D4.1 Scale-up Design Objectives

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Glossary

ADEBO	Aircraft Design Box
ASE	Aeroservoelastic
AFS	Active Flutter Suppression
CAD	Computer-aided Design
CFD	Computational Fluid Dynamics
CFRP	carbon-fiber-reinforced polymers
CPACS	Common Parametric Aircraft Configuration Schema
EAS	Equivalent Airspeed
FCC	Flight Control Computer
GFEM	Global Finite Element Model
GLA	Gust Load Alleviation
HIL	Hardware-in-the-Loop
HTP	Horizontal Tail Plane
LTI	Linear Time-invariant
MDO	Multidisciplinary Design Optimization
MLA	Manoeuvre Load Alleviation
PDF	Portable Document Format
PID	Proportional-Integral-Derivative
RCE	Remote Component Environment
SAS	Stability Augmentation System
SFC	Specific Fuel Consumption
SMR	Short and Medium Range
SUAVE	Stanford University Aerospace Vehicle Environment
UAV	Unmanned Aerial Vehicle
UNICADO	University Conceptual Aircraft Design and Optimization
VTP	Vertical Tail Plane

Table of contents

List of Figures

1 Executive Summary

The deliverable “D4.1 Scale-up Design Objectives” explains the main idea of 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 Multidisciplinary Design Optimization (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 explains what the consortium envisions to be a well interacting workflow to achieve an improved aircraft design. With the use of passive and active load alleviation methods, wing shape control for drag reduction and active flutter suppression (AFS) for maintaining stability, it is expected to reduce the structural weight and drag of the aircraft with respect to a reference configuration. Hence, the maximization of the range is found to be the ideal overall objective of the optimization process. The full-scale aircraft considered is the D150 which is an A320-like short and medium range (SMR) aircraft with a high significance for industry. In this document, it is also shown how the active structural control methods can be validated on the demonstrator aircraft in flight. The main contributor of the deliverable is DLR, who has experience with MDO. TUM, ONERA and SZTAKI contributed significantly to the deliverable by exploring the integration of their methods and tools in connection with the overall scale-up workflow.

2 Motivation (DLR-SR)

To show the benefits of Flight Phase Adaptive Aero-Servo-Elastic Aircraft Design Methods in an integrated aircraft design the performance claims should be demonstrated in a scale-up task. The D150 aircraft was defined as a Flexible Aircraft Benchmark and is therefore used as the baseline reference for this scale-up task. A derivative aircraft, which is a product from the collaborative workflow will exhibit a higher aspect ratio leading to a more flexible wing. Aeroelastic tailoring will be applied to the carbon-fiber-reinforced polymers (CFRP) wing structure in conjunction with active control augmentation, which requires an advanced flight control architecture. Through application of manoeuvre load alleviation (MLA) and gust load alleviation (GLA) functions the wing structural weight tends to reduce. High aspect ratio wings are more prone to flutter instabilities within the certification envelope. AFS will allow for further weight savings compared to classical designs, as it is assumed that the certification margins will be relaxed in the future. Furthermore, wing shape control, which is mostly associated with the introduction of many individually actuated trailing edge flaps [3], offers the opportunity to reduce the drag in design flight conditions and thus increase the efficiency. The main objectives of the scale-up task are demonstrating the applicability of the collaborative design process to a passenger aircraft and the evaluation of the benefits of aircraft with and without active structural control with respect to structural weight reduction and aircraft performance parameters.

3 Scope of Scale-up Task (ALL)

The focus of FliPASED is to include primary and secondary flight control in a collaborative workflow. Within DLR previous experience has been gained in projects like Digital-X and Victoria [4, 5], where a comprehensive load analysis process [10] is set-up. Furthermore, steps have been taken to incorporate active control systems within the design cycle [7]. While the efforts within FliPASED deemphasize the aerodynamic design, they mainly target the inclusion of the control technologies in the design workflow. The aerodynamics will consist primarily of low fidelity aerodynamics, like methods based on potential flow theory. Therefore, transonic effects like shocks and wave drag are neglected in the scale-up task. This was decided 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 taken in FliPASED compared to efforts mainly focusing on aero-structural optimization [8]. Hence, complementary capabilities will be demonstrated. The findings of FliPASED may be integrated in MDO workflows, where more realistic aerodynamic properties are considered, in the future. Goal of FliPASED is to demonstrate the benefits of including active control technologies early in the design rather than considering them as an afterthought.

3.1 Interactive Workflow of Scale-up task (ALL)

The Scale-up task includes many different tools which have to be connected. The interactive workflow is depicted in Figure 1. At first the aspect ratio is the considered input parameter. The different blocks are described below.

3.1.1 CPACS dataset and conceptual analysis (TUM)

The CPACS dataset of D150 is already available. Depending on the design freedom, the corresponding variables will be updated by a Python script using Tixi library during the optimisation.

Before the CPACS dataset flows into next block for aeroelastic modelling, the configuration needs to be checked in a conceptual design block to see if it is feasible with regard to flight dynamics. Different tools like in-house tools ADEBO and UNICADO [14], open source tool SUAVE [12] will be compared to investigate which is capable of this task and can be easily integrated into a MDO toolchain. After the feasibility check, the configuration can be fed for aeroservoelastic modelling.

3.1.2 cpacs-MONA (DLR-AE)

The parameterized aeroelastic structural design process cpacs-MONA is used for the scale-up task within FLIPASED. The tool is used to perform a simultaneous structural and aeroelastic design of the load carrying structure of an aircraft configuration. The process includes preliminary mass and loads estimation based on conceptual design methods followed by a parameterized set-up of simulation models and an optimization model. These models are used for a comprehensive loads analysis followed by a component wise structural optimization. The latter takes stress, strain, buckling and control surface efficiency as constraints into account. The detailed structural modelling allows also for the use of well-established structural optimization methods. The data basis for the simulation models and the various analyses is a suitable CPACS dataset.

A schematic of the different tools incorporated within cpacs-MONA are shown in Figure 2.

The input to the cpacs-MONA block during the first iteration is a CPACS dataset. The CPACS dataset describes a wide range of characteristics of the aircraft, like the geometry, global aircraft parameter, the structural construction concept, material data etc., in a structured, hierarchical manner. cpacs-MONA reads from the CPACS dataset information about the wing planform, the wing topology like ribs, spars

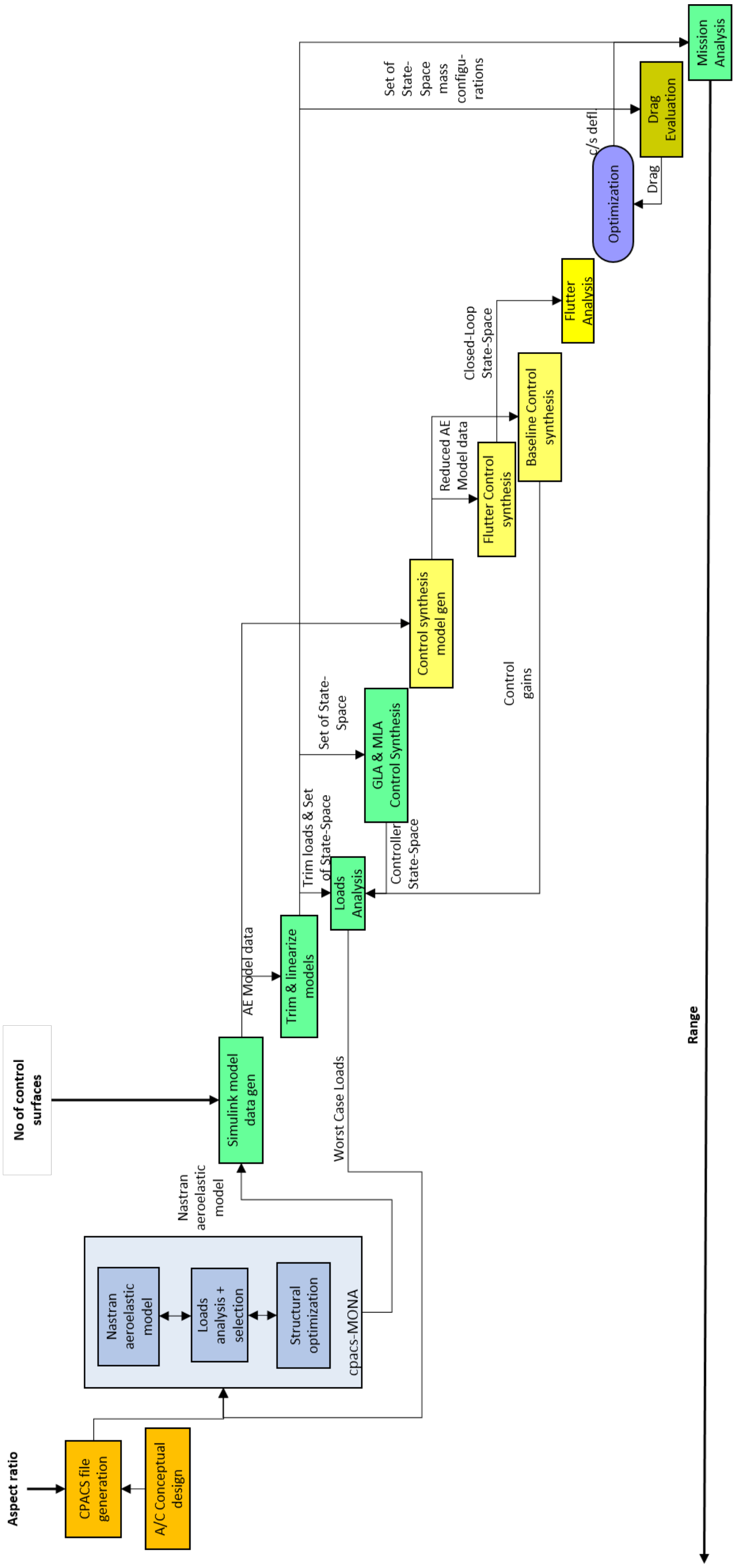

Figure 1: Diagram of the scale-up Workflow

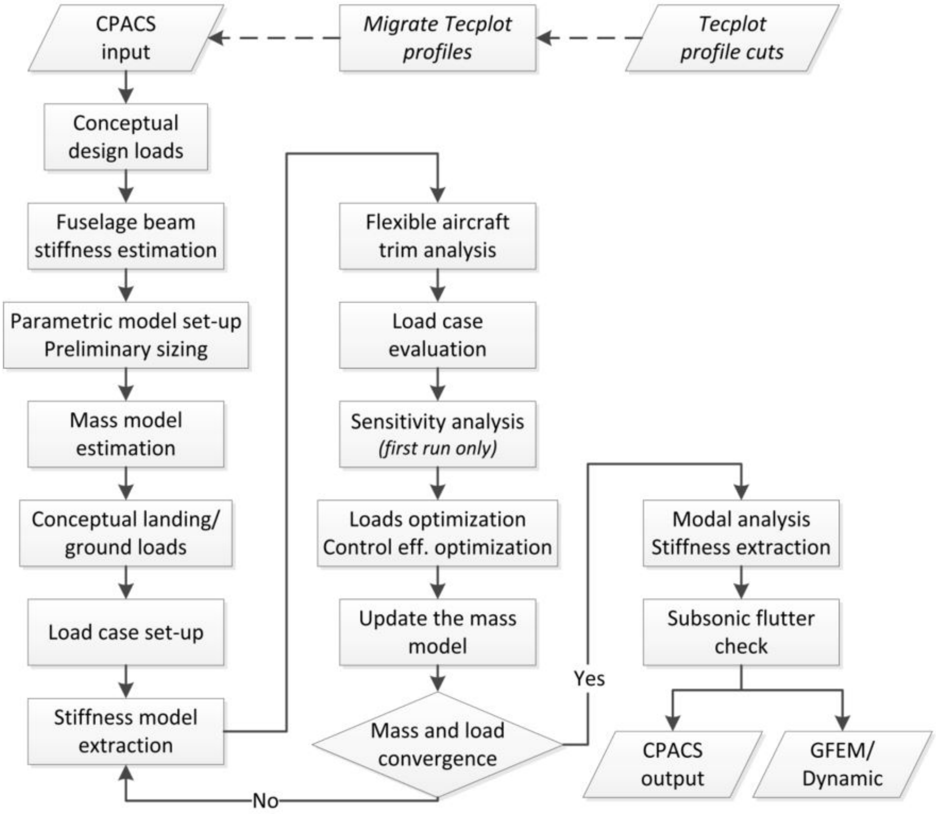

Figure 2: Process flow of cpacs-MONA

and stringer positions and initial thicknesses together with the engine, pylon and landing gear positions and dimensions. It also uses information about aircraft masses like design, primary and secondary masses plus the dimensions of the control surfaces and fuel tanks. As optional input Tecplot profile cuts from the outer geometry of the aircraft's wings and the engine, generated from a CAD-model, can be extracted. The profile cuts will then be migrated into the existing CPACS dataset and the outer shape of the engine and its center of gravity will be updated.

The output from this block are the necessary NASTRAN decks required to perfrom aeroelastic loads analyses. This NASTRAN aeroelastic model corresponds to the design that has been structurally optimized using the loads obtained from the loads process within cpacs-MONA.

From the second iteration onwards, the loads calculated within cpacs-MONA are appended with loads received from the loads analysis block developed by DLR-SR. A selection of the critical loads is performed and these selected loads from the merged loadset are used for the structural optimization, whereafter the NASTRAN aeroelastic model is provided as an output.

In Figure 2, a few of the primary blocks within cpacs-MONA are highlighted for better understanding.

3.1.3 Simulink Model Data Generation (DLR-SR)

The block ”Simulink Model Data Generation” receives Nastran decks from the ”cpacs-MONA” block. It then extracts the information and calculates the relevant aeroelastic model data by means of a Matlab based tool [6]. Subsequently, the aeroelastic model data provided can be used by block ”Trim and linearize models” to determine different operating conditions and linerize the Simulink model of the scale-up aircraft. Furthermore, simulation included in the block ”Loads Analysis” can be run and models for controller synthesis can be generated by ”Control synthesis model generation”.
At first the number of control surfaces is fixed. If it is considered a design variable at a later stage, it can be adapted in this block.

3.1.4 Trim and Linearize Models (DLR-SR)

As mentioned before this block receives aeroelastic model data from the ”Simulink Model Data Generation” block. By means of a Matlab Simulink based aircraft model it trims and linearizes for different operting points. For the ”Loads Analysis” block trim loads are calculated. The ”GLA and MLA Control Synthesis” block receives linearized models for the synthesis of GLA and MLA control laws and both the ”Drag Evaluation” and ”Mission Analysis” block require a set of state-space models relating to different mass cases within cruise. This set represents discrete points of the defueling process.

3.1.5 Loads Analysis (DLR-SR)

The ”Loads Analysis” block calculates the worst case loads of the closed-loop system with the GLA and baseline controller active. That is why the GLA controller state-space system and the baseline controller gains are fed to the loads analysis. Furthermore, this block receives state-space models corresponding to a grid of flight conditions of the open-loop system and the trimmed loads in order to linearly simulate different gust encounters. At various monitoring points the loads of the gust simulations are observed. Adding them with the trimmed loads and extracting the maximum loads yields the worst case loads. As a first step the activity of the MLA and flutter controller are neglected. Fundamentally, however, all control law functions affect the loads. The worst case loads are fed back to the ”Structural Sizing” block. By doing so, a convergence loop is closed, which provides the opportunity to adapt the material properties, either by strengthening the structure or decreasing the weight and downsizing the structural properties.

3.1.6 GLA and MLA Control Synthesis (DLR-SR, ONERA)

The ”GLA and MLA Control Synthesis” block receives a set of state-space models corresponding to different flight conditions. For the synthesis of the GLA controller the state-space models are prepared

by selecting the relevant inputs and outputs, reducing the model order and normalizing the inputs and outputs. In the sequel a GLA controller is determined by means of the structured H_∞ method. The resulting controller is then passed to the ”Loads Analysis” block.
For the synthesis of the MLA controller design, the state-space models are prepared by selecting the relevant inputs and outputs; including the input/output delays, reducing the model order and normalizing the inputs and outputs. The MLA controller is computed in a fully automatic manner by simply setting the time-response expected to the manoeuvre. The controller is synthesized by means of the structured H_∞ method. The resulting controller is then passed to the ”Loads Analysis” block.

3.1.7 Control Synthesis Model Generation (SZTAKI)

Separate models are developed for the baseline and the flutter suppression control design. Both models are based on the Simulink Model Data Generation block of DLR-SR. This block uses the same Simulink structure, however, the structural dynamics and the unsteady aerodynamics subsystems are reduced. Therefore, in addition to the Simulink files, this block requires the K_{hh}, M_{hh} and Q_{hh} data of the structural dynamics and aerodynamics. The reduction is done based on the bottom-up modeling approach ([15, 16]) which provides a sufficiently low order model for the control design. A set of linear time-invariant (LTI) models at different flight conditions is obtained by trimming and linearizing the nonlinear Simulink block. This set of models is saved as a mat file with name FlexACModel. The baseline controller accepts the rigid body, 12 state linearized models as input. This model is obtained from the FlexACModel by residualizing the unsteady aerodynamics and flexible states. This model is saved as a mat file with name RigACModel. The two sets of LTI state space models are the outputs of the block. These outputs are used by the Flutter Control Synthesis and the Baseline Control Synthesis blocks, respectively.

3.1.8 Flutter Control Synthesis (SZTAKI)

The flutter suppression control design is based on the FlexACModel. First, the corresponding inputs and outputs are selected. Then, an LTI H_∞ controller ([13]) is designed for the flutter suppression and the block sets the controller as a state space model at the output in a mat file. The flutter suppression controller is utilized by the Flutter Analysis Block.

3.1.9 Baseline Control Synthesis (SZTAKI)

The baseline controllers are designed via successive loop closure ([11]) based on the RigACModel as the input of the block. The PID structure of the block is fixed and the block saves the Simulink block of the controller with the configured PID controllers as the output.

3.1.10 Flutter Analysis (SZTAKI)

The Flutter Analysis block receives the FlexACModel of the Control Synthesis Model Generation block and the flutter suppression and baseline controllers of the Flutter Control Synthesis and Baseline Control Synthesis blocks. The analysis is done in the frequency domain in two aspects. First, it assesses the performance of the two controllers acting together simultaneously. Second, it checks the robustness margins and flutter margins of the resulting controllers and if the minimum requirements are satisfied a pass flag is set and a PDF report is automatically generated. The pass flags and the PDF are finally set as the outputs of the block.

The main algorithms of each block and their adaptation to the MDO/RCE framework is given in deliverable D2.2 Report on tool adaptation for collaborative design.

3.1.11 Drag Evaluation (DLR-AE, DLR-SR)

The drag evaluation is important for the mission analysis and thus the determination of the range. For each considered mass configuration a state-space model is provided to the ”Drag Evaluation” block. The induced drag in cruise is then minimized by determination of the optimal deflection of the control surfaces. The final result is given to the ”Mission Analysis” block.

	Reference aircraft	Designed aircraft
Aspect ratio	conventional	high
Number of ailerons per wing	8	8
Drag control	-	passive/active
MLA control	-	passive/active
GLA control	-	passive/active
AFS control	-	passive/active
Assessment criterion	range	range

Table 1: Comparison between aircraft configurations

3.1.12 Mission Analysis (DLR-SR)

For the overall aircraft performance the aircraft is considered to operate in cruise. The flight conditions within cruise only changes due to defueling. To account for this change in mass a few discrete mass cases of the current aircraft configuration are received from the ”Trim and Linearize” block. They represent different fuel levels. The necessary thrust for a mass case is then estimated by means of the overall drag, which is minimised through the optimal control surface deflections provided by the ”Drag Evaluation”. The fuel consumption for a mass case is then determined based on the required thrust. As soon as a certain level of fuel is consumed, a new mass case representing the predominant fuel level is chosen. Summing up the distances of each mass case leg provides the overall aircraft range.

3.2 Scenarios for Scale-up task (DLR-SR)

In order to judge the increase in range of the designed aircraft with secondary flight control, i.e. GLA, MLA, AFS and drag control, a reference aircraft is considered. It is assumed to exhibit a lower range compared to the high aspect ratio and actively controlled aircraft.

Table 1 shows the similarities and differences between the aircraft configurations. As mentioned the aspect ratio is a parameter, that can be varied for the collaborative aircraft design process. The number of ailerons will stay the same. However with an increase in aspect ratio also the control surface area will increase. Secondary control laws are only applied for the designed aircraft. Different configurations can be considered here. How much a single or a combination of control law functions improve the range and affect the design of the aircraft can be examined by switching the control law functions from passive to active or vice versa.

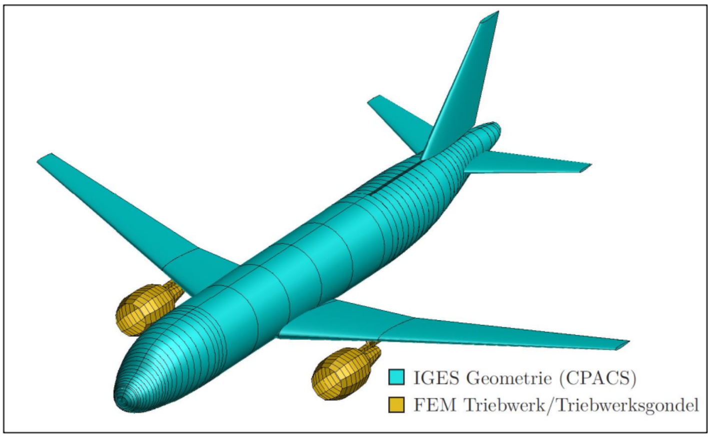

Figure 3: IGES-geometry of the D150-configuration

4 Reference Model (DLR-AE,DLR-SR)

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. Therefore it is important to have a model including all the components necessary for aerodynamic, structural and control evaluation. The idea is not to design a new aircraft but to apply control design technologies to a high aspect ratio variant of the reference model. For the scale-up task it was decided to select the D150 aircraft model. A brief description is listed below.

4.1 D150: DLR 150Pax Model (A320 like)

The D150 configuration was developed within the DLR project VAMP [18]. It is comparable to the Airbus A320-200 aircraft. Data published by the manufacturer and input data to the preliminary design program PrADO for the application example Airbus A320, are collected for the D150 configuration [9]. Its geometry is shown in Figure 3. Table 2 lists some parameters of the D150 configuration. The cruise speed V_C and cruise Mach number M_C are assumed to be equal to the maximum operational speeds V_{MO} and M_{MO}. The values for V_{MO} and M_{MO} for the Airbus A320 are given in the EASA Type-Certificate Data Sheet [2]. The dive speed V_D is determined 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 are used for the four profile sections. They originate from the geometry of the DLR-F6 configuration. The DLR-F6 configuration is similar to the geometry of the Airbus A320. It was developed in the 1980s as a publicly-available geometry for aerodynamic studies.

Using the D150 configuration provides the following advantages and disadvantages.
For:

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

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

Table 2: 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

The DLR-D150 was selected by the consortium as the preferred reference model for the scale-up task. All considered reference models are found in deliverable D1.5.

The primary reason for choosing the D150 is its relevance to industry and on-going research activities in different projects. An A320-like configuration is considered to be a SMR aircraft. Moreover, 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 the reduction of induced drag, i.e. drag due to lift distribution. However, the developed tools and methods are intended to be applicable even in a potential future workflow involving high fidelity CFD simulations.

4.1.1 Relevance to research community/industry

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

- VirEnfREI-DLR - LuFo funded project involving DLR and Airbus. It involves establishing an MDO framework for aircraft design with respect to industrial requirements and its application to the design of an SMR aircraft.
- MuStHaF-DLR - LuFo funded project involving DLR institutes. It is targeted towards future high aspect ratio SMR aircraft configurations considering different wing technologies, e.g. multi-functional control surfaces, control algorithms for AFS and online flutter stability monitoring.
- MAJESTIC - DGAC funded project involving ONERA and Airbus. The project 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 from 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.

5 Evaluation of Mission Criteria (DLR-SR)

It is assumed that the segments taxi, takeoff, climb, descent, approach, landing and contingency need a constant amount of fuel including an additional final reserve of fuel. Hence, the cruise segment will have an allotted amount of fuel. Therefore, only the cruise segment will be evaluated. For simplification, the cruise segment is discretized in reasonable sub-parts, each with constant mass properties. Thus, the fuel consumption in cruise is modelled step-wise, i.e. for each step a model of the D150 aircraft with the corresponding mass properties needs to be created. The optimal altitude will be determined by the aircraft's polar, i.e. flying at the maximum L/D point. This polar is based on induced drag calculations plus an assumption for unaccounted parasitic drag parts. Furthermore, wingshape control leads to a even smaller drag. The engine is selected for the class of aircraft beforehand and will not be adapted to design changes during the automated design workflow. Therefore, the engine characteristics are known and a typical specific fuel consumption (SFC) can be assumed.

The mission criteria to be evaluated is the range achieved during the cruise segment. Thus, mass cases for fuel states along a defueling vector in the cg diagram have to be prepared. For these mass cases the flexible aircraft is trimmed at a given starting flight point. With the required thrust and the SFC of the engine the flight time to the next fuel state is calculated. This flight time and the velocity determines the range of the segment. At certain fuel states a step climb is initiated to adapt the altitude to the current aircraft mass, while preserving the optimal C_L. The sum of all the ranges between the mass states is the objective function to be maximized.

It is assumed that with AFS, GLA, MLA and wingshape control, the range can be further improved.

6 Scale-up Objective Function (DLR-SR)

The overall objective function for the scale-up task will be based on evaluation of the mission criteria range in the cruise segment, as mentioned in the previous section. 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 AFS 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, as mentioned in the previous section. 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.

The technologies employed are:

- Manoeuvre Load Alleviation Control Functions
- Gust Load Alleviation Control Functions
- Active Flutter Suppression
- Wing Shape Control for drag reduction in cruise
- Passive Load Alleviation with aeroelastic tailoring
- Control surface layout (trailing edge no. of surfaces)

Finally, a comparison to assess the benefits when one or a combination of the technologies are employed can be performed.

7 Technologies to be Demonstrated with the T-Flex Aircraft (ALL)

7.1 Baseline Control (SZTAKI)

The baseline controller provides a stability augmentation system (SAS) as well as waypoint/trajectory following capabilities for the T-FLEX demonstrator as well as for the D150 aircraft. The nested inner-/outer-loop control structure and the corresponding design tools and guidelines are the same for the two aircraft, only the specifications are different since the rigid body dynamics are significantly faster on the demonstrator. Moreover the control allocation is also designed for the two flight vehicles using similar principles, but the D150 and the T-FLEX have sligthly different control effectors (conventional vs V-tail, single vs. dual engine)

For the design of a flutter controller its interaction with the other control laws of the flight control system needs to be considered. A possible control strategy is based on frequency separation. It assumes that the flutter modes are high enough so that their behavior does not influence the slower rigid body modes and the controllers can be designed separately. However, special care must be taken for both the T-FLEX and for the D150 during such a baseline controller design, so that the frequency separation is ensured. Within the scale-up task, similarly to the flight testing campaign of the T-FLEX demonstrator, the design of a baseline controller, based on the described frequency separation principle, is pursued to ensure proper functioning of the control laws.

The control laws are synthesized based on non-smooth optimization techniques over a range of velocities, what is also used as a scheduling variable for the control law gains. The Matlab systune command tunes fixed-structure control systems subject to both soft and hard design goals. Systune can tune multiple fixed-order, fixed-structure control elements distributed over one or more feedback loops or scheduled via online measurable parameters. For an overview of the method see [1], the tuning workflow is described in [11] and in 'https://www.mathworks.com/help/control/ref/lti.systune.html'.

The control laws are implemented onboard the flight control computer (FCC) of the aircraft, where proportional gains are implemented in simple 1-D lookup tables (schedules with velocity), the integral action is first discretized using zero-order-hold at a $200Hz$ and the integral gain is implemented as lookup tables, while the derivative gains are mostly routed via havig access to the derivative of the quantities in feedback (for example pitch rate (q) in the pitch angle loop). The generic nested loop architecture and the model based design principles are carried over from the demonstrator to the scale-up task. Within the flight test campaign to validate the flight control laws the control behavior and control tuning used the dynamical mathematical model of the aircraft implemented in hardware-in-the-loop (HIL) environment, what is the standard practice for autopilot design from small UAVs up to the large commercial aircraft.

The control laws were validated in subsequent tests. First only the inner loop angle tracking was tested, later the velocity and altitude tracking and later the full flight trajectory following. After the initial investigation and fine tuning of the actuator and sensor calibration, the subsequent control laws were tested and showed very good handling quality behavior even without manual tuning and iterative refinement, what is the target for both demonstrator and full-scale aircraft, to reduce costly flight test campaigns and validate the flight control system in simulations and iron bird setups.

The aircraft was flown with the rigid (-0) wingset in full autopilot mode, but the aeroelastically tailered (-2) wing was also flown in augmented (SAS) mode.

Based on extensive simulation tests the flutter prone (-1) wing will be also able to fly with the same baseline controller up to 45 m/s, nearly the flutter boundary and only after that it is necessary to have the flutter control law which adds additional damping to the wing torsional and bending modes to reduce oscillation prior to flutter speed and extend the flutter free envelope.

7.2 MLA (ONERA)

The validation of the MLA control strategy may be done by applying the following experiment

- Fly at a given cruise velocity and condition, without discrete gust disturbances. If discrete gust encountered, delete the experiment.
- Apply a reference signal on the load factor e.g. from 1g to 2.5g. Typical reference signal are to go from 1g to 2.5g in 6 seconds (typical manoeuvre used in civilian aircraft).
- Measure the load factor and loads along the wings with and without the MLA function.
- Compute the distance of the loads with and without the MLA function and evaluate the relative load reduction.

7.3 GLA (DLR-SR)

The task of GLA control is to optimise the loads on the wings and tail for discrete and continuous turbulence so that the structural weight of the aircraft can be minimized. The GLA controller is synthesized with the structured H_∞ method. Further details are described in [17].

The validation of the GLA control on the demonstrator aircraft can be performed in flight. However, as it is not possible to decide when to switch on turbulence, a minimum number of legs at trimmed steady level flight need to be flown with the GLA control laws switched on and off. The comparison of the switched on and off configurations provides evidence on the mean effectiveness of the GLA controller.

7.4 Active Flutter Suppression (SZTAKI)

The method used for flutter suppression is based on structured robust control design for systems with a mixture of parametric and dynamic uncertainty [13]. The proposed method alternates between an analysis step and a synthesis step. Samples of the parametric uncertainty are computed during the analysis steps, thus yielding an array of uncertain systems containing only dynamic uncertainty. The controller is then synthesized on this array of uncertain models. This synthesis step itself involves an alternation between constructing a D-scale for each of the uncertain systems and tuning a single controller for the entire collection of scaled plants. The controller tuning is performed using structured control design techniques. The proposed method is utilized to design a flutter suppression controller for a flexible aircraft. The aircraft dynamics are described by both a high-fidelity and a reduced-order model. The design objectives for flutter suppression are to achieve robust stabilization in the presence of mixed uncertainty. The proposed structured design method yields a single, low-order, LTI controller, which increases the flutter speed and high-fidelity simulations are provided to assess the controller performance. Similar design techniques with additional scheduling of mass values are expected to work on the scale-up aircraft.

7.5 Wingshape Control (DLR-SR,DLR-AE)

The task of the wingshape control is to reduce the induced drag of the aircraft in cruise. As the drag is not directly measurable the thrust estimation can be used instead. Thus, the thrust has to be minimized in flight through aileron deflection, where the ailerons of the left and right wing are deflected symmetrically.

To test the effectiveness of the wingshape control on the demonstrator the aircraft needs to be trimmed for a certain speed at a certain height. This leg is then flown with and without wingshape control for different speeds. The comparison of the two data sets then provides information on the drag reduction achieved.

8 Conclusion

The deliverable D4.1 demonstrates how the scale-up design objectives are defined. The scale-up task involves an integrated aircraft design workflow, enabled using an MDO approach involving aeroelastic tailoring for the optimization of the wing structure in conjunction with active control augmentation. The active control methods involved are the baseline control for manoeuvring the aircraft, GLA and MLA for load alleviation, flutter suppression to maintain stability of a high aspect ratio aircraft within the entire flight envelope and wing shape control for drag reduction.

The overall scale-up design objective is to maximize the range of the chosen D150 aircraft. Here, only the range travelled within cruise is considered to be of relevance. A set of models of the D150 aircraft are provided featuring different fuel levels. Thus, the cruise is divided in parts with constant fuel levels that are lowered stepwise. Finally, the goal is to find the aircraft design that provides the longest range with the chosen passive and active technologies - aeroelastic tailoring, GLA, MLA, AFS and wingshape control, while keeping the fuselage and the amount of payload unchanged. This optimization can be repeated for different combinations of technologies. The comparison of the combinations will then demonstrate what range benefit can be achieved when structural control and passive load alleviation are considered at an early stage of aircraft design. It is assumed that the most promising design features a high aspect ratio with an improved drag performance, which can only be achieved due to the new technologies. Flight testing the demonstrator aircraft with a new set of wings will provided further knowledge on how the proposed technologies can be pushed from a preliminary development stage to a flight ready implementation.

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