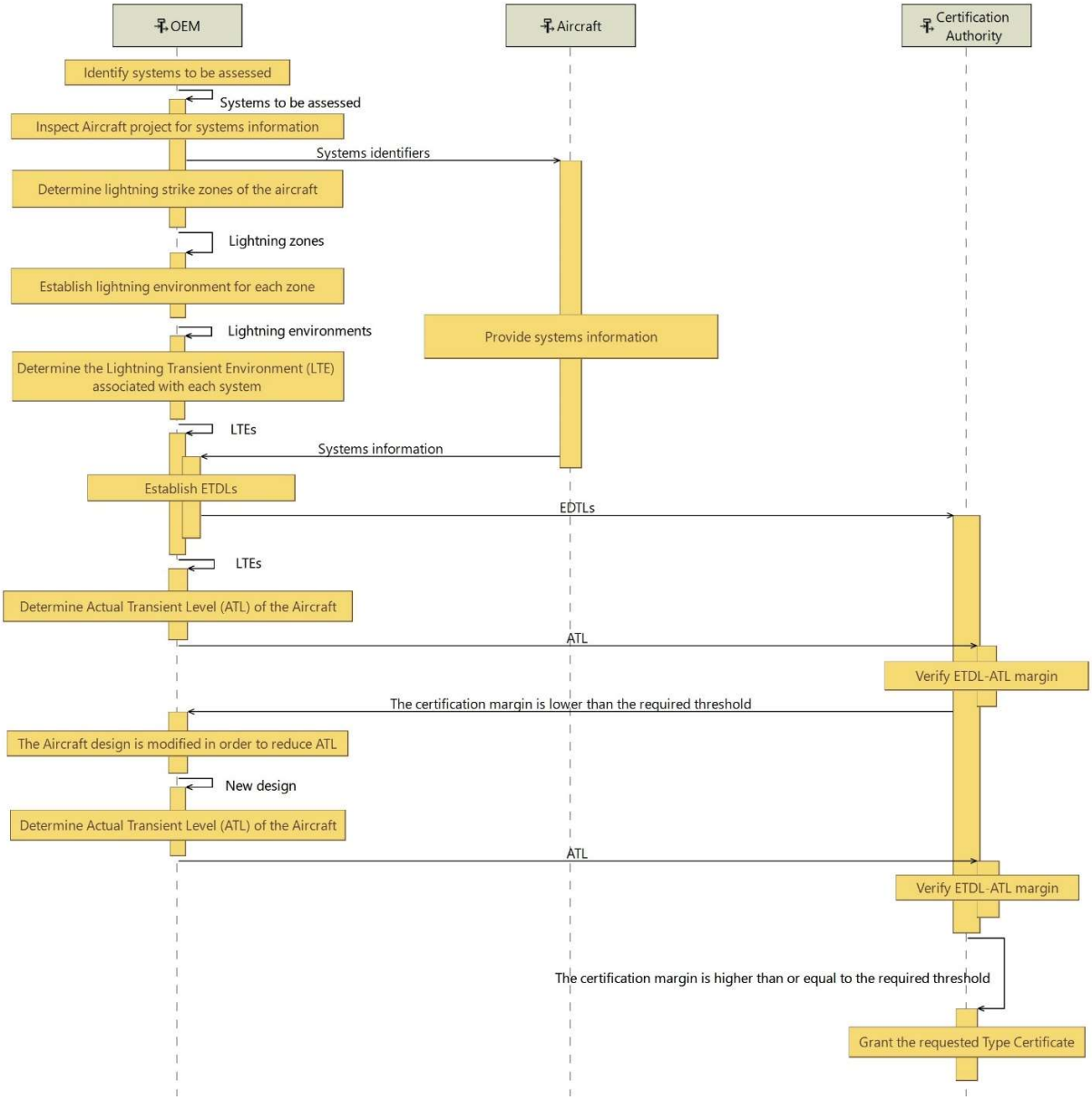

Fig. 3: Visualization of the OptiMALE scenario "Application for lightning protection certification", as sequence diagram in Capella

In the AGILE 4.0 framework the scenario model is defined using the MBSE tool Capella [18], and a visualization as sequence diagram is provided by Fig. 3.

The presented scenario can be used to validate several needs. The need N0002 (from the OEM), "The UAV shall be compliant with civil regulation", is extremely broad and the scenario validates only a part of it, since it explicitly aims to one specification of the civil certification specification 25. The need N0008 (from the operator), "The operator shall be able to use the UAV also in severe atmospheric condition", is also partially validated by this scenario, because the specification "Protection against the indirect effect of lightning" concerns one of the most critical aspect for operation in bad weather condition. Finally, the procedure described in the scenario strictly follows the AMC 20-136 which is defined by the certification authority itself (EASA in this specific case), therefore the need N0016 (from the certification authority), "The UAV certification process shall be accepted by the certification authority", is also validated by the scenario.

Downloaded by Marco Fioriti on March 20, 2023 | http://arc.aiaa.org | DOI: 10.2514/6.2021-3080

C. Requirements Definition

Needs are often fuzzy and not directly usable by the designer to define a practical solution. The requirements are derived by the needs and contain exactly the same information, but they follow strict syntax rules (the "requirement patterns" [15]), which force them to clarify and better define the information contained in the parent need.

ID	Name	Requirements	Type	Parent
R0057	Radio communications	The avionics shall communicate with the ATC and other vehicles using the aeronautical radio frequencies	Functional	N0020
R0058	Identification	The avionics shall allow the vehicle identification from the ATC and other vehicles	Functional	N0020
R0059	Terrestrial navigation	The avionics shall use terrestrial navigation aids	Functional	N0020
R0060	Satellite navigation	The avionics shall use satellite navigation aids	Functional	N0020
R0061	Collect optic images	The avionics shall collect electric optic and infrared images	Functional	N0003
R0062	Collect radar images	The avionics shall collect 3D images using radar transmission	Functional	N0003
R0063	No navigation aids	The avionics shall navigate the vehicle with inertial and air data only	Suitability	N0024
R0064	Autonomous flight	The avionics shall navigate the vehicle autonomously	Suitability	N0010
R0065	Controllability	The avionics shall allow the flight control of the vehicle	Suitability	N0010 N0025
R0066	Beyond line of sight	The avionics shall communicate with the operator beyond the line of sight	Functional	N0011
R0067	Transmit telemetries	The avionics shall transmit the telemetries to the operator	Functional	N0025
R0068	Receive commands	The avionics shall receive the commands from the operator	Functional	N0025
R0069	Transmit real time images	The avionics shall transmit optic and radar 3D images in real time	Functional	N0026
R0028	Operating temperature	The avionics shall be able to work with a temperature between -20 and 60 Celsius degrees	Environmental	N0014

Tab. 3: OptiMALE requirements driving avionics design

Often the requirement syntax forces the information contained in a single need to be split into several requirements. This is the case of need N0020 "The UAV shall operate in civil airspace", which derives 4 different requirements highlighting different capabilities: communicate and be identified by the air traffic controller (ATC) and other vehicles, be able to use terrestrial and satellite navigation aids. Less frequently, a single requirement can be associated with more than one need. The controllability requirement R0065 can be derived either by N0010 "The UAV shall fly autonomously" or by N0025 "The UAV shall be remote-controlled", since independent from the flight mode, the UAV is controlled by the same flight control system using the same control surfaces.

Differently from needs, requirements also have an associated type, and the latter defines the syntax rule followed by the requirement. Functional type requirements, like R0066 "The avionics shall communicate with the operator beyond the line of sight", define what functions ("communicate with the operator") need to be performed to accomplish the objective (which is not stated in the requirement) and possibly the condition in which the function need to be performed ("beyond the line of sight"). Requirement R0063 "The avionics shall navigate the vehicle with inertial and

air data only" is of suitability type since it defines a characteristic (the UAV can be navigated) to whom a certain performance ("with inertial and air data only") is associated.

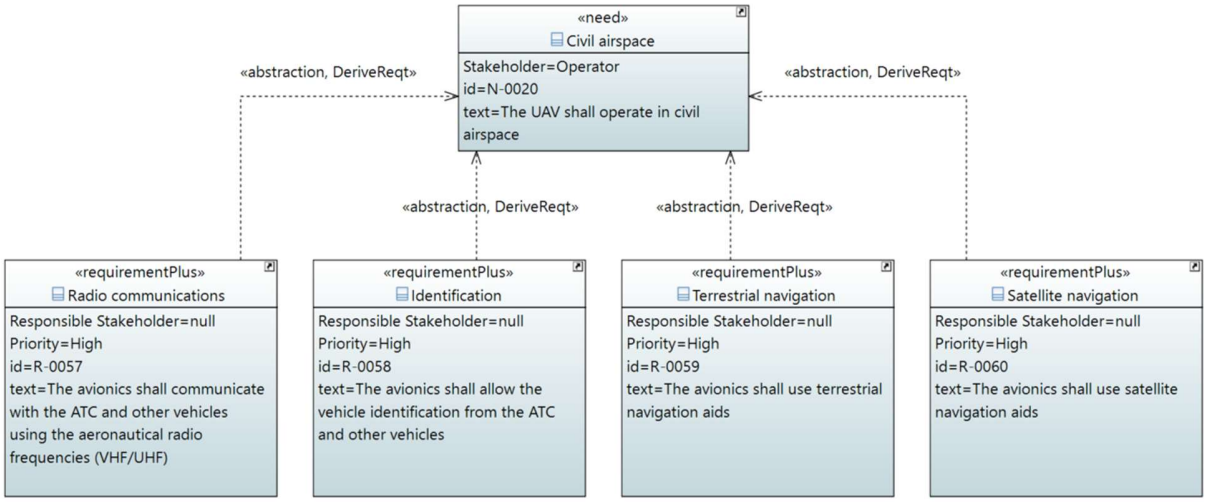

Fig. 4: Requirements traceability diagram showing the connection between the "Civil aerospace" need and the derived requirements

Once all the requirements are defined either in a table like Tab. 3, or directly in the dedicated interface, the AGILE 4.0 framework allows the automatic generation of the requirements model and the latter's connection with the stakeholders and needs models. The described model-based approach improves the traceability and the consistency of the entire requirement definition process; for example, the requirements can be grouped easily according to a specific criterium (e.g. according to the requirement's type), and the requirement's connection with the parent need and the associated stakeholder is constantly tracked, see Fig. 4.

V.Design Process

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 Section IV. 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.

A. Disciplinary Capabilities

One of the key enablers of the AGILE 4.0 approach is using the CPACS data schema [13] as a format to express the product model. 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.

Descartes (Airbus DS) [14] 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.

Downloaded by Marco Fioriti on March 20, 2023 | http://arc.aiaa.org | DOI: 10.2514/6.2021-3080

Lagrange (Airbus DS) [19] 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) [20] 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 [21]. 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 [22], 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 [23], it allows to consider viscous drag, which is neglected by VLM and Euler equations.

MUST is a 3D panel method library for steady and unsteady frequency domain aerodynamic analysis developed by DLR [24]. 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 [25] 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.

Once the influence coefficient matrix is obtained, the aerodynamic forces due to the free-stream flow direction or the surface deformation are obtained with a simple matrix multiplication as the aerodynamic linear system has been already inverted within the MUST internal process. The library can be used to obtain directly the aerodynamic loads given the flow orientation, the structural deformations, or the control surfaces deflections. Otherwise, only the aerodynamic influence coefficients matrix is computed, and then the loads are obtained by a dedicated external module (like FAEDO) responsible for the coupling with the structural and flight mechanics analyses. The latter approach is usually preferred in the case of multiple load cases, and it is also used in the OptiMALE design process.

FAEDO 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) method presented in [26]. Fig. 5 shows an example of the flexible-trimmed aerodynamic loads which are obtained with FAEDO.

Downloaded by Marco Fioriti on March 20, 2023 | http://arc.aiaa.org | DOI: 10.2514/6.2021-3080

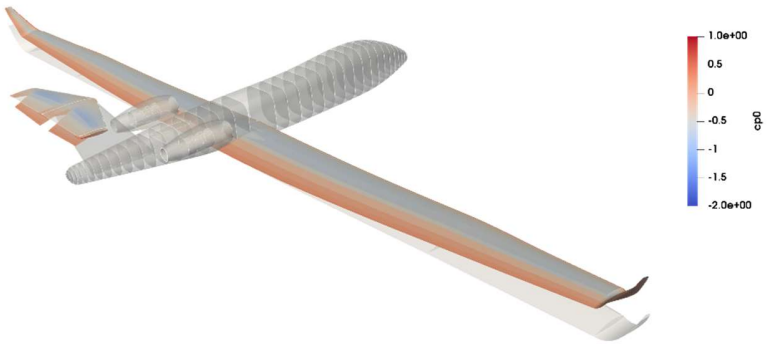

Fig. 5: Example of flexible-trimmed load obtained with FAEDO

The unsteady aeroelastic stability analysis described in [27] is available in FAEDO for the computation of the flutter and divergence conditions. The finite state approximation of the aerodynamic term is obtained with the matrix fraction approach (MFA) [28], starting from the generalized aerodynamic forces (GAF) matrix computed by MUST. Then, given the structural stiffness, damping and mass matrices, the non-linear aeroelastic eigenvalue problem is solved with the continuation method [29]. Although the unsteady aeroelastic stability analysis is currently not directly integrated in the design workflow, it is used offline in the post-processing phase to check the stability of the optimized configuration.

ASTRID (POLITO): the OBS design process is carried out with ASTRID tool developed by Politecnico di Torino [30] [31] [32]. 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.). As shown in Fig. 6, 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.

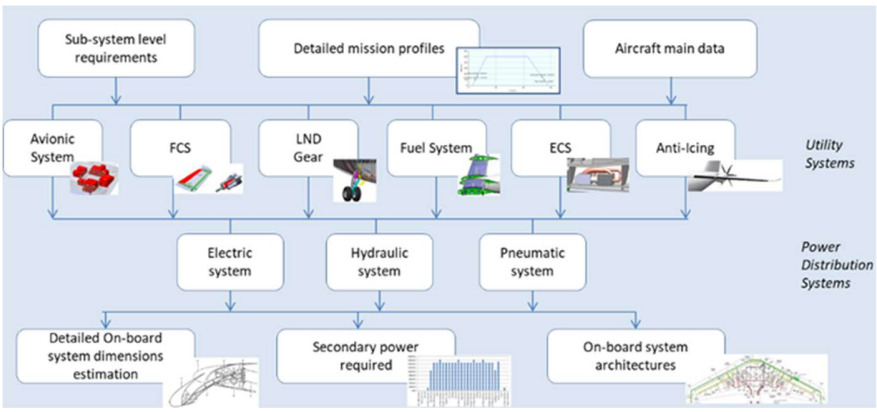

Fig. 6: ASTRID on-board system design process

Downloaded by Marco Fioriti on March 20, 2023 | http://arc.aiaa.org | DOI: 10.2514/6.2021-3080

Downloaded by Marco Fioriti on March 20, 2023 | http://arc.aiaa.org | DOI: 10.2514/6.2021-3080

PySysTher (CONCORDIA) is a tool that allows the thermal risk prediction of on-board systems and components [33]. 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 (discussed in more detail in [34]), 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).

B. Design Workflow

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. 7. represents the collaborative multidisciplinary workflow deployed for the design of the OptiMALE configuration

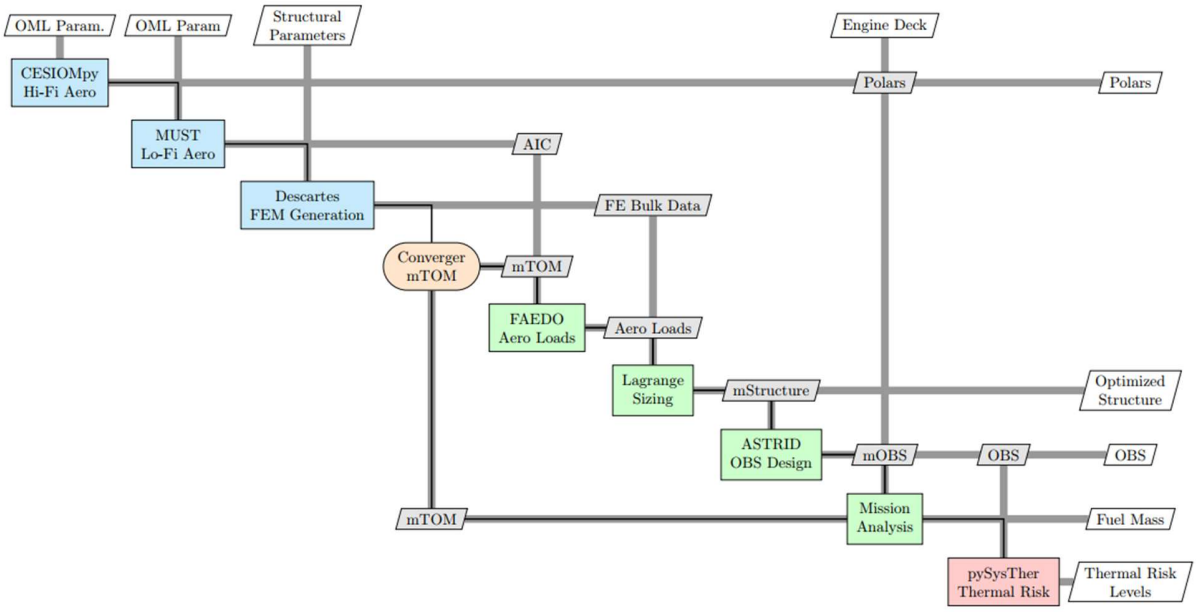

Fig. 7: OptiMALE design workflow.

As can be seen, 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.

Downloaded by Marco Fioriti on March 20, 2023 | http://arc.aiaa.org | DOI: 10.2514/6.2021-3080

C. Airframe Sizing Results

The global finite element model (GFEM) obtained with Descartes consists of linear and surface elements defined according to Nastran's bulk data format, and it is shown in Fig. 8. The rib and spar caps as well as the rib posts are defined as CROD elements carrying axial tension-compression and torsional loads. The stringers of both the upper and lower side of the wing box are modeled with CBAR elements in order to support the bending moments in the wing skin and limit buckling fields. CBAR elements are also used for all the fuselage beam elements, which are stringers and frames. The 2D elements are all defined as CQUAD4 or CTRIA3 cards, depending on the local mesh definition. The surface elements for the wing internal structure, like rib, spar web, upper and lower skin, are all defined as thick metal plate exploiting the possibility to assign membrane, bending and shear stiffness properties given by the PSHELL card in combination with the MAT1 card for the material properties definition. All the skin elements, as well as the fuselage internal walls and bulkheads, are defined as composite elements by means of the PCOMP and MAT8 cards. Currently, the same symmetrical stacking sequence is used for all the composite elements: [45°, -45°, 90°, 0°].

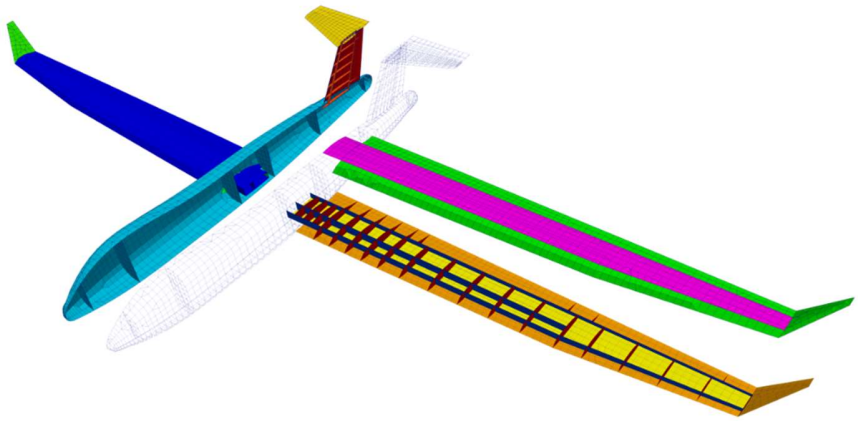

Fig. 8: OptiMALE GFEM obtained with Descartes

In the current implementation of the design process, only four static load cases are considered for the structural sizing procedure: the pull-up maneuver with 2.5 load factor, the pull-down maneuver 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.

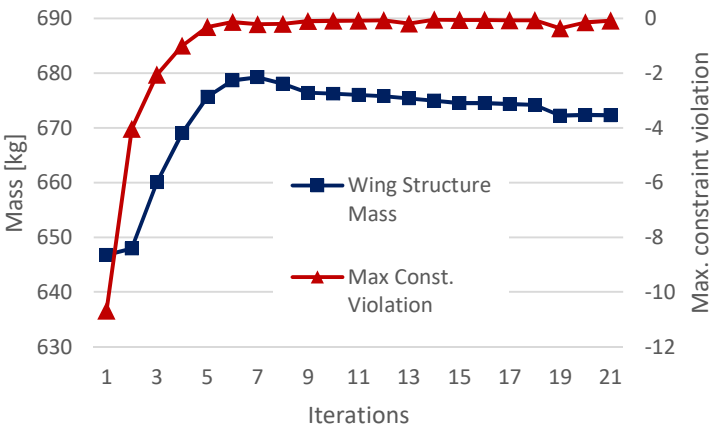

Fig. 9: Objective and maximum constraint violation

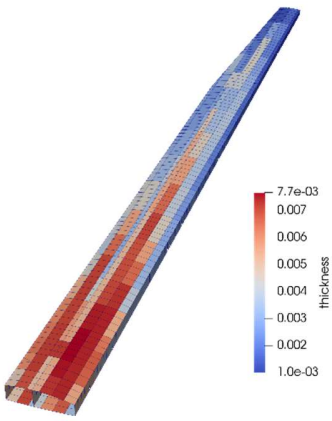

Fig. 10: Optimized wing-box

As shown in Fig. 9, 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.

D. On-Board System Design Results

The systems architecture selected is a more-electric one as from the high-level requirements. As shown in Fig. 11, the only power system is the electric one that is directly connected with aircraft engines by means of high voltage starter generators [35]. Since the high-power demand, high voltage bus (i.e. 270 VDC) has been selected to reduce electric machines and wire size [31]. The primary FCS, the ECS for the avionics thermal management, the hydraulic motor pump and the de-icing system are directly connected to the 270 VDC bus. The avionics, lights, fuel pumps and batteries are connected to medium (i.e. 115 VAC) and low voltage (i.e. 28 VDC) buses supplied, respectively, by DC-AC and DC-DC converters. As for the initial requirement, the high lift devices and the landing gear are hydraulically actuated. However, to avoid the use of a heavy complete hydraulic system, the hydraulic users are supplied by an electric motor pump. In particular, for the de-icing system, the TMEDS (Thermo-Mechanical Expulsion System) has been selected for power and mass constraints. For ECS, the vapor-cycle technology has been selected, considering that cabin pressurization is not needed.

The results in terms of mass and power are depicted in Fig. 13. As usual for MALE UAV the avionic system represents the system with a greater mass together with the landing gear and electric system. The power requirement is driven by the avionics and the electrical de-icing system. The latter represents a power-demanding user also considering the notable aircraft wingspan.

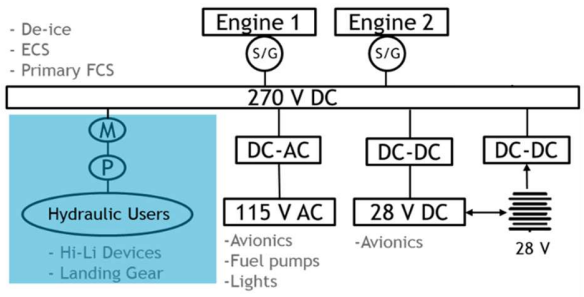

Fig. 11: OBS architecture schematic

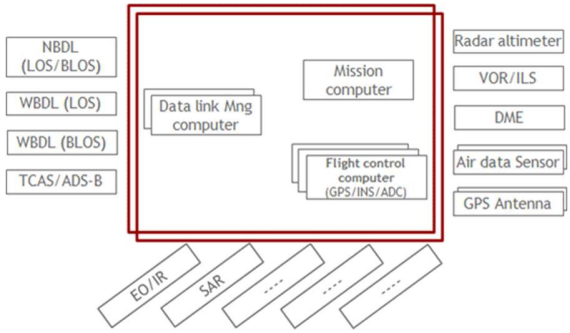

Fig. 12: Avionic system architecture

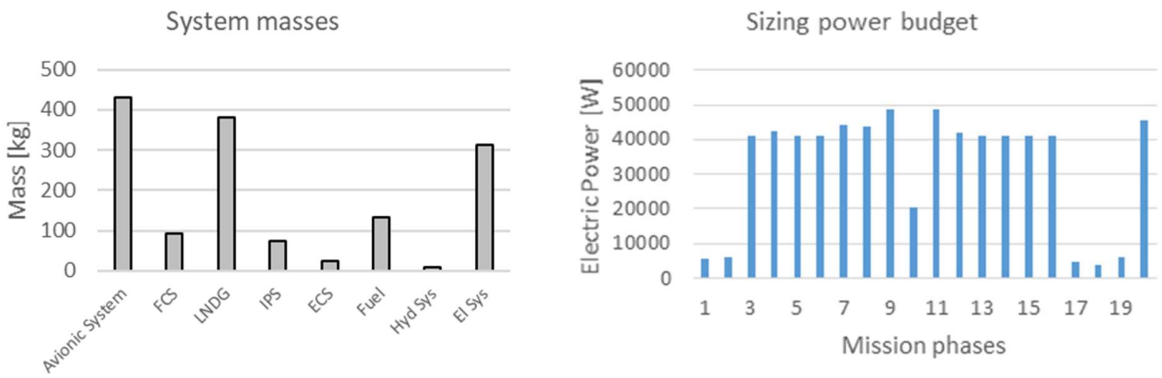

Fig. 13: OBS mass and power assessment

The avionic system is designed considering both functional and performance requirements. As usual, the functional requirements are evaluated to define the equipment list[13], as shown in Tab. 4. Considering the specific aircraft typology (i.e. MALE UAV), the main requirements are regarding the surveillance capabilities, the autonomous flight

[13] See Appendix A for the avionics nomenclature used in the table.

Downloaded by Marco Fioriti on March 20, 2023 | http://arc.aiaa.org | DOI: 10.2514/6.2021-3080

operation and the beyond line of sight (BLOS) operation. The surveillance requirements demand the collection of optical, infrared and radar images. These requirements shape the aircraft sensors suite that should include an Electro-Optical / Infrared (EO/IR) turret and a specific radar sensor (i.e. Synthetic Aperture Radar). The autonomous flight operation can be achieved using a mission computer capable of following the mission steps and re-schedule them if needed. This computer should be connected to the FCC and inertial and air sensors. The BLOS operation requirement demand for a BLOS satellite data link. The other requirements demand additional, quite common, equipment.

The avionic architecture is depicted in Fig. 12. It contains the equipment selected and their redundancy level usually adopted in MALE UAV [36].

Equipment	Requirement ID												
	R57	R58	R59	R60	R61	R62	R63	R64	R65	R66	R67	R68	R69
VHF/UHF radio	X										X	X	
TCAS/ADS-B/trans		X											
VOR/ILS - DME-P			X					X					
GPS receiver				X				X					
EO/IR					X								
SAR						X							
ADS							X	X	X				
INS							X	X	X				
Radar altimeter							X	X					
Mission computer							X	X					
FCC							X	X	X				
DLMC										X	X	X	X
WBDL (BLOS)										X	X	X	X
WBDL (LOS)											X	X	X
NBDL											X	X	

Tab. 4: Functions-equipment matrix

E. Overall Aircraft Design Results

After structural sizing and on-board system design, the last tool updating the mass breakdown is the mission analysis. For both surveillance and transfer missions, the fuel consumption is estimated with a simplified method based on Breguet's equation for each different segment of the mission. According to the requirement, the cruise altitude is above the commercial flight level; therefore the Breguet's assumption of constant lift coefficient along the entire cruise segment is a reasonable approximation. For the transfer mission, the estimated fuel consumption is 2530 kg, and the final cruise altitude of 17550 m is below the ceiling altitude. For the surveillance mission this study resulted in a higher fuel consumption of 4658 kg, which is used as the reference fuel mass for the maximum take-off mass definition.

Downloaded by Marco Fioriti on March 20, 2023 | http://arc.aiaa.org | DOI: 10.2514/6.2021-3080

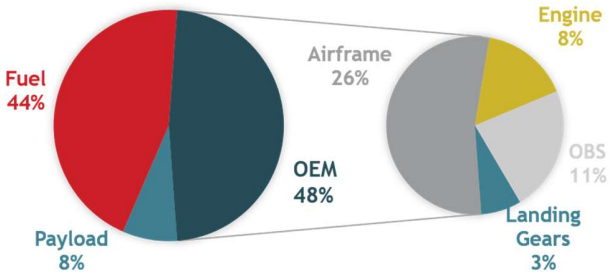

Fig. 14: Overall OptiMALE mass breakdown

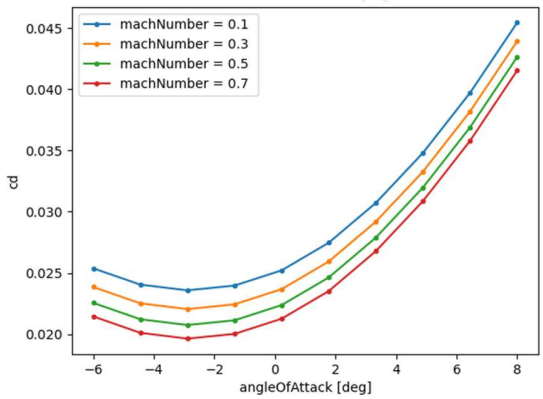

Fig. 15: Drag polar used in mission analysis

The design process exhibits a good convergence behavior, being the delta on maximum take-off mass below 2% after three iterations. The final maximum take-off mass is 10433 kg, with the breakdown shown in Fig. 14.

VI. On-Board Systems and Airframe Interactions

Section V describes the design process implemented at the time of submission, which, in addition to the classic structural integrity and mission performance aspects, includes also the on-board system design. However, several other disciplinary competencies are currently being integrated into the project framework and will allow to understand better the interaction between on-board system design and airframe sizing for the OptiMALE configuration. The following Subsection describes several studies highlighting this interaction. They are currently conducted outside the workflow described in Section V, but can already explain the influence of aspects like lightning protection and thermal risk assessment on the airframe sizing.

A. On-Board Systems Layout

As a further result of OBS design, the installation layout of the avionic, electric and FCS systems has been carried out. The installation layout is needed to perform the EMC analysis or thermal risk assessment, and it includes the system components and their connecting cables. As shown in Fig. 16, two main compartments have been identified. Considering the available volume and the mutual radio frequency (RF) interference of the systems involved, it was decided to keep separated the avionic and the electric system, as well as to identify different cable routings for the different systems. The first one has been installed in the forward compartment close to the surveillance sensors and a satcom antenna. The electric system has been installed in the rear compartment close to the electric starter generators. The FCS actuators, as for their control unit, are constrained by their own control surface position. The connection between each component is roughly defined, as shown in Fig. 17.

Fig. 16: Installation layout for FCS, avionics and electric system

Downloaded by Marco Fioriti on March 20, 2023 | http://arc.aiaa.org | DOI: 10.2514/6.2021-3080

Downloaded by Marco Fioriti on March 20, 2023 | http://arc.aiaa.org | DOI: 10.2514/6.2021-3080

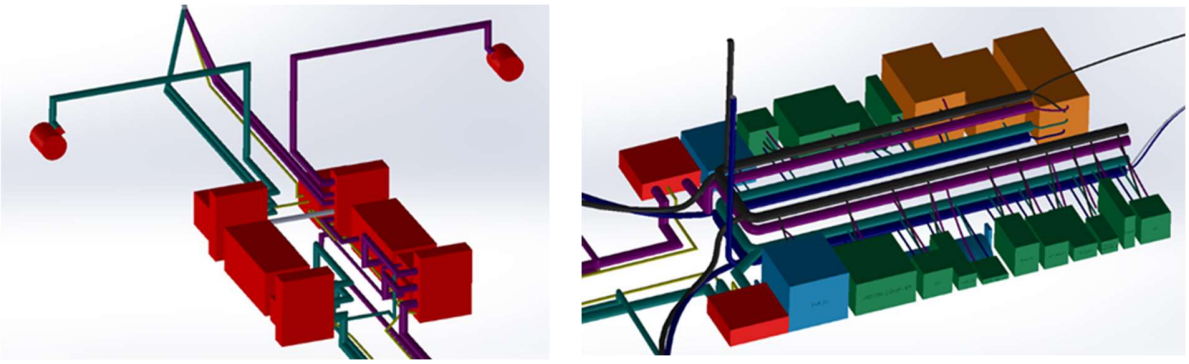

Fig. 17: Cable connection of electric (left) and avionics (right) component

B. Influence of Lightning Protection on Airframe Sizing

In order to assess the impact of lightning protection, against the lightning indirect effects (LIE), on the overall aircraft design, it an investigation was performed using the CST Studio Suite commercial tool [37]. To guarantee the reliability and accuracy of the results, the capabilities of a 3D and 2D EM analyses were combined, thanks to the interacting packages included in the CST Suite. 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. Then, to obtain a fast and accurate investigation of the real-world cables in a complex electro-magnetic environment, the capabilities of "CST Cable Studio" package of the Suite were used. According to the procedure defined by the scenario in Subsection IV.B, 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 [38]) on three different lightning entry/exit points; following the worst case condition is chosen for each sub-system. In order to carry out the electro-magnetic simulation campaign, a detailed avionics layout description is necessary, not only in terms of equipment placement and cable connections, as presented in Subsection VI.A, but also including the holes for the cables to cross structural elements like fuselage walls and wing ribs. Another input of the lightning strike simulation is the geometrical definition of all the internal and external structural surfaces with the associated thickness and material properties (CFC, Aluminum, glass fiber, etc.) In the studies presented in this section, these input data are obtained from the FEM defined by Descartes. The FE model used here is similar to the one presented in Section V, except for the wing skin material, which in this case is aluminum 7075[14].

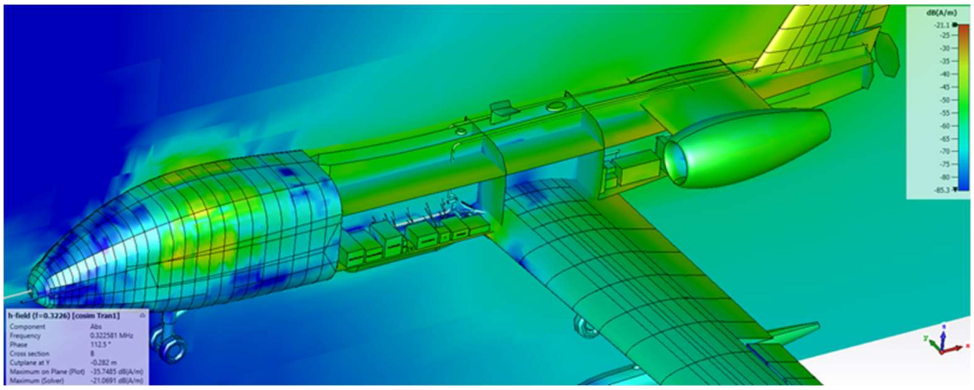

Fig. 18: Internal magnetic field due to the lightning strike

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 [39], which is the international

[14] In Section V, all the skins including the wing skin are composite. The lightning strike simulations are currently executed off-line, outside the workflow presented in Section V, and as initial investigation we decided to start with a less critical (from the EMC prospective) case considering a fully metallic wing.

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[15].

The simulation observables are the ATLs related to 17 avionics equipment. ATL values are related to the disturbance current induced at the equipment port, due to the lightning strike. 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 CFC 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.

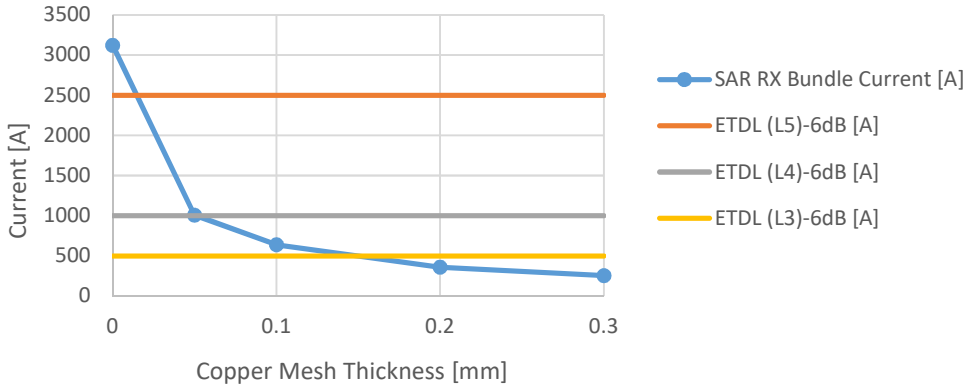

Fig. 19: ATL and ETDLs of the SAR RX for the bundle injection case.

Fig. 19 provides an example of the obtained results, in terms of total bundle current at the equipment input port, for one of the EUT-equipment under test: the receiver of the synthetic radar aperture, SAR RX. Starting from the evaluation of different entry/exit point cases, the total bundle current and the maximum pin current is computed, according to 5 different thickness values of the copper mesh layer. The evaluation was conducted starting from zero-thickness case (without any copper mesh) to 0.3 mm and considering the worse lightning entry/exit point combination. As expected, the bundle current decreases with the copper mesh thickness. The ATL in terms of bundle current is then compared with the ETDL of the equipment considering different qualification level[16]. As can be seen, for the SAR RX, even the higher qualification level of the equipment is not sufficient to meet the certification requirement, hence the need to use the copper mesh layer. With a thickness of 0.1 mm and a qualification level L5 or L4 the SAR RX meets the certification requirements. However, in order to lower the SAR RX qualification level to L3 the copper mesh thickness needs to be at least 0.2 mm thick.

[15] Note that the qualification level affects also the costs, being the equipment with the highest qualification level also the most expensive.

[16] Note that the required margin of 6dB is already subtracted from the ETDL to ease the reading of the graph.

Downloaded by Marco Fioriti on March 20, 2023 | http://arc.aiaa.org | DOI: 10.2514/6.2021-3080

Downloaded by Marco Fioriti on March 20, 2023 | http://arc.aiaa.org | DOI: 10.2514/6.2021-3080

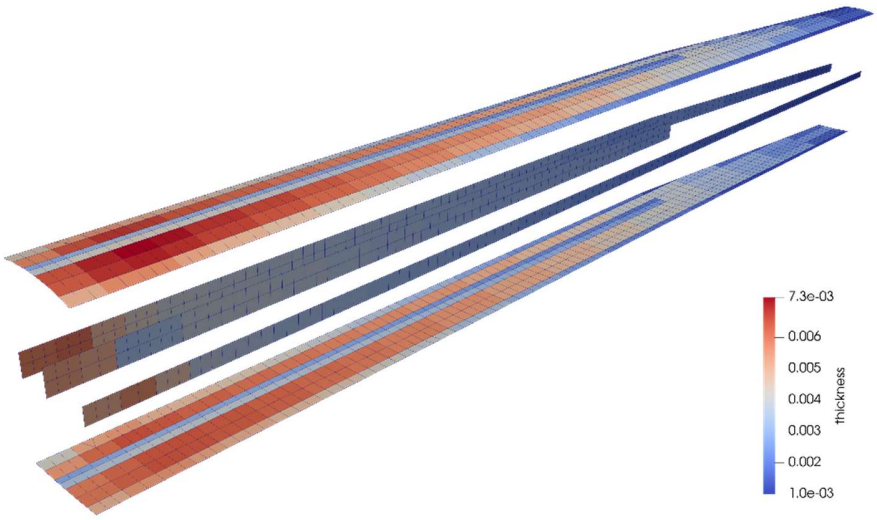

Fig. 20: Wing-box structure optimized considering a 0.2 mm copper mesh thickness

Once the available qualification level for each avionics equipment is defined, the copper mesh thickness is set according to the worst condition. It must be underlined that the mesh layer must be able to protect the structure against both direct and indirect effects of the lightning strike. The copper mesh layer considered in the simulation campaign is taken from a commercial supplier datasheet [40], and it has a strand width of 0.4 mm with a diamond size of 5x2 mm, being able to protect the CFC against the direct lightning effects. However, the study of LDE (Lightning Direct Effects) is out of the scope of the present project. This additional layer has a negligible structural stiffness, but its contribution to the aircraft's empty operative mass is significant. The OptiMALE airframe mass without the copper mesh layer is 2046 kg, whereas the copper mesh layer with a thickness 0.2 mm has a mass of 47.7 kg, which is the 2.3% of the previous. The additional mass results in increased aerodynamic loads and, therefore, in an increased structural thickness. The metallic OptiMALE wing-box is optimized with and without the increased load due to copper mesh weight. The increased load results in a wing-box structure heavier by 2.8 kg, which represent a 0.3 % increase in the wing-box mass[17].

The study presented in this Subsection is not integrated into the design process presented in Section V; therefore the actual impact on the overall aircraft design is certainly higher than the results obtained here due to the iterative update of the overall structural mass. In the near future, the lightning simulations will be also integrated with the design workflow through a surrogate model. Therefore the optimal copper mesh thickness will be defined by the optimizer accounting for the mass increase as well as for the lightning protection constraint.

C. Thermal risk analysis of the avionics bay

The thermal risk of the OBS depends on the cooling architecture defined for the avionics and electric compartments. In this paper, 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 [34]. Therefore, the preliminary thermal risk analyses enabled finding the optimal location of the inlet and outlet flow sources to minimize OBS thermal risks (Fig. 21). 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. 22). In future work, the thermal risk analysis will be integrated into the MDO workflow as an additional constraint to the optimization problem.

[17] The increase of the overall airframe mass due to the copper mesh is therefore 50.5 kg, which is the 2.5% of the airframe overall mass without copper mesh.

Downloaded by Marco Fioriti on March 20, 2023 | http://arc.aiaa.org | DOI: 10.2514/6.2021-3080

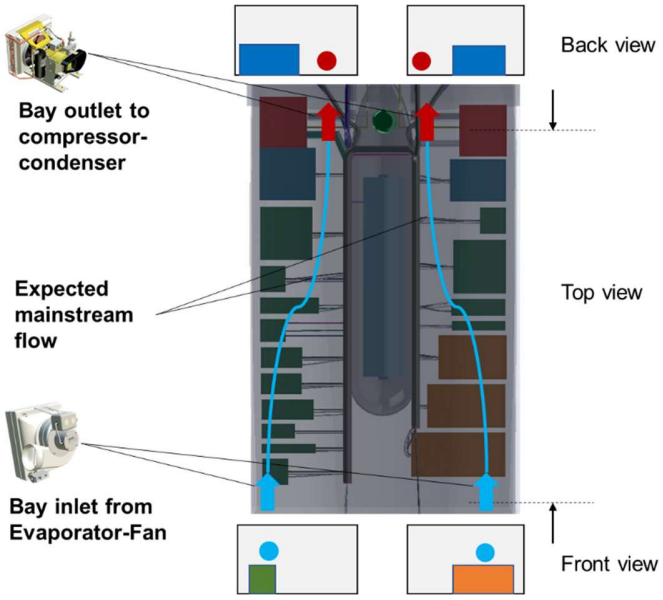

Fig. 21: Location of the ventilation sources

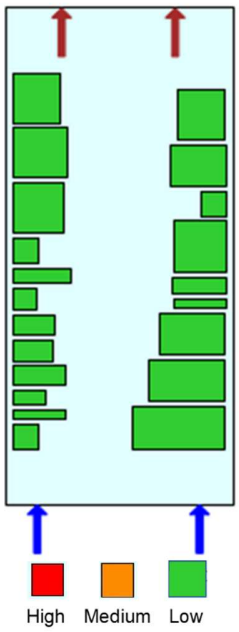

Fig. 22: Thermal risk predictions using pySysTher

VII. Conclusion and Outlook

This paper presents the certification-driven design process of the OptiMALE UAV configuration developed within the EU funded project AGILE 4.0, and the results obtained at the time of submission. The focus of the presented study is the inclusion in the preliminary aircraft design process of certification aspects which are usually considered in later design stages, like on-board systems design, lightning protection and thermal risk assessment.

The complexity associated with the enlarged design domain highlights the capabilities of the AGILE 4.0 framework. The requirement modeling allows to immediately identify the associated stakeholders from the detailed sub-system requirements. In particular, this paper shows the complete modeling of the avionics requirements. The connection between the requirements model, the design process capabilities, and the executed analysis is also shown in this paper, focusing again on the on-board systems domain. The multidisciplinary design workflow is automatically assembled starting from the input/output definition, allowing the automatic reconfiguration of the MDO tool chain.

In addition to the results obtained with the MDO workflow, two offline studies are presented: the analysis of the lightning protection and airframe sizing interaction, and the thermal risk analysis of the avionics bay. The studies show that the impact of electro-magnetic and thermal aspects on the OptiMALE design is not negligible and can lead to a more reliable solution since the early phases of the design process. The next step of the development of the OptiMALE design study within the AGILE 4.0 project will be the integration of both aspects into the MDO workflow.

A. Appendix: On-Board System Nomenclature

In this section, the avionics nomenclature is defined, as used in Tab. 4.

VHF/UHF radio	**Very High Frequency / Ultra High Frequency radio**
TCAS/ADS-B/trans	**Integrated module including: Traffic Collision Avoiding System/ Automatic Dependent Surveillance – Broadcast/ transponder**
VOR/ILS - DME-P	**Integrated module including VHF Ominidirectional Range / Instrument Landing System – Precision Distance Measuring Equiment**
EO/IR	**Electro-optic / Infrared turret**
SAR	**Synthetic Aperture Radar**
ADS	**Air Data System**
INS	**Inertial Navigation System**
FCC	**Flight Control Computer**
DLMC	**Data Link Management Computer**
WBDL (BLOS)	**Wide Band Data Link (Beyond Line of Sight)**
WBDL (LOS)	**Wide Band Data Link (Line of Sight)**
NBDL	**Narrow Band Data Link**

Tab. 5: Avionics nomenclature

Acknowledgments

The research presented in this paper has been performed in the framework of the AGILE 4.0 project (Towards cyber-physical collaborative aircraft development) and has received funding from the European Union Horizon 2020 Programme under grant agreement n◦ 815122. The authors are grateful to the partners of the AGILE 4.0 Consortium for their contribution and feedback.

For the contribution of Concordia University to the project, the authors acknowledge the financial support of the Natural Sciences and Engineering Research Council of Canada (NSERC), GrantNumber CRDPJ 538897-19 and R.G.P.I.N./5515-2019, and the Consortium de recherche et d'innovation en aérospatiale au Québec (CRIAQ). The authors are grateful to the partners of the AGILE 4.0 Consortium for their contribution and feedback.

Downloaded by Marco Fioriti on March 20, 2023 | http://arc.aiaa.org | DOI: 10.2514/6.2021-3080

VIII. References

[1] P. D. Ciampa and B. Nagel, "AGILE Paradigm: The next generation collaborative MDO for the development of aeronautical systems," *Progress in Aerospace Sciences,* vol. 119, p. 100643, 11 2020.

[2] P. D. Ciampa, P. S. Prakasha, F. Torrigiani, J.-N. Walther, T. Lefebvre, N. Bartoli, H. Timmermans, P. D. Vecchia, L. Stingo, D. Rajpal, I. van Gent, G. L. Rocca, M. Fioriti, G. Cerino, R. Maierl, D. Charbonnier, A. Jungo, B. Aigner, K. Anisimov, A. Mirzoyan and M. Voskuijl, "Streamlining Cross-Organizational Aircraft Development: Results from the AGILE Project," in *AIAA Aviation 2019 Forum*, 2019.

[3] P. D. Ciampa and B. Nagel, "Accelerating the Development of Complex Systems in Aeronautics via MBSE and MDAO: a Roadmap to Agility," in *in AIAA AVIATION 2021 FORUM, VIRTUAL EVENT*, 2021.

[4] R. Heinrich, Ed., AeroStruct: Enable and Learn How to Integrate Flexibility in Design, Springer International Publishing, 2018.

[5] S. Woehler, G. Atanasov, D. Silberhorn, B. Fröhler and T. Zill, "Preliminary Aircraft Design within a Multidisciplinary and Multifidelity Design Environment," in *Aerospace Europe Conference 2020*, 2020.

[6] T. W. Lukaczyk, A. D. Wendorff, M. Colonno, T. D. Economon, J. J. Alonso, T. H. Orra and C. Ilario, "SUAVE: An Open-Source Environment for Multi-Fidelity Conceptual Vehicle Design," in *16th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, 2015.

[7] L. A. Mccullers, "Aircraft configuration optimization including optimized flight profiles," 1984.

[8] L. Cavagna, S. Ricci and L. Travaglini, "NeoCASS: An Integrated Tool for Structural Sizing, Aeroelastic Analysis and MDO at Conceptual Design Level," in *AIAA Atmospheric Flight Mechanics Conference*, 2010.

[9] J. P. Jasa, J. T. Hwang and J. R. R. A. Martins, "Open-source coupled aerostructural optimization using Python," *Structural and Multidisciplinary Optimization,* vol. 57, p. 1815–1827, 2 2018.

[10] G. K. W. Kenway and J. R. R. A. Martins, "Multipoint High-Fidelity Aerostructural Optimization of a Transport Aircraft Configuration," *Journal of Aircraft,* vol. 51, p. 144–160, 1 2014.

[11] G. J. Kennedy and J. R. R. A. Martins, "A parallel finite-element framework for large-scale gradient-based design optimization of high-performance structures," *Finite Elements in Analysis and Design,* vol. 87, p. 56–73, 9 2014.

[12] D. Sarojini, J. Xie, Y. Cai, J. A. Corman and D. Mavris, "A Certification-Driven Platform for Multidisciplinary Design Space Exploration in Airframe Early Preliminary Design," in *AIAA AVIATION 2020 FORUM*, 2020.

[13] DLR, [Online]. Available: https://www.cpacs.de/. [Accessed 2021].

[14] R. Maierl, Ö. Petersson and F. Daoud, "Automated creation of aeroelastic optimization models from a parameterized geometry," in *15th International Forum on Aeroelasticity and Structural Dynamics, Bristol*, 2013.

[15] L. Boggero, P. D. Ciampa and B. Nagel, "An MBSE Architectural Framework for the Agile Definition of System Stakeholders, Needs and Requirements," in *AIAA Aviation*, Washington, 2021.

[16] [Online]. Available: https://www.eclipse.org/papyrus/. [Accessed 2021].

[17] European Union Aviation Safety Agency, Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes, EASA, 24 June 2020.

[18] [Online]. Available: https://www.eclipse.org/capella/. [Accessed 2021].

[19] G. Schuhmacher, F. Daoud, Ö. Peterson, M. Wagner, F. Brégier and B. Gerwert, "MULTIDISCIPLINARY AIRFRAME DESIGN OPTIMISATION," in *28th International Congress of the Aeronautical Sciences, ICAS*, 2012.

[20] CFSEngineering, "CEASIOMpy Documentation," [Online]. Available: https://ceasiompy.readthedocs.io/en/latest/.. [Accessed 27 May 2021].

[21] Airinnova, "PyTornado Documentation," [Online]. Available: https://pytornado.readthedocs.io/en/latest/.. [Accessed 27 May 2021].

[22] T. D. Economon, F. Palacios, S. R. Copeland, T. W. Lukaczyk and J. J. Alonso, "SU2: An Open-Source Suite for Multiphysics Simulation and Design," *AIAA Journal,* vol. 54, p. 828–846, 3 2016.

Downloaded by Marco Fioriti on March 20, 2023 | http://arc.aiaa.org | DOI: 10.2514/6.2021-3080

[23] G. W. H. van Es, "Rapid Estimation of the Zero-Lift Drag Coefficient of Transport Aircraft," *Journal of Aircraft,* vol. 39, p. 597–599, 7 2002.

[24] F. Torrigiani and P. D. Ciampa, "Development of an Unsteady Aeroelastic Module for a Collaborative Aircraft MDO," in *2018 Multidisciplinary Analysis and Optimization Conference*, 2018.

[25] L. Morino, "A General Theory of Unsteady Compressible Potential Aerodynamics," 1974.

[26] J.-N. Walther, A.-A. Gastaldi, R. Mairel, A. Jungo and M. Zhang, "INTEGRATION ASPECTS OF THE COLLABORATIVE AERO-STRUCTURAL DESIGN OF AN UNMANNED AERIAL VEHICLE," in *In Proceedings of DLRK*, Friedrichshafen, 2018.

[27] F. Torrigiani, R. Bombardieri, J.-N. Walther, R. Cavallaro and P. D. Ciampa, "Flutter Sensitivity Analysis for Wing Planform Optimization," in *International Forum on Aeroelasticity and Structural Dynamics 2019*, 2019.

[28] L. Morino, F. Mastroddi, R. D. Troia, G. L. Ghiringhelli and P. Mantegazza, "Matrix fraction approach for finite-state aerodynamic modeling," *AIAA Journal,* vol. 33, p. 703–711, 4 1995.

[29] P. Mantegazza and C. Cardani, "Continuation and direct solution of the flutter equation," *Computers & Structures,* vol. 8, p. 185–192, 4 1978.

[30] L. Boggero, M. Fioriti, S. Corpino and P. D. Ciampa, "On-Board Systems Preliminary Sizing in an Overall Aircraft Design Environment," in *17th AIAA Aviation Technology, Integration, and Operations Conference*, 2017.

[31] F. Tomasella, M. Fioriti, L. Boggero and S. Corpino, "Method for Estimation of Electrical Wiring Interconnection Systems in Preliminary Aircraft Design," *Journal of Aircraft,* vol. 56, p. 1259–1263, 5 2019.

[32] M. Fioriti, L. Boggero, S. Corpino, P. S. Prakasha, P. D. Ciampa and B. Nagel, "The Effect of Sub-systems Design Parameters on Preliminary Aircraft Design in a Multidisciplinary Design Environment," *Transportation Research Procedia,* vol. 29, p. 135–145, 2018.

[33] F. Sanchez and S. Liscouët-Hanke, "Thermal risk prediction methodology for conceptual design of aircraft equipment bays," *Aerospace Science and Technology,* vol. 104, p. 105946, 9 2020.

[34] F. Sanchez, A. M. Huzaifa and S. Liscouët-Hanke, "Ventilation considerations for an enhanced thermal risk prediction in aircraft conceptual design," *Aerospace Science and Technology,* vol. 108, p. 106401, 1 2021.

[35] P. D. Vecchia, L. Stingo, F. Nicolosi, A. D. Marco, G. Cerino, P. D. Ciampa, P. S. Prakasha, M. Fioriti, M. Zhang, A. Mirzoyan, B. Aigner and D. Charbonnier, "Advanced turboprop multidisciplinary design and optimization within AGILE project," in *2018 Aviation Technology, Integration, and Operations Conference*, 2018.

[36] S. Chiesa and M. Fioriti, "UAV Logistic Support Definition," in *Handbook of Unmanned Aerial Vehicles*, Springer Netherlands, 2014, p. 2565–2600.

[37] Dassault Systems, [Online]. Available: https://www.3ds.com/de/produkte-und-services/simulia/produkte/cst-studio-suite/. [Accessed 2020].

[38] EUROCAE ED-105, "Aircraft Lightning Test Methods," 2005.

[39] Radio Technical Commission for Aeronautics, "Environmental Conditions and Test Procedures for Airborne Equipment, DO-160," 2014.

[40] Dexmet Corp., "Expanded Material Configuration Chart".

Downloaded by Marco Fioriti on March 20, 2023 | http://arc.aiaa.org | DOI: 10.2514/6.2021-3080