DIGITAL MULTI-DISCIPLINARY DESIGN PROCESS FOR MOVEABLES AT VIRTUAL PRODUCT HOUSE

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Abstract

This work presents the virtual design activities performed within the Virtual Product House start-up project. In this project a multidisciplinary process chain is developed at the VPH, an integration plateau combining several DLR institutes and builds up a close linkage to industry and certification authority. This setup enables multiple stakeholders to collaborate by linking their individual capabilities in a distributed process. Thus, a multidisciplinary analysis could be performed to investigate and improve aircraft designs and assess the impact of modifications on an existing configuration. Low and high-fidelity methods are utilized to enable on the one hand a holistic evaluation of the aircraft characteristic and on the other hand detailed investigations with respect to certification by analysis. As starting point, three disciplines are considered: aerodynamic, structural and system design. The initial use case focuses on a high-lift configuration. In this paper, the interconnected process will be explained, the disciplinary methods highlighted and first results presented.

1 INTRODUCTION

The investigation of complex systems requires a collaborative work of various stakeholders. In the past decade intensive work was performed at DLR to build up multi-disciplinary process chains for transport aircraft configurations. Therefore, new methods were implemented and existing tools extended to improve the interfaces and collaboration between disciplines. Most recently the DLR-internal project VicToria [1] was successfully completed. Part of the project dealt with the linkages between varying disciplines and the investigation of different approaches to perform multi-disciplinary optimizations (MDO) [2] [3]. The biggest challenge within this and many other MDO projects is the coordination and implementation of interfaces between different disciplines and the availability of a common environment. To improve the exchange and collaboration between DLR institutes, the Virtual Product House (VPH) was established within the Center for Eco-efficient Materials & Technologies (ECOMAT) in Bremen to build up a working plateau inside DLR involving additional research facilities, aircraft manufacturer, supplier and certification authority. In comparison to preceding projects, the here presented virtual process chain focuses not solely on design activities but is extended with regards to virtual manufacturing [4] and virtual testing [5]. Moreover, the basis for a common collaborative framework was build up. This framework enables on the one hand the general provision of capabilities in form of tool boxes by the respective stakeholder and on the other hand the connection of additional internal and external partners to the provided development environment. For the initialization of the VPH, a small team composed from five DLR institutes brought together their individual expertise and creates the first VPH End-to-End process chain, shown in FIG 1. The virtual design receives a virtual product description as input, e.g. an aircraft configuration defined in the CPACS data format [6] [7]. Within the virtual design, the dimensioning of a single component, like an actuator, up to assemblies combining different disciplines, e.g. the outer shape and structural concept of an outer flap, takes place. The resulting virtual product is labelled “as designed”. This output is forwarded to the virtual manufacturing process. There, the idealized part is transferred into a discrete component and is labelled “as built”. Finally, this component is examined in the virtual testing process, by simulating selected failure cases to ensure a safe operation. After

doi: 10.25967/550048

completion of this third process step, the virtual product is labelled “as tested”.

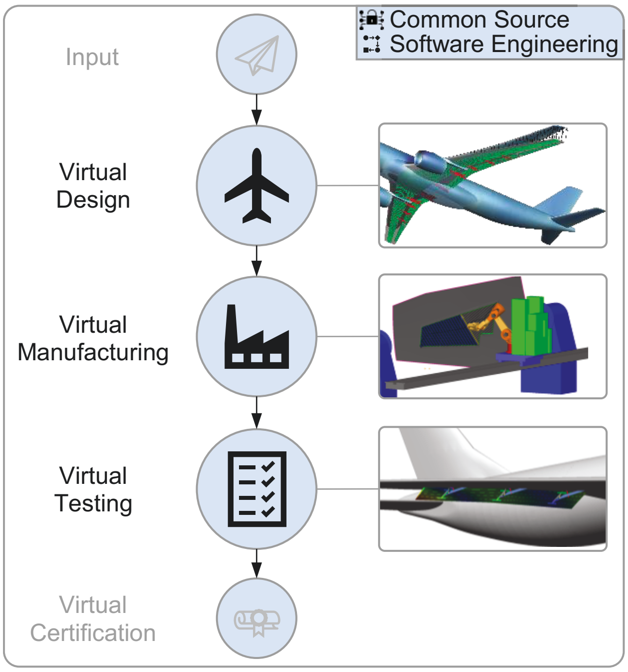

FIG 1: VPH process

The virtual design includes the analysis of aerodynamic characteristics, the optimization of the primary wing structure as well es the dimensioning of the actuation system to drive the wing moveables along the trailing edge. Thereby, each process step is performed in consideration of a potential “Certification by analysis” [8] [9]. However, a simulation process, which pursues a virtual certification, requires a suitable IT infrastructure. Hereby, questions regarding traceability of data, preservation of individual capabilities and quality management are of interest. The concept is called Common Source environment [10].

In the VPH start-up project the initial use case “Multifunctional moveables” was selected together with the industry partners (Airbus Operations, FFT Produktionssysteme, IABG, Liebherr-Aerospace). Up to this date, the main focus of most MDO processes was on clean wing configurations. Therefore, the application of available methods considering high-lift configurations was required to evaluate the essential parts of a state of the art high-lift system and associated requirements.

While creating the VPH process, the overall objective is the deployment of a tool environment, which can be utilized in a common environment and applied flexibly and modularly on various use cases beyond the VPH start-up project. Therefore, each discipline makes their individual capabilities available within the Remote Component Environment (RCE) [11]. This enables an explicit definition of interfaces to other disciplines without revealing the underlying analysis and algorithms and enables the wiring of complex, multi-disciplinary analysis and optimization processes.

The realization and demonstration of this approach for the application and combination of both low- and high-fidelity methods is the core of this project. In the following, the multi-disciplinary design process will be outlined including the pre-defined inputs, process monitoring and resulting outcome, which is passed on to the virtual manufacturing and testing processes. Moreover, the utilized methods covering aerodynamic analysis, system design and structural optimization are presented. Finally, first results and opportunities associated with this process will be shown.

2 MULTI-DISCIPLINARY DESIGN PROCESS

A schematic visualization of the virtual design process is given in FIG 2. On the left the necessary inputs are listed, composed of a CPACS data set describing the aircraft, a

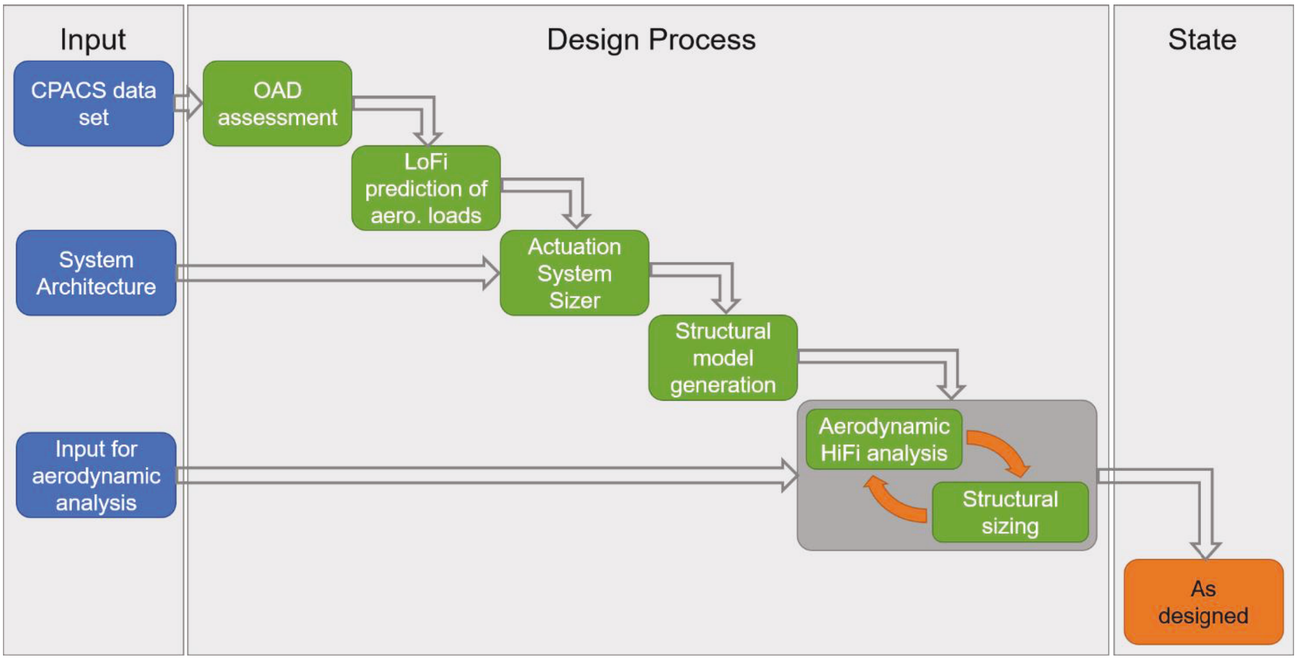

FIG 2: Multi-disciplinary and multi-fidelity VPH design process

description of the to be investigated system architecture and inputs for the aerodynamic analysis. In the center of the figure, the step-by-step procedure of the virtual design analysis is outlined. Thereby becomes clear, that the virtual design process is not only a multi-disciplinary but also a multi-fidelity process. The utilized methods are ranging from handbook approaches over potential-theoretical procedures up to the utilization of Reynolds-averaged Navier-Stokes (RANS) equations and Finite-Element (FE) methods. Most methods are based on the standardized CPACS format. Thus, these tools require only one interface to exchange information and guarantee consistency within the design process. Accordingly, the implementation of additional tools requires only a single interface to the central CPACS data set, as sketched in FIG 3, to contribute to the overall design process.

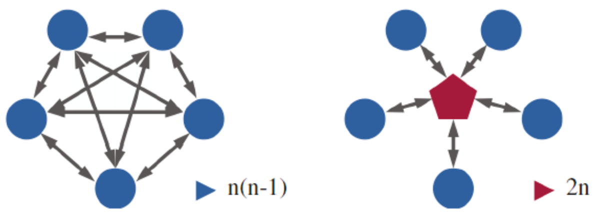

FIG 3: Number of interfaces in multi-component assessment processes [1]

In addition should be noted, that key performance indicators (KPI) are tracked after each disciplinary evaluation to provide a short summary and enable a quick traceability of changes during the execution. These KPIs comprise single values, e.g. structural mass or aerodynamic coefficients, as well as figures, which display information like the underlying high-lift system architecture or areal pressure distributions. Furthermore, the workflow executor can choose between two high-performance computing infrastructures to perform the compute-intensive CFD simulations, either the DLR CARA cluster or the North German Supercomputing Alliance (HLRN) provided through the Center for Industrial Mathematics (ZeTeM), University Bremen. After passing all design steps, the resulting virtual product is labelled "as-designed".
Parts of the virtual design results are directly forwarded to the subsequent processes. A parametric description of the sized actuation system is provided to the virtual testing, while the virtual manufacturing receives a sized structural model of the outer flap with smeared stiffnesses for each property region.

3 UTILIZED METHODS FOLLOWING THE DESIGN PATH

3.1 Wing Moveables Process tool and aerodynamic calculations using LIFTING LINE

To reduce the effort for the overall aircraft assessment for different high lift configurations the Wing Moveables Process tool (WMP) has been developed. The main capabilities of the WMP process are to enable quick overall aircraft validation and feasibility analysis of the input parameters for a given high-lift design.
The Wing Moveables tool is a derivative of the previously in cooperation with Airbus developed Wing-Moveables-Process [12], now solely based on methods and tools that were developed at DLR. It is fully written in Python. All tools and methods used for assessment with this process are open-source and thus not license bound.
To ensure a common input basis with other DLR aircraft design processes, the CPACS format is used as the central input database. The required input data includes the aircraft shape and geometry (including all moveable wing devices), load cases and flight missions. In addition, already available engine performance maps can be imported into the process.
The process itself consists of a modularized approach, in which most of the individual modules are independent of each other. The current modularization is depicted in FIG 4.

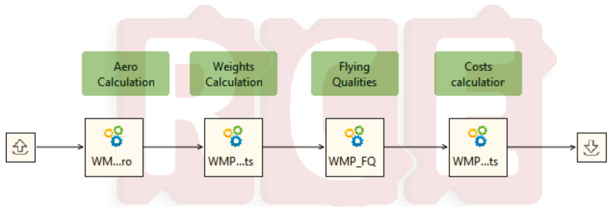

FIG 4: The currently implemented sequential modularized approach of the WMP process

During the initialization the wing moveables tool creates a hierarchical element structure based on the CPACS file. Inside this structure moveable components are defined as children of their wings. Also, flight conditions and their associated configurations are stored separately. All calculations performed in the modules of the WMP use this structure and map their results back into this format.
In the first step of the WMP tool the validity of the input data and the chosen aircraft configuration is checked by deriving a schematic 2D-view of the wing moveables layout from the 3D-aircraft data using the TIGL library [13]. In addition to the visualization, it is checked if the edges of the moveable devices are well defined or if they intersect each other. Furthermore, basic geometric parameters as wing area or wingspan are derived from the parametrized aircraft geometry.
Afterwards, an aerodynamic analysis is performed. This analysis is performed for each relevant flight condition individually. Since the main goal of the WMP is the assessment of wing moveables layout, the focus is the analysis of maneuverability of each configuration. To meet this requirement, roll rate and roll maneuvers are calculated and provided in the form of KPI values. For the flight conditions, the calculations can be performed with all control surfaces operable, as well as in faulty configurations with partially inoperable or incorrectly deflected control surfaces. Inputs for these calculations are derived from the preliminary aerodynamic calculation tool LIFTING LINE, that is being developed at DLR. Exemplary results of this tool can be found in 4.2. Additionally, high lift performance during take-off and landing is assessed, including the calculations for maneuverability during these phases. Further processing of the take-off and landing capabilities is utilized to create performance maps.
Further results of the WMP include the flight envelope and cost calculation for wing and moveables.
Future implementations to the tool will be engineering improvements and software improvements to expand the capabilities of the WMP while further speeding up the

process and reducing calculation time.
The initial aerodynamic assessment and loads calculation is performed using the open source multiple lifting line program LIFTING LINE, that is being developed and maintained at DLR. LIFTING LINE computes aerodynamic load factors using a potential-theoretical procedure over multiple lifting surfaces that are modeled by flat plates [14]. Input data for LIFTING LINE is generated by its wrapper, CPACS4LILI. CPACS4LILI transforms 3D geometric data into flat panels, that serve as input for LIFTING LINE. The CPACS4LILI software was modified and extended for the VPH use case. The ability to calculate extendable high lift devices was added and verified in [15]. This modification now enables the calculation of track rear link flaps, slats and ailerons.

FIG 5: Implementation of the Panel deflection correction within CPACS4LILI

The modelling of high lift devices with tracks within LIFTING LINE is performed by elongating, repositioning and rotating the panels of the moveable device. To emulate the shape of the extended flap, as depicting in FIG 5. The shape of the curvature can be individually defined for each input geometry by an input parameter to represent different high lift systems. A visualization of the three-dimensional model with fully extended flaps of the present use case can be seen in FIG 6.

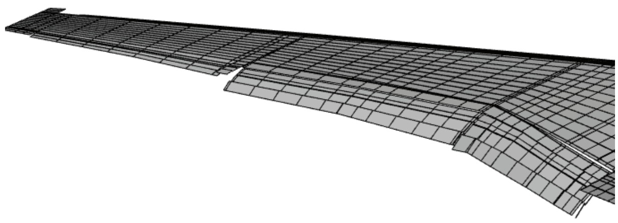

FIG 6: Aerodynamic Panel model with extended high lift devices

The aerodynamic virtual design approach presented here is considered to gain early data on the overall aircraft performance and to provide an initial set of input data for the kinematic actuator sizing. The procedures and methods are mostly well known and taken from literature. The approach during this step of analysis is to allow for a wider design space. Inputs, that do not meet required KPI-values can then be excluded without further calculation during the high-fidelity analysis and structural calculations.

3.2 Control surface mechanism and actuation system sizing

Within this work, an interface was built in order to use the aerodynamic loads generated by the LIFTING LINE tool (see section 3.1) in the sizing process for the mechanisms and the actuation system. In the first step, the control surface mechanisms are designed. One result of this design are requirements for the actuation system in terms of actuator loads, angles and speeds. These are subsequently used to size the actuation system. The tool, which computes these used to be integrated into the WMP, which was presented in section 3.1. A comprehensive presentation of this sizing tool is depicted in [16]. This section describes the general mechanism and system design process, the resulting outputs and highlights the extensions, implemented during the VPH start-up project.
The mechanism and actuation system sizing tool requires information on the control surface dimensions and positions within the wing as well as their settings for the different high-lift configurations. This information is obtained from the CPACS file.
Utilizing the aerodynamic loads determined by the load cases on the control surface, the station loads are calculated. This means that the loads are split onto the flap support stations. In order to get a complete mechanism design, loads need to be obtained for all defined control surface settings. These settings are taken from the CPACS file and calculated for the profile sections, where the support stations are located. With this a 2D kinematic synthesis and analysis is performed in order to obtain the kinematic joint coordinates for the chosen mechanism type. This approach is depicted in [17]. A subsequent kinetostatic analysis allows the calculation of all joint loads, which is used for the sizing of the mechanisms. Moreover, the required actuator angles, velocities and torques are calculated for all required control surface settings. For the high-lift system, a constant actuation speed is assumed, which assures the flap deployment in a fixed amount of time.
Sizing of the mechanism components is conducted utilizing knowledge-based methods. As a result of the mechanism sizing process, the coordinates of the resulting kinematics are written into the CPACS file in order to be used as flap attachment for the structural model generation (see FIG 8). For that the CPACS standard was extended by the kinematic description of control surface mechanisms as of CPACS version 3.3 [6]. Moreover, the work focussed mainly on further development of the use case mechanism type (track-rear-link) and the interfaces with CPACS files.
The architecture of the actuation system, which incorporates all parts of equipment and their interconnection, is represented by a Design Structure Matrix (DSM) giving the possibility to easily alter the system architecture input for architecture studies. Within the VPH start-up project an actuation system architecture based on an existing high-lift system is used as a given input. Although such architectures are in itself the result of a design process according to [18], their generation is not within the scope of the current work. A detailed description of the actuation system architecture for this use case is given in [5].
Based on the given systems architecture and the actuator load requirements as determined by the mechanism design, the actuation system is sized. Within this work the focus lies on a preliminary sizing of the actuation system, rather than a detailed design of all parts of equipment. This serves as a measure to generate the end-to-end capabilities of the VPH process on which more detailed design tools can build upon in the future. The system architecture of the reference system is a centrally actuated system with a mechanical transmission through drive shafts. The actuation system sizing tool comprises sizing methods for each type of equipment the actuation system

is composed of, such as actuators, gear boxes, and shafts. In the mechanical rotational domain, at least a torque and angular speed is required for sizing. According to the system architecture a calculation network is generated, which computes all necessary values for equipment model sizing. Result of the sizing process are mainly mechanical parameters, such as equipment masses, inertias and stiffnesses. The results are stored in a system equipment parameter file, which is later used for the simulations in the VPH virtual testing process [5].

3.3 Structural model generation

For the assessment of the structural integrity based on finite element (FE) analyses in the VPH process models are required. In early design stages global finite element (GFEM) models are used to gain insight into the structure behaviour. These consist of levels of idealization and discretization that allow the evaluation of a large number of designs in a time-efficient manner.
To reduce the effort for modeling and structural evaluation, a design environment for thin-walled lightweight structures (DELiS) with the focus on structure mechanics has been developed. The core of DELiS is a parametric model generator which creates computational structural mechanics (CSM) models of lightweight thin-walled structures. It has been developed initially for the aircraft pre-design process including wings, fuselage and empennage. However, due to its flexibility and the use of synergies to aircraft wings, wind turbine blades or space launcher structures can also be generated.
Based on the same abstract database, it is possible to create models with variable level of detail. Exemplarily, wings can be modeled as simplified beam, or in a fine wing model, stringers can be created using beam elements or smeared as an extra shell layer. With the support of several commercial finite element (FE) solvers many other applications can be used, such as sizing tools that require a specific FE solver. Thus, DELiS facilitates interfaces to these sizing tools. So forth it includes the modelling, the simulation and the evaluation process. Based on Python programming language it is platform independent and can access most major libraries. The structural description of a database is interpreted and transferred in an abstract object oriented data model. Therefore, new interfaces can be added conveniently, FE models can be derived smoothly and sizing results can be used to update the model easily.
DELiS utilizes CPACS as an input database for the model generation. In the context of the current project shell-based idealization is applied, using additional beam elements to reproduce the influence of skin doublers in the domain of stiffening element flanges.
In the first step DELiS reads the hierarchical CPACS structure and creates initial top level CPACS objects, components and structure elements [19]. These objects are extended with metadata describing associations between structural elements. In the second step the wing and its moveables are partitioned by a grid of spars and ribs on the wings planform. This grid is refined by so called imaginary ribs and spars to achieve the desired mesh density. The skins of a wing are mapped on one or several bays of adjacent spars and ribs. Lastly, points on the outer hull, the so called jig-shape, of the wing is calculated. For this task the TIGL library [13] provides appropriate methods to obtain the geometry in 3D space. These keypoints are aggregated to lines and areas for each structure element using a graph-based approach. The created domains in skins and stiffening elements are later represented as individual property regions and used for the structural sizing with VErSO.

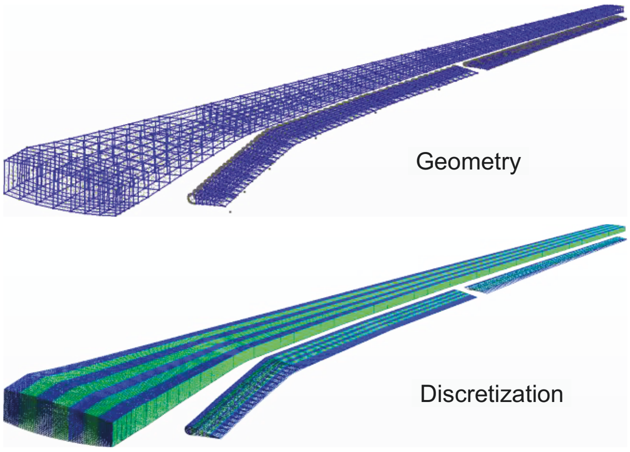

FIG 7: Modeling steps during CSM model creation

Besides geometry, the finite element properties for profiles and sheets are generated and mapped to the respective set of lines and areas. This collection of geometry and FE-properties yields a compact interface to all common CSM solvers. The relationships between all items allow the creation of an associative, parametric model [4]. The current implementation of the VPH process uses a Nastran model.
DELiS was extensively used and improved in MDO projects. These projects however were mostly focussed on high-speed wing design [20]. The VPH startup-project and its focus on moveables and low speed configurations required an extensive extension of the implementation. First of all an explicit structural modelling of moveable devices was implemented. Different structural concepts can be represented. Special effort was put into the implementation of the kinematics modelling. For the current model a track rear link kinematic is used. The associated data from the kinematic synthesis in ASySi is used via CPACS to include a structural representation of track and kinematics.

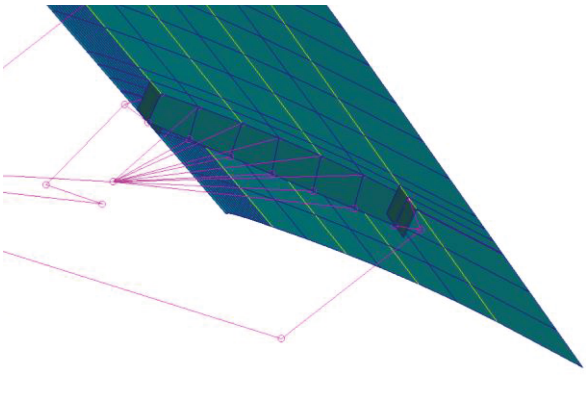

FIG 8: Track rear link kinematic elements connected to the moveable integral load introduction

Depending on the available information about beam dimensions and material the structural components are

automatically either modelled as rigid body or beam elements. At each joint position additional multi-point constraints are applied to allow the representation of certain failure cases in later investigation steps.
All modelling is performed in the jig shape or cruise configuration. Deployment of the kinematics and structure into a high-lift configuration is implemented as coordinate transformations based on the path description for each track in CPACS.

3.4 Fluid-structure interaction sizing process

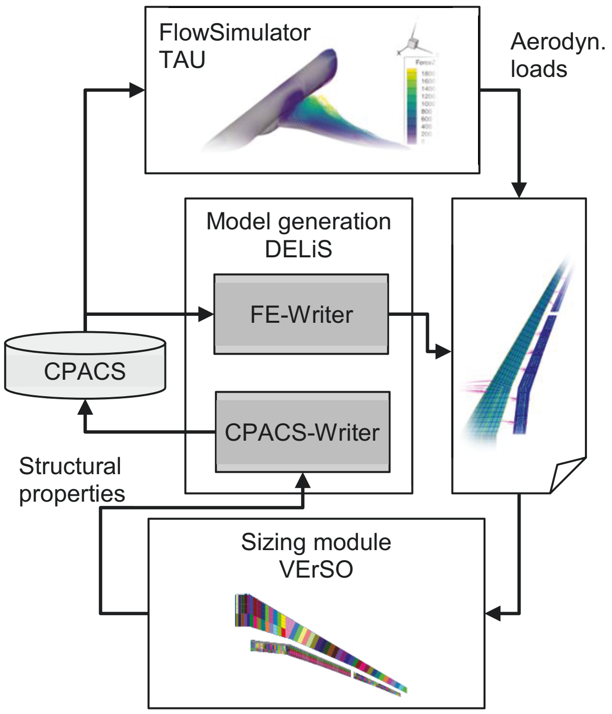

FIG 9: FSI approach

The iterative fluid-structural sizing process describes the last step in the virtual design. In each iteration the aerodynamic loads on a flexible wing are determined and mapped onto the associated structural model. Using model and loads a structural sizing with respect to chosen criteria is performed. The FSI process is based on compute-intensive high-fidelity simulations for the evaluation of the aerodynamic and structural behaviour of the virtual product in combination with a sizing-optimization of the primary wing structure. The iterative interaction between flow simulation and structural evaluation is sketched in FIG 9.
The flow simulation is based on a process by A. Merle [21] and enables the assessment of a flexible wing for the occurring aerodynamic loads. The FlowSimulator [22] process utilizes the flow solver DLR TAU code [23] in combination with the FE solver MSC Nastran. The process requires four inputs. The current CSM grid, a CFD grid and TAU parameter files for the desired number of load cases, which should be evaluated. Both grids are provided in jig shape. In the course of an iterative process aerodynamic loads are provided by the RANS simulation and forwarded to the FE model, which in turn returns displacement vectors along the wing. The displacements are mapped back on the CFD grid to apply a corresponding wing deformation and thus represents a flexible wing. Then, the aerodynamic simulation is restarted to assess the flow conditions and aerodynamic loads for the adapted wing shape. This iterative coupling process between aerodynamic and structure is converged, as soon as the displacement alteration between the last two iterations does not exceed a defined threshold. Thereby, the wing flight shape for a selected flight condition is found. The associated aerodynamic forces are mapped onto the structural wing model as defined by DELiS. Model and loads are then forwarded to the structural sizing process. Here the in-house sizing tool VErSO is used [1], [2], [24]. The fundamental concept of the structural sizing approach is shown in FIG 10.

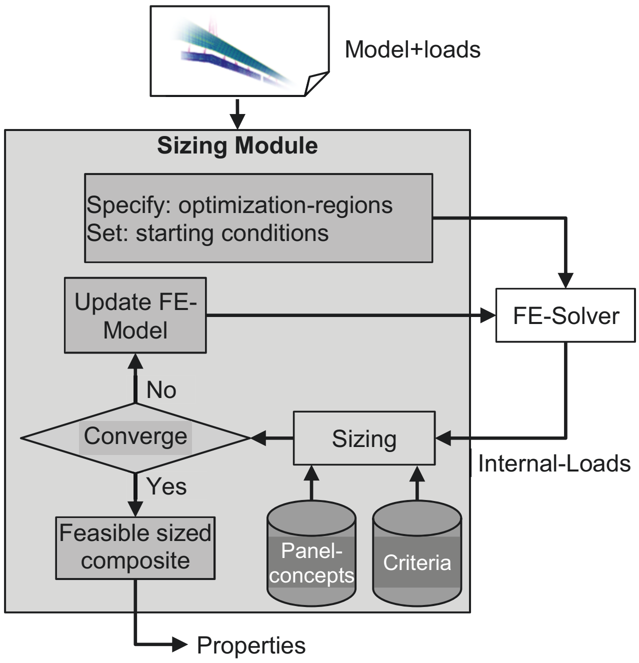

FIG 10: Sizing approach

The property regions of skins and stiffening elements, as shown in FIG 11, are used as optimization regions. During the structural model creation starting conditions for these regions are applied. In a first step these are used in a finite element calculation to determine the section loads on each individual optimization regions.

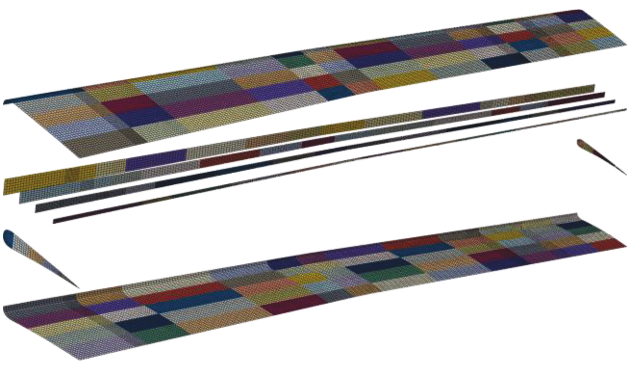

FIG 11: Moveable sizing regions

Based on these loads sizing criteria are evaluated to determine the structural integrity. In the current process these consist of failure as well as local and global stability criteria. Analytical as well as numerical methods are used for the structural assessment. Several different concepts for each sizing regions may be used, however, the focus here is on monolithic unstiffened composite regions. For these, the chosen criteria are evaluated by means of lamination parameters to assure a time-efficient optimization process. In case one or more optimization regions fail to fulfill all necessary requirements, the underlying composite definition is updated. As this update entails a change in the stiffness distribution and therefore, the section loads on the sizing regions, an update of the finite element model and the results with respect to the considered load cases is performed. This iterative process is carried out until all sizing criteria are met. Convergence is checked based on the mass properties of the evaluation model. The resulting properties of the optimization regions are used to update the underlying finite element model as well as to calculate the structural mass breakdown which is then used to update the CPACS description of the reference aircraft. In the next process section, these properties are used to simulate the manufacturing process.

4 APPLICATION ON HIGH-LIFT CONFIGURATION

4.1 Aircraft configuration

For the demonstration of the VPH End-to-End process, a long-range aircraft was selected, which was already used in several research projects in the past years. Thus, comprehensive reference data is available. However, most investigations focused on the clean wing configuration. Solely, the aerodynamic shape of a high-lift system, as shown in FIG 12, was designed in a previous project. It represents a classical high-lift design composed of slats and single slotted flaps on a track rear link kinematic. A description of an associated system design and structural concept for the trailing edge devices was not available at the beginning of the project. Thus, necessary extensions for the modelling of the high-lift configuration were accomplished to create a consistent CPACS data set. In the context of the project, the aircraft was postulated as certified aircraft and the available model defined as virtual product.

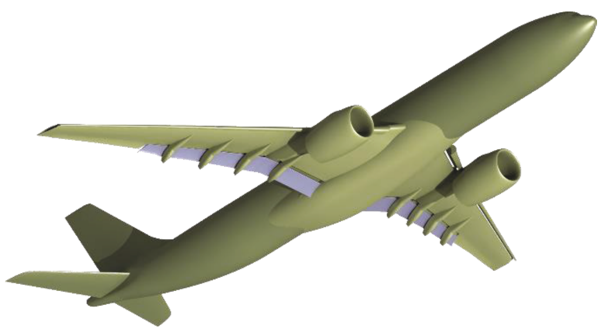

FIG 12: Geometry of high-lift configuration

Ensuing from this configuration baseline, the outer flap was selected as initial use cases to evaluate the impact of various modifications, e.g. the structural concept. Thereby, aspects of a potential virtual certification were considered. Accordingly, the VPH End-to-End process should enable the evaluation of upgrades for existing aircraft.

4.2 Results

Results from the OAD design process amongst others include the visualization of active wing components, as seen in FIG 13. An analysis of the maneuverability of the aircraft is performed for each given flight condition.

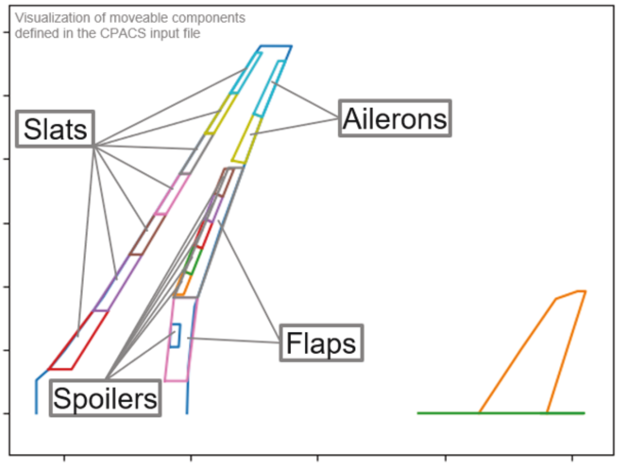

FIG 13: Visualization of moveable components defined in the CPACS input file

According to the aircraft configuration, roll performance is calculated for a given setting of trailing edge devices. For the landing configuration (see TAB 1) fully deflected flaps and slats combined with a given aileron defection are evaluated. For the takeoff configurations partially deflected high lift devices are used. Calculations are performed over a period of time while taking roll rate and bank angle into account.

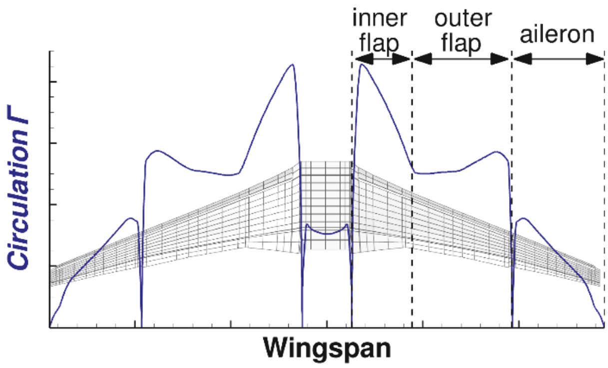

FIG 14 Circulation Distribution of the trailing edge devices during takeoff

The circulation distribution along a spanwise panel row covering all trailing edge devices, calculated for the takeoff load case using LIFTING LINE, is shown in FIG 14. The circulation is plotted on the vertical axis over the wingspan. For orientation, the geometric description of the panels used by LIFTING LINE, is set as background. Based on the circulation, the individual trailing edge devices are

identifiable. In this particular panel row, the highest circulation can be found on the inboard side of the inner flap. The outer flap is characterized by an almost constant circulation. The deflected aileron features a declining circulation towards the wing tip. These results obtained with the aid the low-fidelity method LIFTING LINE are utilized for both, the WMP and the subsequent system sizing.
The sizing processes along the virtual design are based on a selected number of load cases. An overview is listed in TAB 1. The system sizing takes all high-lift configurations into account. The dominating loads are expected for the wing design wing-flap speeds V_F in combination with a 2g load factor *n*. Additionally, the clean configuration is evaluated at design dive speed V_D and *n*= +2.5g. For the assessment of the system sizing load cases LIFTING LINE is applied. In contrast, the structural sizing load cases are investigated by using RANS and FE solver. For the structural sizing was assumed, that the dominating aerodynamic loads arise for the clean wing configuration at design dive speed V_D in association with a +2.5g and -1g load factor *n*. In addition, the high-lift configuration Take-Off 3 is analyzed with high-fidelity methods to investigate the aerodynamic and structural behavior of the outer flap at V_F and *n*=+2g.

System sizing load cases			
Name	Configuration	Speed	Load factor
SSLC Ref	Clean	V_D	+2.5g
SSLC 1	Take-Off 1	V_F	+2g
SSLC 2	Take-Off 2	V_F	+2g
SSLC 3	Take-Off 3	V_F	+2g
SSLC 4	Landing	V_F	+2g
Structural sizing load cases			
Name	Configuration	Speed	Load factor
FSILC 1	Take-Off 3	V_F	+2g
FSILC 2	Clean	V_D	+2.5g
FSILC 3	Clean	V_D	-1g

TAB 1: Load cases within virtual design process

According to the input for the system architecture, the outboard flap is held by three support tracks for the reference aircraft. Based on their position in spanwise direction, the kinematic synthesis is performed for each track.
FIG 15 depicts the kinematic synthesis and analysis results for one of the track-rear-link mechanisms in the x-z-plane. The mechanism comprises of a rotary actuator, which is connected to the flap fitting via the drive strut. The flap is attached to the flap fitting, which rests on the track. Moreover, the flap fitting is guided by the rear link. Rear link, actuator and track are attached to the support beam (not shown in FIG 15), which is mounted to the wing. Besides the kinematic joint coordinates and the mechanism mass, which are calculated by the mechanism design, the actuator torques are obtained, which are used for the sizing of the actuation system.

Using the result of the system actuation synthesis, the locations of each system joint along the deployment path at a track are written to CPACS. This information is used by the structural model generation.

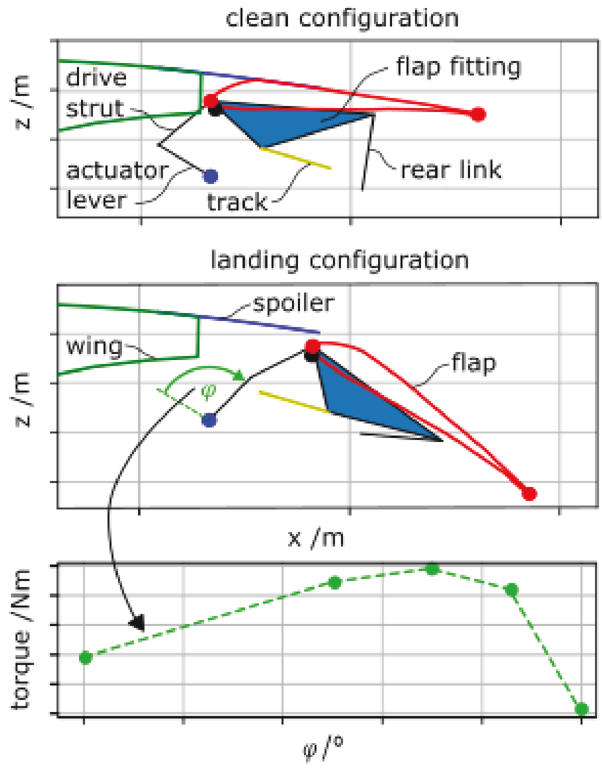

FIG 15: Kinematics of the mechanism at one of the three supports of the outboard flap for retracted (clean) and extended (landing) configuration

For the current investigations a composite multi-spar concept with integral load introduction (CMFIL) based on [25] is used with a classical differential concept based on homogeneous materials acting as a reference for comparison. Both structural concepts can be automatically generated with DELiS based on a respective CPACS description as shown in FIG 16.

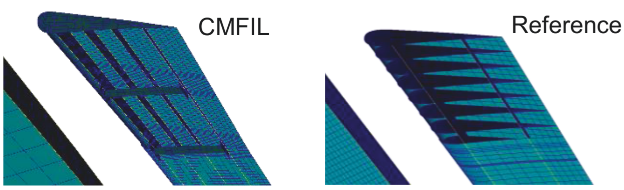

FIG 16: Moveable structural concepts under investigation

Based on the jig-shape modeling the deployment of the moveables is implemented based on coordinate transformations along the actuation path as defined in CPACS for each track position. The deployment is verified against the target in the CAD geometry. Thus, it is possible to represent every possible trailing edge configuration for each moveable. As an example, the configuration belonging to the Take-Off 3 configuration is shown in FIG 17.

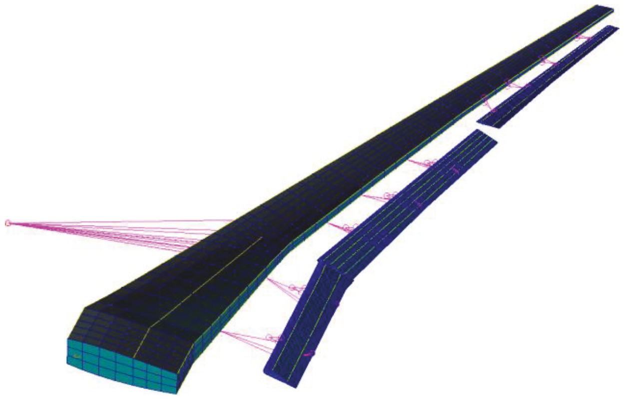

FIG 17: Full VPH reference aircraft wing in take-off 3 configuration

The corresponding loads and required properties with respect to sizing criteria are calculated in a fluid-structure interaction approach.
The analysis of the fluid structural interaction requires the availability of consistent models. FIG 18 displays the superimposed models for the FE analysis and the RANS simulation. The structural model for the clean and high-lift configurations is automatically provided by DELiS, while the grids and matching parameter files for the flow simulation are provided as external input. However, the user can choose between different grid resolutions, which are prepared in advanced, since the fully automated and reliable grid generation for the aerodynamic analysis of high-lift configurations is not achieved yet. All three load cases, listed in TAB 1, are investigated in parallel on a cluster, using the FlowSimulator process described in 3.4.

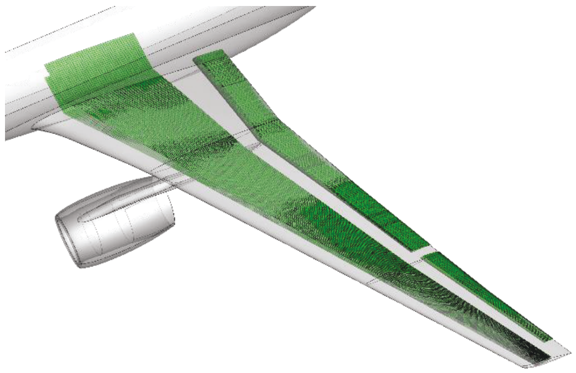

FIG 18: Illustration of the consistency between structural model (green) and the aerodynamic shape (grey)

The results of each simulation are tracked by information about the aerodynamic coefficients and the elastic wing deformation in x, y and z-direction. Additionally, plots are created, providing information about the flow characteristics from a top view. Exemplary results are shown in FIG 19. On the right wing the skin friction coefficient in x-direction is visualized. The contour on the left wing represents the surface pressure coefficient c_p. This allows, for example, to track in the upper left visualization in FIG 19 the flow disturbance downstream of the engine indicated by the green area and the occurring red suction peak along the wing leading ledge. This offers a quick check of the intermediate results.

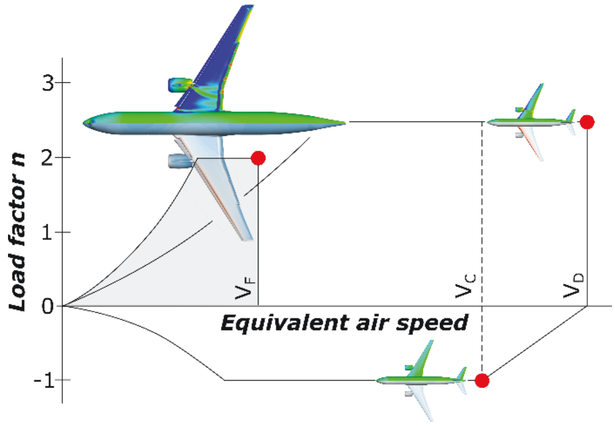

FIG 19: Load cases for high-fidelity analysis

An exemplary history of the FSI sizing loop is outlined in FIG 20. The results were extracted for the +2.5g load case. The sizing process required five iterations to obtain a converged state. The plot presents the changes of the maximal wing deformation in z- direction, the drag coefficient C_D and required angle of attack AoA. The lift coefficient C_L is set as target value by the load case definition and therefore constant. The initial structural model features a uniform thickness distribution along all property regions. After the first structural sizing by VErSO, a significant change in the z-deformation is traceable between the first and second loop. Consequently, the property regions are updated with respect to the occurring aerodynamic loads and allow higher wing deformations. At the same time, the drag coefficient increases slightly by about 2 drag counts (dcts.). In the following sizing loop, the wing deformation in z-direction varies slightly, while C_D and AoA increase. In the end, no variations are found between the fourth and fifth loop and thus the structural sizing is converged.

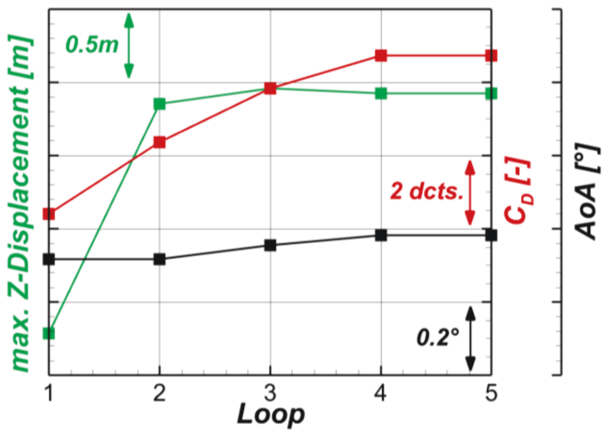

FIG 20: Exemplary history of FSI sizing loop for 2.5g maneuver

The masses from the corresponding structural sizing runs are shown in FIG 21. Each structural sizing loop itself is an iteration as explained in 3.4. All internal sizing iterations have in common that the initial step does not meet all requirements, leading to a mass increase in the following steps. After the second internal iteration however, the update of the starting conditions of the sizing regions leads to a rather close approximation of the converged mass. However, it takes several more iterations to get a converged result as very locally sizing criteria are not met or the algorithm detects property regions with potential for weight saving.

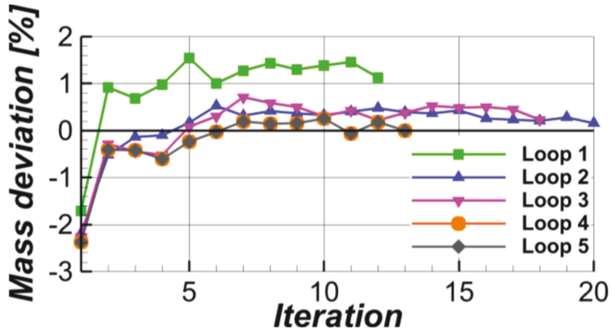

FIG 21: Deviation of sizing result masses compared to converged configuration in the final sizing run

While the difference between the first and second FSI run is comparatively high, from the second loop onwards the overall changes are rather small and show a good convergence towards the final result as each run after the first requires less and less internal sizing iterations. The last two runs are seemingly identical as the loads only change insignificantly.

The deformation of wing and moveable, as shown in FIG 22, are used to check the results after the virtual design. In the lower right part of FIG 22, red represents areas of large and blue of small deformation magnitude. These overall deformation scale shows a reasonable behaviour which still allows the use of linear calculation methods.

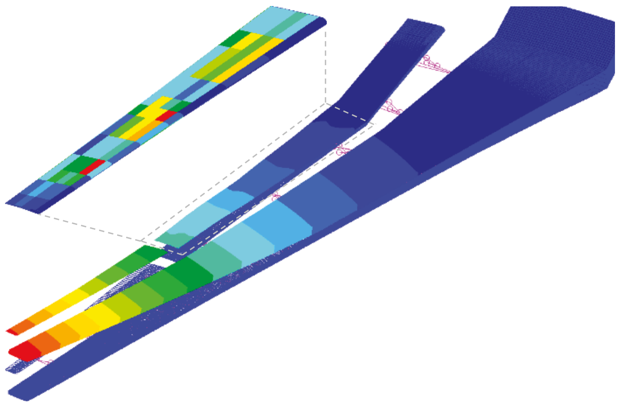

FIG 22: Wing deformation magnitude for FSI 2.5g load case and moveable thickness distribution of sizing result

The upper left part of FIG 22 shows a thickness distribution on the moveable under special consideration. Red depicts domains of high and blue of small thickness. The distribution is in good agreement with the expectations. Especially areas near the load introduction, the skins in the domain of maximum moveable height for maximum bending stiffness and the front- and rearmost spar for torsional stiffness show the maximum thickness.

The final mass determined by the FSI process is in good conformity with reference results as shown in FIG 23.

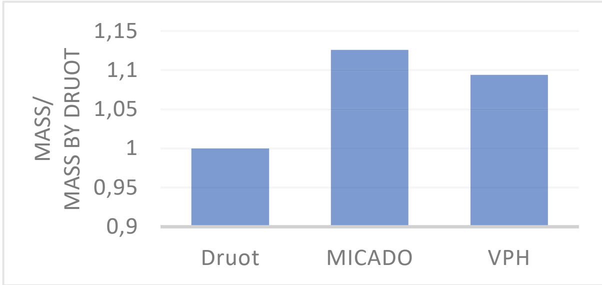

FIG 23: Comparison of VPH results with known mass estimations by [26] and [27]

5 CONCLUSION AND FUTURE WORKS

The presented work shows first results of the virtual design activities in the Virtual Product House. With the aim to create forward-looking virtual product development and certification processes, the participating DLR institutes were able to combine their expertise on the VPH plateau and build a multi-disciplinary design process for wing moveables. This process combines multi-fidelity analysis methods and connected the distributed DLR capabilities in one environment. The first investigations demonstrated the operational readiness. The results meet the expectations. Outputs from the virtual design process were directly forwarded to the virtual manufacturing and virtual testing processes to complement the End-to-End process chain. Moreover, a first external partner was integrated into the common design environment. Building on this, further industrial partners and DLR institutes will join to extend the assessment capabilities. Furthermore, the current process will be utilized for systematic investigations of wing moveables. For example, a variation from composite to metal will be investigated as well as a varying number of flap tracks. In addition, the available design process will be applied to a modification of the existing track-rear link kinematic to an adaptive dropped hinge flap. Finally, the interaction between the design, manufacturing and testing process will be improved to return results from the subsequent processes and consider this information in the virtual design. At the same time, the processes will be further developed and advanced with regards to virtual certification.

6 ACKNOWLEDGEMENTS

The authors would like to thank J. Wild, R. Seidler and S. Melber-Wilkending for providing the geometry of the high-lift configuration, A. Schuster and S. Dähne for the support during the creation of the structural models with DELiS and the sizing with VErSO.

Further, the authors would like to thank the HLRN for providing computational resources.

The Virtual Product House start-up project is funded by the German federal state of Bremen and the European Regional Development Fund (ERDF).

European Union
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European Regional
Development Fund

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