D1.5 Reference Model Definition

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GA number:	815058
Project acronym:	FLIPASED
Project title:	FLIGHT PHASE ADAPTIVE AEROSERVO-ELASTIC AIRCRAFT DESIGN METHODS
Funding Scheme: H2020	**ID:** MG-3-1-2018
Latest version of Annex I:	1.1 released on 12/04/2019
Start date of project: 01/09/2019	**Duration:** 40 Months

Lead Beneficiary for this deliverable:	DLR
Last modified: 30/07/2021	**Status:** Submitted
Due date: 30/11/2020	

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Dissemination Level		
PU	Public	X
CO	Confidential, only for members of the consortium (including the Commission Services)	

“This document is part of a project that has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 815058.”

Glossary

ASE	Aeroservoelastic
AFS	Active Flutter Suppression
CAD	Computer-aided Design
CPACS	Common Parametric Aircraft Configuration Schema
DLM	Doublet Lattice Method
FE	Finite Element
GLA	Gust Load Alleviation
LPV	Linear Parameter-varying
LPI	Linear Time-invariant
MDAx	MDAO Workflow Design Accelerator
MDO	Multidisciplinary Design Optimization
MIMO	Multi-Input Multi-Output
MLA	Manoeuvre Load Alleviation
PID	Proportional-Integral-Derivative
RCE	Remote Component Environment
ROM	Reduced Order Model
TCL	Tool Command Language
W3C	Wold Wide Web Consortium
XDSM	Extended Design Structure Matrix
XML	Extensible Markup Language
XSD	XML Schema Definition
SMR	Short and Medium Range

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1 Executive Summary

The deliverable “D1.5 Reference Model Definition” lays the foundation for the scale-up task in WP4 of the project. In the beginning of the project, several key factors have been identified and objectives as well as performance metrics have been proposed to show the benefits of the MDO tool-chain developed within the project. The insights gained in the FLiPASED project during the flight test and the experience with the method and tools used for the design of active control technologies will then be applied to the design optimization of a full-scale aircraft. This document explorers the reference model alternatives, which are available for the research teams within the project. The model has to be suitable to apply the active control technologies and representative enough to show the benefits of the envisaged aero-servo-elastic optimization framework. During the optimization, a derivative aircraft based on the reference model will be designed. The pros and cons of the individual models will be detailed and the rationale for the final model selection will be presented. The main contributor of the deliverable is DLR, who has vast experience with aircraft simulation models. TUM, ONERA, and SZTAKI contributed significantly to the deliverable by exploring the integration of their methods and tools in connection with the reference aircraft.

2 Motivation

In order to show the benefits of including the Flight Phase Adaptive Aero-Servo-Elastic Aircraft Design Methods (FliPASED) in an integrated aircraft design, it is planned to demonstrate the performance claims in a scale-up task. As baseline reference for this scale-up task a Flexible Aircraft Benchmark will be defined in coordination with the industrial advisory board and used as the reference during the project. The resulting derivative aircraft will have a higher aspect ratio and therefore a more flexible wing. Aeroelastic tailoring will be applied to the CFRP wing structure in conjunction with active control augmentation, which is enabled by advanced avionics and a flight control architecture. Advanced Manoeuvre and Gust Load Alleviation functions will allow for a significantly reduced wing structural weight. Since high aspect ratio wings are more prone to flutter instabilities within the certification envelope, an Active Flutter Suppression will allow for further weight savings compared to classical open loop designs. Wing shape control reduces the drag in off design flight conditions and further increases the efficiency. The two main objectives of the scale up task are the demonstration of the applicability of the collaborative design process to a (full-scale) passenger aircraft and the quantification of the benefits of integrated aircraft and controls design in terms of structural weight reduction and aircraft over-all performance parameters. A comparison of traditional aircraft conceptual design can be seen on Figure 1, where aerodynamics and structures are optimized separately in a sequential order, and the resulting design will be sub-optimal (as shown in Fig. 2). It is well known now that coupled aeroelastic design should be done in a MDO framework, however very few results are available on coupled aero-servo-elastic MDO process, which is the key goal of FLiPASED.

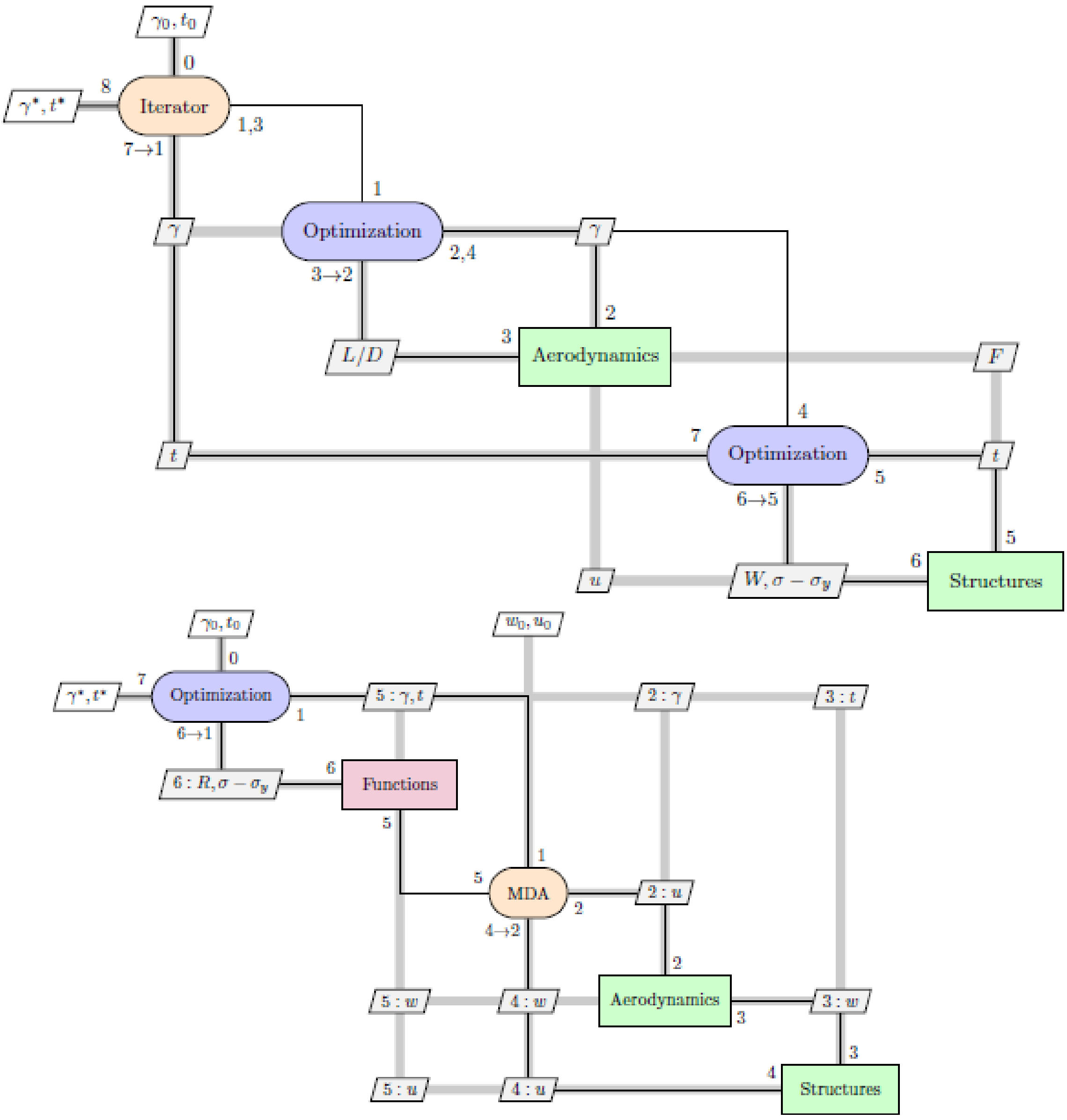

Figure 1: Sequential aero-elastic optimization vs. MDO framework [2]

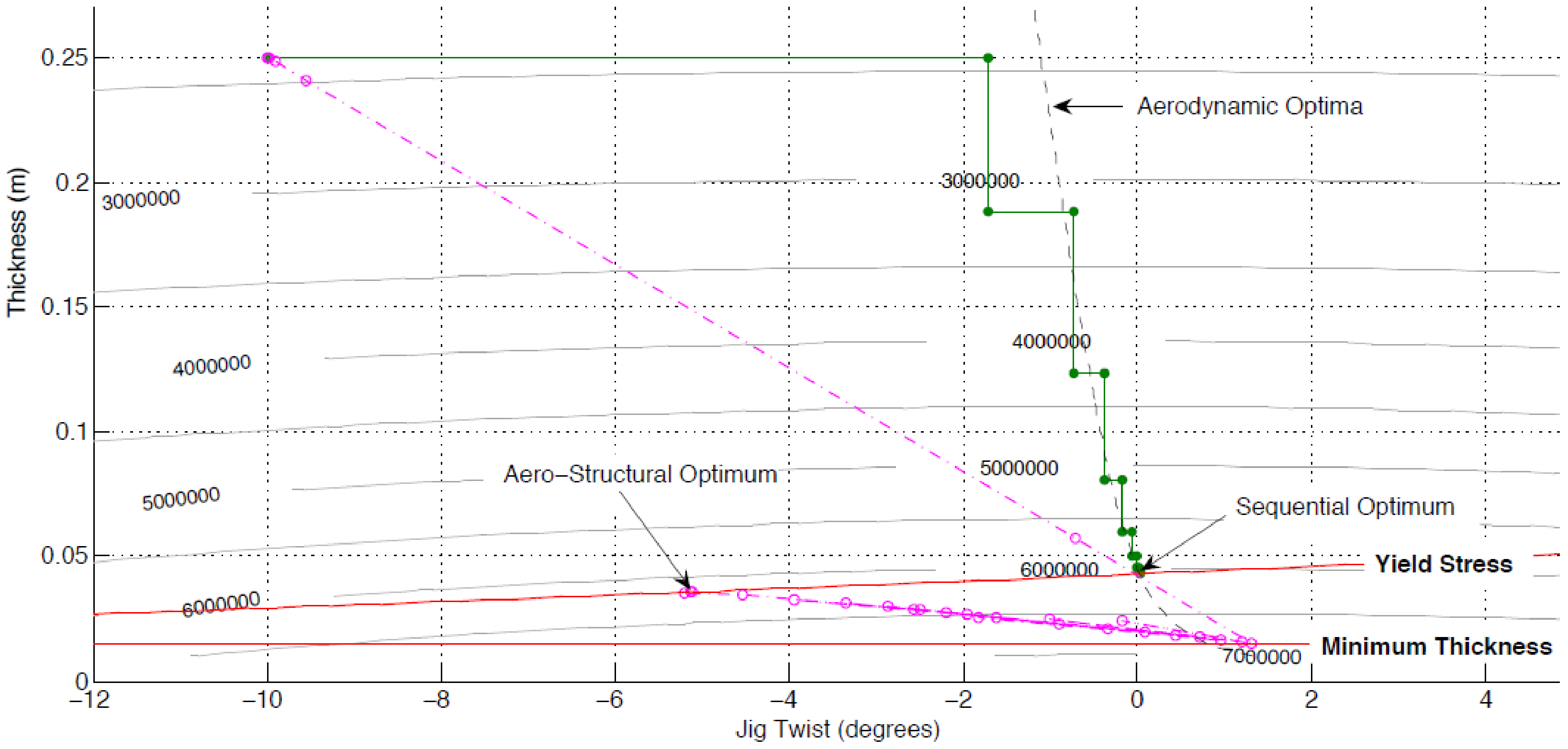

Figure 2: Iterations of sequential vs. global aero-elastic optimization (MDO) [2]

3 Scope of Scale up Task

The focus of the FliPASED project is on including control design as a primary discipline in a collaborative design workflow. Some previous experience is available within DLR, where a comprehensive load analysis process [9] is already included in projects like Digital-X and Victoria [4, 5]. Also, preliminary steps have been taken to consider active control systems within the design cycle [6]. The efforts within the FliPASED project mainly target the inclusion of the control technologies in the design workflow, while deemphasizing the aerodynamic design. The aerodynamics will consist mainly of low fidelity aerodynamics and methods based on potential flow theory. Hence, transonic effects like shocks and wave drag will not be considered in the scale-up task. This is a conscious decision in order to avoid overlap with other projects and to allow quick calculation times. Furthermore, no emphasis is placed on the choice of a particular MDO architecture. This distinguishes the approach in FliPASED compared to other efforts which mainly focus on aero-structural optimization [7] and therefore will demonstrate complementary capabilities. In the future, the findings of FliPASED may be integrated in MDO workflows, where more realistic aerodynamic properties are considered. In the project FliPASED the benefits of including active control technologies early in the design will be demonstrate rather than considering them as an afterthought.

4 Scale Up Objective Function

The overall objective function for the scale up task will be based on evaluation of mission criteria, such as range or blockfuel. This way two primary design goals can be addressed. The first goal is to minimize the aerodynamic drag. Specifically, the induced drag is addressed by high aspect ratio wing designs. However, the resulting slender wing structures tend to be very flexible and defueling the wing tanks change the mass distribution and in turn the shape of the wing. To counteract the detrimental effect on the induced aerodynamic drag, active wing shape control deflects the control surfaces to restore a drag optimal lift distribution for the changing wing mass. The second goal is to minimize the structural weight. This can be achieved by employing active load alleviation control laws to minimize design loads for manoeuvres as well as gusts and turbulence in combination with passive methods for load alleviation such as aeroelastic tailoring. Furthermore, the aforementioned high aspect ratio wings are more prone to an adverse fluid structure interaction called flutter. Conventionally, this is addressed by increasing the wing stiffness or placing additional mass in suitable locations. The employment of active flutter suppression allows to relax these stiffness requirements and therefore save weight. To assess the benefits of the mentioned active control technologies, the mission is analyzed at multiple points of the flight envelope and via various mission profiles, i.e. different mass cases due to defueling. The conjecture is that inclusion of active control theory in the design phase leads to very different wing designs and a large overall fuel savings.

5 Differences between Demonstrator and the Scale up Workflow

The workflow that is setup in WP2, initially addresses the design of wings for the demonstrator. The objective there is to maximize the difference between open loop and closed loop performance of the individual control functions in order to assess and validate their benefits by flight test. Fuel burn and minimal weight are not primary design objectives. For the scale up task, a passenger aircraft is considered. The design objectives have been described in the previous section. Apart from the differing objective functions, the most notable difference of the demonstrator workflow, is that the structure is now sized by the loads, i.e. the employed control functions have a direct impact on the overall weight of the structure. The updated stiffness and mass properties therefore make a convergence loop necessary. Figure 3 shows an early version of the envisaged scale-up workflow. The XDSM diagram shows a convergence loop including structural sizing, controller design of the various functions and the loads analysis of the closed loop aircraft.

A further complication arises, as the CATIA based structural model generation is targeted towards the demonstrator wing. It will be investigated how this model generation process can be adapted to a transport aircraft wing. As contingency, an alternative model generation module (CPACS-MONA) is available at DLR Institute of Aeroelasticity. This module has been used in several MDO workflows before.

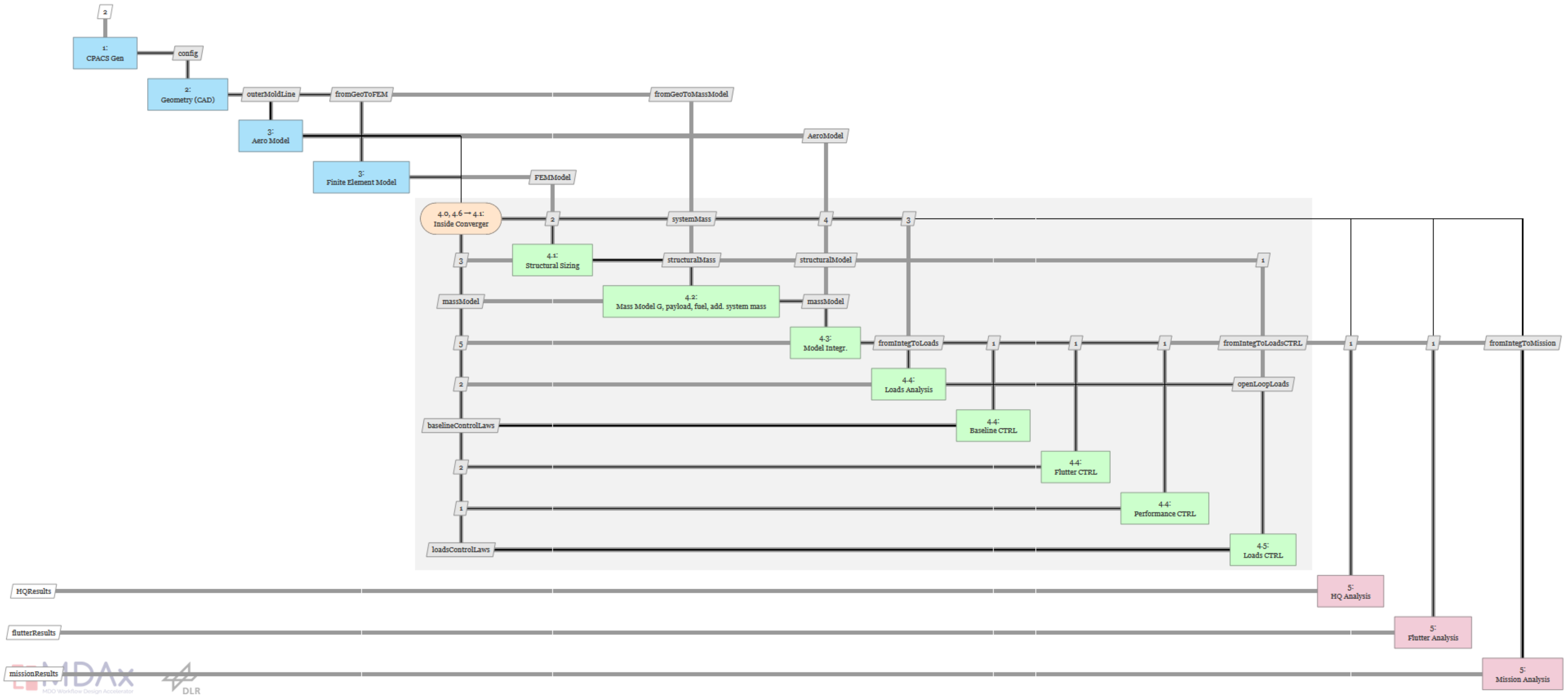

Figure 3: XDSM of scale-up workflow

6 Reference Model Candidates

The intention of the scale-up task is to start from an already feasible, optimized aircraft baseline and show the potential benefits of the ASE MDO workflow with respect to the current state of art. For this reason it is important to have a model which includes all the components necessary for aerodynamic, structural and control evaluation. The team do not want to design a new aircraft, just apply control design technologies to a high aspect ratio variant of the reference model. For the scale-up task, the following models were considered as potential reference configurations. A brief description of each of the models together with their potential benefits and drawbacks are listed below.

6.1 XRF1: Airbus eXternal Research Forum Model (A330 like)

The XRF1 Model is a multidisciplinary aircraft model which is intended to further development and validation of flight physics and broader multi-disciplinary technologies by the external research community. The XRF1 model can be released to research establishments under the terms and conditions of a Framework Non Disclosure Agreement (FNDA). The DLR used this model in several MDO related projects and the FP7 EU project Smart Fixed Wing Aircraft. A parameterization in CPACS format is available and could be used.

Figure 4: Airbus XRF1 FEM model

For:

- Experience at many research establishments across several projects with the XRF1 model
- Mature aircraft dynamic model
- Has also been used for scale-up studies in FLEXOP

Against:

- NDA required from partners using the model
- Rules pertaining to IT security apply
- Restrictions on publications apply

6.2 CRM: NASA Common Research Model (B777 like)

In order to improve the state-of-the-art in computational fluid dynamics, Langley Research Center and Ames Research Center of NASA joined forces to produce data sets using the same research model – the Common Research Model. Using the same Mach numbers and model configurations, they have been able to gather data that is provided to the worldwide research community. One of the main aim of the CRM model is to investigate CFD methods, hence the Common Research Model Wing/Body and Wing/Body/Tail configurations have been used on the drag prediction workshops of NASA since 2009. Details of the model are initially reported in [11], but further research expanded the model to a higher aspect ratio version (uCRM-13.5) for very flexible wing design studies. The following components are available as open source:

- Geometry files for the wing-body-htail configuration of each aircraft (IGES/TIN)
- Aerodynamic mesh files for the wing-body-htail configuration of each aircraft, both in multi-block and overset format (CGNS)
- Structural mesh files for the aluminum wingbox structure including material properties based on a smeared stiffness blade-stiffened panel approach, external control surface and engine masses, and aerodynamic loads for nominal cruise (BDF)
- Reference solutions using the MACH framework and NASTRAN

For:

- Free-to-use CAD model of aircraft
- Structural model available at DLR-AE (FERMAT configuration)
- Aero-loft suitable for high-fidelity CFD

Against:

- CPACS dataset unavailable
- Lesser experience with this configuration in the consortium compared with the other models
- Boeing/NASA-initiated model

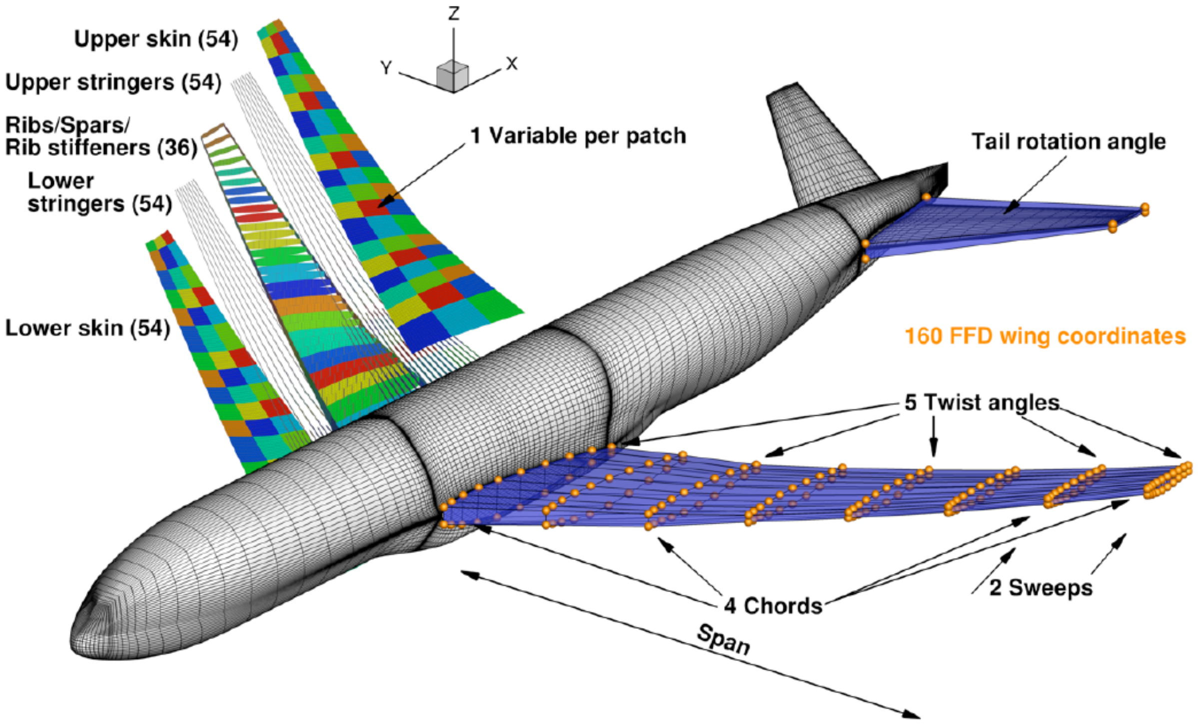

Figure 5: The aerodynamic and structural sizing design variables of the CRM MDO model [10]

6.3 D150: DLR 150Pax Model (A320 like)

The D150 configuration was developed within the DLR project VAMP [12]. It is comparable to the Airbus A320-200. Data published by the manufacturer, for example on the Airbus website, and input data to the preliminary design program PrADO for the application example Airbus A320, are used for the D150 configuration [8]. Its geometry is shown in Figure 6.

Table 1 lists the general parameters of the D150 configuration. The cruise speed V_C and cruise Mach number M_C are set to the maximum operational speeds V_{MO} and M_{MO}. The values for V_{MO} and M_{MO} for the Airbus A320 can be found in the EASA Type-Certificate Data Sheet [3]. The dive speed V_D can be calculated using the diagram of worksheet LTH BM 32 100-05 of the Luftfahrttechnischen Handbuch (LTH), and the dive Mach number $M_D = M_C + 0.07$ from the Acceptable Means of Compliance AMC 25.335(b)(2) of CS25.

The three airfoil profiles used for the four profile sections, using which the planform geometry is built, originate from the geometry of the DLR-F6 configuration. The DLR-F6 configuration is similar to the geometry of the Airbus A320 and was developed in the 1980s as a publicly-available geometry for aerodynamic studies.

For:

- DLR-proprietary configuration
- Relevance to industry - short/medium-range (SMR) configuration
- CPACS dataset available and maintained across various project developments

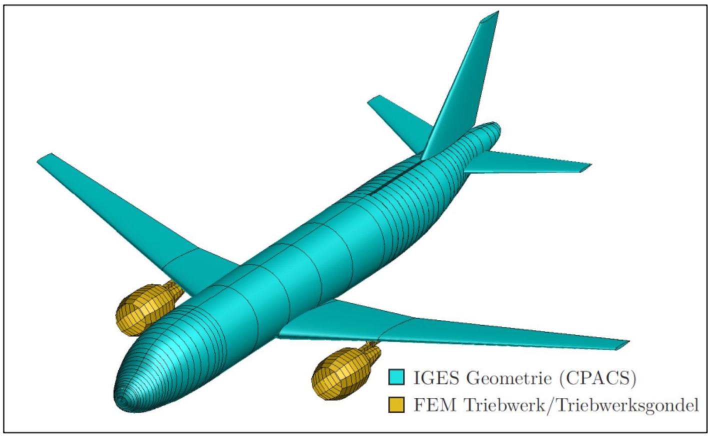

Figure 6: IGES-geometry of the D150-configuration

Wing	
Surface area	$122.3m^2$
Span	$33.91m$
Reference chord	$4.19m$
Aspect ratio	9.4
Taper ratio	0.246
Sweep angle at 25% chord line	24.94^o
HTP	
Area	$30.98m^2$
Span	$12.45m$
Aspect ratio	5.0
Taper ratio	0.33
Sweep angle at 25% chord line	28.0^o
VTP	
Area	$21.51m^2$
Span	$5.87m$
Aspect ratio	1.6
Taper ratio	0.35
Sweep angle at 25% chord line	35.0^o
Operational empty weight (OEM)	$40638kg$
Maximum zero-fuel weight (MZFM)	$60500kg$
Maximum take-off weight (MTOM)	$72500kg$
Cruise Mach number	0.78
Cruise speed / Mach number	$180m/s$ EAS, Mach 0.82
Dive speed / Mach number	$209m/s$ EAS, Mach 0.89
Maximum flight level	$12500m$

Table 1: Main parameters of the D150-configuration

- Experience from several other projects involving D150 model
- No restrictions pertaining to publication

Against:

- Aero-loft not suitable for CFD simulations - aerodynamics restricted to potential flow methods

7 Reference Model Choice and Impact

From the considered choice of models discussed in the earlier chapter, the DLR-D150 was selected by the consortium as the preferred reference model for the scale-up task.

The primary rationale for choosing the D150 is its relevance to industry and parallel on-going research activities in different projects, ie. in a next-generation SMR aircraft. An A320-like configuration is considered to be short and medium range and well-suited for this classification. Moreover, the D150 being a DLR-proprietary model, the availability of a CPACS dataset and freedom pertaining to publications are advantageous.

The drawback of not having a good enough aero loft to carry out CFD simulations as in the case of the D150, is mitigated by the fact that only potential flow methods are intended to be employed. The target performance optimization goal in FLiPASED is only the reduction of induced drag, i.e. drag due to lift distribution and not wave drag and airfoil optimization.

7.1 Relevance to research community/industry

The decision to choose the DLR-D150 is in line with multiple local on-going initiatives and projects. Among others, one can count:

- VirEnfREI-DLR - LuFo funded project involving DLR and Airbus. The project involves establishing an MDO framework for aircraft design, considering industrial requirements and its application to the design of an SMR aircraft. The optimized configuration is to be tested under flight conditions in a transonic wind-tunnel.
- MuStHaF-DLR - LuFo funded project involving DLR institutes. The project is targeted towards future high aspect ratio SMR aircraft configurations considering different wing technologies - multi-functional control surfaces, control algorithms for active flutter suppression, online flutter stability monitoring, among others. A selection of the developed technologies are to be tested in a flying demonstrator of a scaled SMR aircraft wing.
- MAJESTIC - DGAC funded project involving ONERA and Airbus. It is concerned with the aeroelastic modelling methodology and control design for flutter phenomena. The considered use-case is a generic single aisle high aspect ratio configuration.

Apart from this, Dassault-Aviation, a member of the Scientific Advisory Group in FLIPASED, had expressed interest during the initial phase of the project in a potential narrow-body aircraft for scale-up studies as opposed to wide-body aircraft, given their product portfolio in business-jets.

7.2 Impact of reference aircraft on other WPs

The consortium also considered the impact of reference model choice on the rest of Tasks in ever WP - at least in a broad manner depending the choice of Single Aisle or a Wide Body aircraft was discussed and an unanimous decision was made to focus on a single aisle aircraft what is more relevant to the industrial partners of the consortium members.
WP1 is unaffected by the choice of the reference aircraft. Task 1.3 Collaborative Work Process is the same for the conceptual design of a business jet, single or twin aisle aircraft. The MDO work process has slightly different mission profile but that is only a small parameter change in the overall framework.

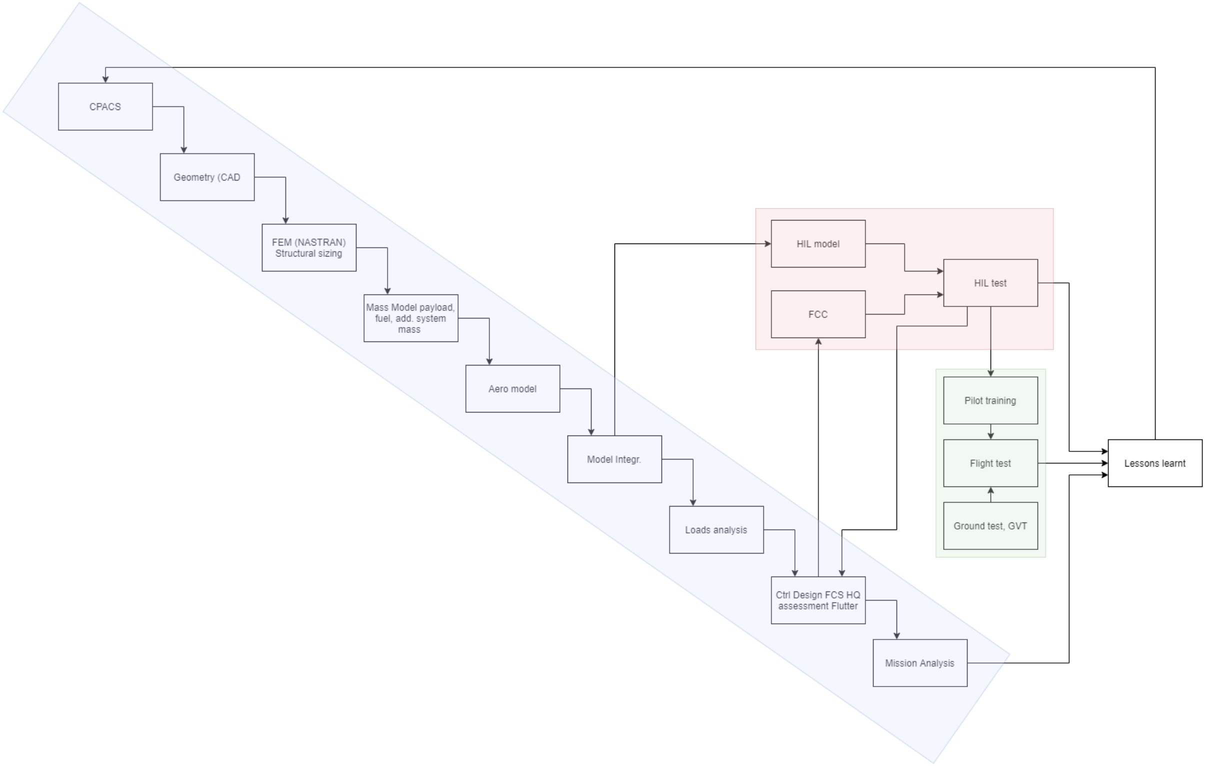

Figure 7: Workflow and inter dependency of tasks within FLiPASED (blue: MDO toolchain, red: simulation based testing and evaluation, green: physical testing)

Task 1.4 Data Analytics for Model Validation is also unaffected by the choice of aircraft, since it only focuses on analyzing the results. It might be possible that the consortium is able to achieve lower fuel efficiency improvements due to shorter wingspan or lower number of individual flight control surfaces fitted to the wing (in comparison to a widebody airplane), but the analysis tools will be unaffected. Within WP2 several tasks are connected to both the demonstartor and to the scale-up task, namely Task 2.1: Tool Adaptation: Structural Design, Task 2.2: Tool Adaptation: Aerodynamics, Task 2.3: Tool Adaptation: Aeroelasticity, Task 2.4: Tool Adaptation: Movables Design, Task 2.5: Tool Adaptation: Control Design . These are all using the same software framework for the demonstrator and the scale-up workflow, but their parameters and their fine tuning are different. These generic tools have for example the aircraft geometry (CAD) as an input parameter and they provide outputs based on the user defined tuning knob settings. For example the FEM model might have condensation points every 10 cm or at every 100 cm. Hence a large 65 m wingspan aircraft might be represented by fewer condensation points than a 7 m wingspan demonstrator. Also, the number and location of the sensors and flight control actuators are just a parameter for the on-board, model-based, flight control system. The tools developed within WP2 are generic in a sense that both workflows (and different aircraft configurations within each workflow) use them with the adequate parameter settings. It might be possible that in the demonstrator workflow fuel level and c.g. position do not play such an important role, that every model and every tool has to account for fuel variation, but changes in the velocity are already captured and hence the tools are meant to handle parameter variations within the workflows. Within the scale-up workflow these variations are more pronounced but they are only quantitatively different no fundamental change are foreseen between them.

WP3 contains all activities related to the physical testing of the demonstrator. The overall activities are

Figure 8: Flight control surfaces of the Airbus A320 family, as well as the D150

performed to validate the predictions and provide feedback about the performance of the tools within the MDO toolchain. There is no direct feedback between the demonstrator flight test results and the scale-up task. It is the aim of the consortium to mature the tools via lessons learnt within the flight test campaign, as seen in Figure 7, but it is not possible to characterize the type and impact of the feedback before evaluating the toolchain results and the demonstrator flights. The impact on the scale-up workflow is even more distant, since lessons learnt during the flight test will provide indirect feedback to a large SMR or widebody aircraft, hence the choice of reference aircraft being 70 m or 35 m in wingspan has no direct impact on the tasks within WP3.

Tasks within WP4 are directly impacted by the choice of the scale-up model, and since the project is delayed due to difficulties in the flight test campaign, as well as due to the pandemic, the consortium selected the model which involves the least amount of uncertainty. This being the DLR internal D150 model, where Task 4.1: Aircraft design objectives is significantly helped by the ongoing and newly launched projects of DLR and ONERA, where the interest of their industrial partner Airbus lies in the SMR aircraft domain. It is foreseen that synergies between FLiPASED and these projects could be leveraged and design objective setup will receive feedback from Airbus and Dassault. Task 4.2: Implementation of reference A/C data into tool chain is also heavily impacted by the choice of this decision, since large part of the D150 dataset are already in the CPACS format, what is the descriptor language for the FLiPASED toolchain. Moreover, both DLR-AE and DLR-SR has working experience with these models. In principle the most profound changes in the existing D150 and the one needed for the demonstration of enhancements in FLiPASED are the addition of flaps, sensors and actuators on the wing. These have to be incorporated into any scale-up aircraft model, since public models of the XRF1 and CRM both have the standard, limited number of, flight control surfaces and no inertial sensors within the wing. These additions will be incorporated into the D150 derivative, where minimum size of actuators and wing thickness might restrict the consortium to split the most outer ailerons into 2 pieces instead of 4 individual pieces, what could have been feasible on an A350 sized wing. The consortium is well aware of the fact that even 8 individual trailing edge primary flight control surfaces on an SMR aircraft will lead to more optimized wing shape, and will allow more tailored load alleviation, as well as flutter mitigation and drag optimization in comparison to the single aileron on the A320 wing (see Fig. 8). While it might be possible to fit 16 ailerons to the trailing edge of an A350 size aircraft (see Fig. 9), the incremental effects of 8 vs. 16 ailerons on the wing will be less pronounced than fitting 2 vs. 4 ailerons [1].

Figure 9: Flight control surfaces of a state-of-art widebody aircraft (Airbus A350)

Task 4.3: Development of avionics Systems Architecture for reference A/C will be also mainly unaffected by the choice of the reference aircraft. As stated above the size, weight and power requirements of the actuators fitted in a lower thickness SMR aircraft might allow less individual control surfaces (i.e. 8 instead of 16) but we foresee a highly over-actuated system with large number of redundant control surfaces where similar issues have to be solved in the 8 or 16 actuator case. On the other hand we do not see a similar limiting constraint in the sensor placement problem. Task 4.4 concerns the design study itself. Since SMR aircraft has lower range it might be beneficial from simulation time perspective to choose this instead of a long range aircraft. It is not clear for the consortium at the moment what type and how many simulation runs will be performed after each iteration cycle, but the overall methodology with distinctive load cases and gust encounters to assess the performance of the load alleviation functions will be the same irrespective of the aircraft type. We intend to run hundreds of simulation points instead of the few cases listed in the certification requirements of EASA, since the active control functions can be evaluated only in a dynamic setting. System benefit assessment (Task 4.5) will be also mostly unaffected by the choice of medium or long range aircraft, since the baseline performance and the outcome of the optimization, in terms of performance gains, increase in complexity, certification effort, and overall design effort will be compared.

8 Conclusion

The Deliverable D1.5 pertains to the selection of a reference model for the scale-up task in WP4 within FLIPASED. The scale-up task involves an integrated aircraft design workflo, enabled using an MDO approach involving aeroelastic tailoring for the optimization of the wing structure in conjunction with active control augmentation for load alleviation, flutter suppression and wing shape control, leading to direct drag reduction.

The DLR-D150 model is chosen as the baseline reference for this scale-up task. The primary motivation behind the selection is its relevance to both industry and parallel on-going projects along several national fronts, ie. in an SMR aircraft, as well as its maturity and availability for the consortium members. The studies performed within the scale-up will be beneficial in demonstrating the benefits of including mature-levels of active control technologies right from an early preliminary design phase of aircraft development, rather than considering as a subsequent design step inherently leading to more sub-optimal solutions.

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