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COLLABORATIVE HIGH FIDELITY AND HIGH PERFORMANCE COMPUTING-BASED MDO STRATEGIES FOR TRANSPORT AIRCRAFT DESIGN

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Abstract

Aviation is undergoing a transformation, fueled by the Corona pandemic, and methods to evaluate new technologies for more economical and environment-friendly flight in a timelier manner and to enable new aircraft to be designed (almost) exclusively using computers are sought after. The DLR project VicToria brings together disciplinary methods and tools of different fidelity for collaborative multidisciplinary design optimization (MDO) of long-range passenger aircraft configurations, necessitating the use of high-performance computing. Three different approaches are being followed to master complex interactions of disciplines and software aspects: an integrated aero-structural wing optimization based on high-fidelity methods, a multi-fidelity gradient-based approach capable of efficiently dealing with many design parameters and many load cases, and a many-discipline highly-parallel approach, which is a novel approach towards computationally demanding and collaboration intensive MDO. The XRF-1, an Airbus provided research aircraft configuration representing a typical long-range wide-body aircraft, is used as a common test case to demonstrate the different MDO strategies. Parametric disciplinary models are used in terms of overall aircraft design synthesis, loads analysis, flutter, structural analysis and optimization, engine design, and aircraft performance. The different MDO strategies are shown to be effective in dealing with complex, real-world MDO problems in a highly collaborative, cross-institutional design environment, involving many disciplinary groups and experts and a mix of commercial and in-house design and analysis software.

Keywords: multidisciplinary design optimization, aircraft design, high-fidelity analysis, high-performance computing, design software

1. Introduction

The development, testing and production of new aircraft and helicopters are associated with considerable temporal and financial risks due to the product and manufacturing complexity. In order to accelerate the introduction of innovative technologies for more economical, more environmentally friendly and safer air vehicles and to better control the technological risks involved, DLR's guiding concept "The Virtual Product" aims at virtualizing the design, development and manufacturing processes, including the definition of an appropriate validation strategy. This guiding concept takes benefits from the continuous development of numerical methods and high-performance computing suggesting that numerical simulations will be applied to a much greater extent for design than in the past.

Multidisciplinary design optimization (MDO) based on a combination of low- to high-fidelity numerical simulation methods, is on the verge of bridging the existing gap between conceptual and preliminary aircraft design. This will enable the use of physics-based methods to cover complex multidisciplinary interactions at an early stage in the overall aircraft design process, and will be of great importance for reliably designing enhanced conventional as well as innovative unconventional aircraft configurations. There is a clear need for research with regard to the use of multi-fidelity, multi-mission, multidisciplinary optimization of realistic aircraft configurations with many design parameters and all relevant constraints. However, various challenges with respect to improved physical modelling, multidisciplinary simulation and optimization on high performance computers, the number disciplines involved, and the amount of communication and iterations among disciplinary experts required to complete the design task must be addressed.

Several of these challenges are being addressed in DLR's research project VicToria (Virtual Aircraft Technology Integration Platform, 2016-2020). VicToria deals with laying the foundations for the comprehensive digital description and development of aircraft and helicopters, taking advantage of modern materials, improved physical modeling, multidisciplinary simulation and optimization on high performance computers while considering relevant physical effects. In addition to highly parallel, highly accurate solvers for fluid/structure coupled simulations also rapid methods for designing and optimizing engines and the overall vehicle are being used. Furthermore, an integrated load process that satisfies the needs of multidisciplinary optimization is being established. With this complete digital representation of the product with all its functionalities and characteristics, it will be possible to set up a "digital twin" that can be used to assess and make use of the potential of new technologies in a virtual design environment by performing trade-off studies and to estimate the impact of new technologies in terms of, for example, weight, fuel burn or environmental impact.

The MDO activities in DLR's research project VicToria bring together computationally intensive disciplinary analysis and design methods from low to high fidelity, necessitating the use of high-performance computing resources for the MDO of long-range commercial transport aircraft configurations. DLR is thus continuing its efforts in this field based on its previous collaborative high-fidelity-based MDO activities in the Digital-X and AeroStruct projects [1],[2],[3],[4],[5],[6],[7],[8].

2. Overview of MDO architectures and process chains

Within the DLR project Digital-X [1] both gradient-based and gradient-free MDO formulations were investigated [4]. While the gradient-based MDO formulation focused on high-fidelity tools, the sequential gradient-free MDO process was based on a multi-level, multidisciplinary feasible (MDF) formulation, comprising low-fidelity, mid-fidelity and high-fidelity disciplinary tools and sub-processes [5]. Setting up the distributed MDO process involved disciplinary expert groups from eight DLR institutes at six sites. DLR's Remote Component Environment (RCE) [7] was used to integrate their tools and sub-process into the overall MDO process, which turned out to be computationally very intensive. The disciplinary tools in a running workflow were executed on workstations with different operating systems at six DLR institutes and on one HPC cluster. The high-fidelity aspect of the workflow introduced very long run times as well. The total run time of a single design analysis (or outer iteration of the optimizer) was of about 24 hours. The workflow had to be restarted often from a state saved at each outer optimizer iteration due to network failures, tool node restarts, and tool node overload. This brought the "effective" run time of a single design analysis, computed as the total workflow run time divided by the number of evaluated designs, to about 56 hours, or more than 2 days. The total run time of a full optimization of the XRF1 long range wide body aircraft (see Section 3) was estimated at 2-3 months.

The objective was to minimize the mission fuel burn of a simplified XRF1 with a conventional all-aluminum fuselage and wing. All design constraints (such as stability margin, landing/takeoff distance, or structure failure criteria) were satisfied within the respective disciplinary sub-processes, so that the outer optimizer worked on an unconstrained optimization problem. Although the complete aircraft configuration was analyzed, only the wing was parameterized with nine selected design parameters, consisting of seven planform parameters and two section parameters. The outer optimizer was a derivative-free Subplex method. More details on the setup of the MDO process, the disciplinary models and the optimization results can be found in [5].

Although the general feasibility of highly collaborative, multi-level MDO with many disciplinary groups was confirmed, the long effective run time of a single design analysis and the challenges associated with the distributed execution of tools and sub-processes motivated moving to an all-HPC based solution. The goal was to explore and evaluate different highly parallel multi-level MDO strategies and to develop a multi-disciplinary HPC integration framework. Another objective was to optimize a more complex powered aircraft configuration with both aluminum and composites wings, parameterized with hundreds of design variables and subject to realistic loads and constraints, including flutter.

This motivated investigating gradients-based MDO formulations, which naturally lend themselves to dealing with many design parameters, as well as novel MDO formulations that can deal with the complexity of real-world MDO problems, including the design of more flexible wings. To this end, three different MDO approaches are being followed in VicToria, which are schematically shown in Fig. 1 to Fig. 3:

1) Integrated process chain for high-fidelity aero-structural wing optimization (Fig. 1). This approach introduces an integrated process chain for aero-structural wing optimization based on high-fidelity simulation methods [3],[8]. The main feature of the process chain is the integrated structural wing box sizing in the parallel static aeroelastic analysis. The focus of this approach is to get a better understanding of multidisciplinary interactions and of the influence of aeroelastic tailoring and structural concept for more flexible wings in the context of wing design and optimization. Furthermore, this approach has been designed for applications with larger geometrical changes and the usage of global optimization strategies.
2) Sensitivity-based multi-fidelity approach (Fig. 2). This approach establishes a multi-fidelity gradient-based process chain that aims at investigating several ways of employing design sensitivities for aircraft MDO [13]. The main disciplines engaged are aerodynamics, structure and propulsion, under the overall aircraft design constraints. Efficient methods for computing cross-disciplinary sensitivities are being developed and employed.
3) Many-discipline highly-parallel approach (Fig. 3). The main goal of this approach, which is also referred to as Cybermatrix, is to deal with the complexity of real-world MDO and to enable effective involvement of many disciplines [14]. The Cybermatrix MDO protocol is a novel approach towards computationally demanding and collaboration intensive MDO. Each discipline is represented by an analysis or design sub-process, which may be of arbitrary type: gradient-based or derivative-free optimization, or a specific design method. Parallelism is sought not only in the execution of the overall MDO process chain, but also in its definition and assembly, such that serial-like bottlenecks can be avoided both in machine and in people. The disciplines comprise: overall aircraft synthesis, aerodynamics, wing structure, fuselage structure, loads, and flight stability.

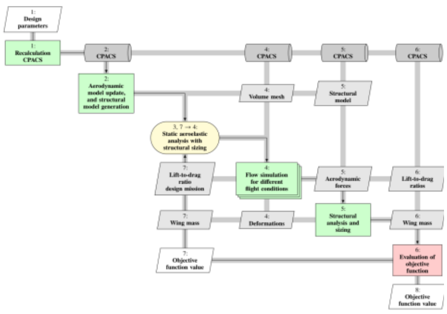

Fig. 1. Integrated process chain for high-fidelity aero-structural wing optimization

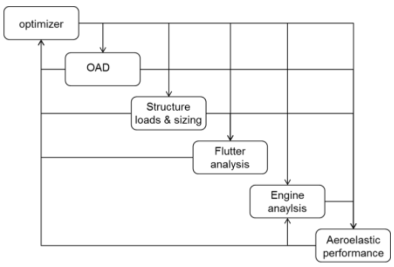

Fig. 2. Sensitivity-based multi-fidelity approach

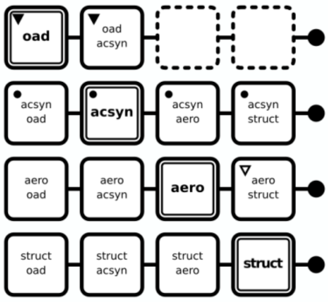

Fig. 3. Many-discipline highly-parallel approach: process definition matrix

3. Description of baseline aircraft configuration

The different MDO strategies are executed and compared based the XRF-1 as a baseline. XRF1 is an Airbus provided industrial standard multi-disciplinary research test case representing a typical configuration for a long-range wide body aircraft [9]. The XRF1 research test case is used by Airbus to engage with external partners on development and demonstration of relevant capabilities and technologies. The XRF-1 is shown in Fig. 4.

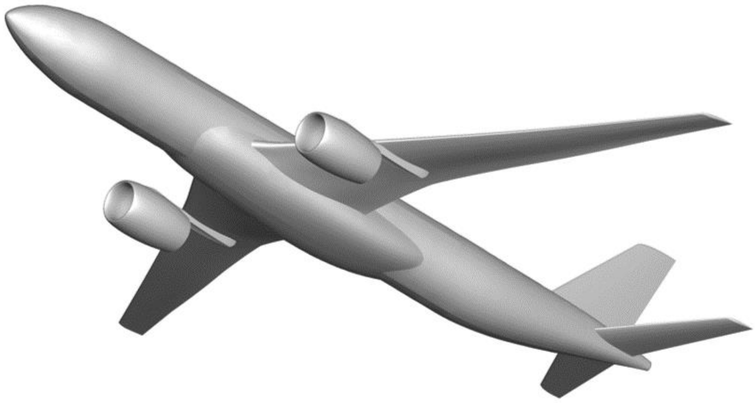

Fig. 4. Half-model of XRF-1 generic long-range transport aircraft used as a baseline for all three MDO strategies.

4. Results

In the following, selected results obtained with all three approaches taking the XRF1 and CRM as a baseline are summarized. Details of the different MDO approaches and more detailed results can be found in [10][16][23].

4.1 Integrated process chain for high-fidelity aero-structural wing optimization

The integrated process chain for high-fidelity aero-structural wing optimization, which is described in detail in [10], was used to optimize the twist and thickness distribution of the Airbus XRF1 research configuration with a conventional composite wing structure. The corresponding result is the baseline configuration for the comparison with the optimization results for the more flexible wing. In the next step the more flexible wing has been introduced by changing the structural concept and the maximum strain allowable. For the more flexible wing the composite layer distribution of the skins, spars and ribs and the twist and airfoil thickness distribution have been optimized. In the last step an aero-structural wing planform optimization with fixed composite layer distribution has been performed for the more flexible wing.

In Table 1 an overview of the selected flight missions and load cases for structural wing box sizing is given.

			Study mission	**High speed mission**	**Design mission**
Flight missions	Weight factor	w_i	0.6	0.1	0.3
	Cruise Mach number	Ma	0.83	0.85	0.83
	Range	R	4000 nm (7408 km)	4000 nm = (7408 km)	6500 nm = (12 038 km)
	Payload	m_P	40 800 kg	40 800 kg	-
			Pull up maneuver	**Push over maneuver**	**Roll maneuver**
Load cases	Altitude	H	0 m	6096 m	0 m
	Mach number	Ma	0.552	0.784	0.552
	Lift coefficient wing fuselage	$C_{L,WB}$	0.739	−0.319	0.493
	Load factor	n	2.5	−1.0	1.667

Table 1: Flight missions and load cases.

With the consideration of geometry constraints for the integration of the landing gear, engine, and the control surfaces a better comparability of the optimization results with the baseline aircraft configuration is achieved. Fig. 5. gives an overview of the geometrical constraints, which have to be fulfilled for each optimized wing design.

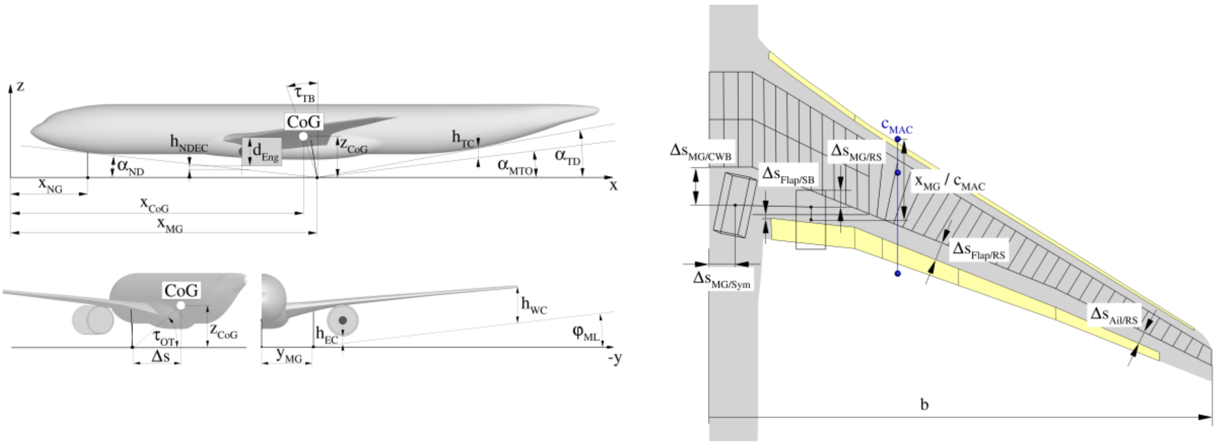

Fig. 5. Geometrical constraints.

The objective function of the multi-mission aero-structural wing optimizations is the combined fuel consumption of the three selected flight missions. With the selected weighting factors the expected relative frequency of the missions in operation has been considered.

Table 2 gives an overview of the design parameters and a selection of constraints. The design parameters include wing planform and wing section parameters. In addition, the percentage ply share in 10% steps of the skins, spars and ribs have been used as design parameters for the more flexible wing optimization. For the conventional composite wing structure of the baseline configuration a fixed standard ply share has been used.

The constraints consist of mass constraints, geometrical constraints for landing gear, engine and control surface integration, and flight mission and structural sizing constraints. A selection of the considered constraints is given in Fig. 5. and Table 2.

Design parameters	Wing area	S
	Aspect ratio	A
	Leading edge sweep angle	φ_{LE}
	Taper ratio inboard	$\lambda_{5/2}$
	Taper ratio mid wing	$\lambda_{9/5}$
	Taper ratio outboard	$\lambda_{14/9}$
	Twist distribution	$\varepsilon_1,\ \varepsilon_5,\ \varepsilon_8,\ \varepsilon_9,\ \varepsilon_{15}$
	Relative thickness distribution	$(t/c)_1,\ (t/c)_5,\ (t/c)_9,\ (t/c)_{14}$
	Rear spar position inboard	x_{RS}/c
	Percentage ply share of skins, spars and ribs	$\left(PS_{0°,skin}\right)_i,\ \left(PS_{0°,spar}\right)_j,\ \left(PS_{0°,rib}\right)_k$
Constraints	Maximum take-off mass	$m_{MTO} = 245\,000\,\text{kg}$
	Maximum payload	$m_{P,max} = 48\,000\,\text{kg}$
	Residual mass ratio	$m_{Res}/m_{MTO} = 0.3763$
	Wingspan	$52\,\text{m} \leq b \leq 65\,\text{m}$
	Fuel tank volume	$V_F \geq V_{F,req}$
	Outer main gear wheel span	$9\,\text{m} \leq 2\,y_{MG} \leq 14\,\text{m}$
	Nose gear static load ratio	$F_{NG}/m\,g = 5\,\%, \ldots, 20\,\%$
	Tip back angle	$\tau_{tb} \geq 15°$
	Overturn angle	$\tau_{ot} \leq 63°$
	Take-off rotation angle	$\alpha_{TO} \leq 9°$

Table 2: Design parameters and a selection of constraints.

For the more flexible wing the structural concept and the maximum strain allowable have been changed. The structural concept of the conventional composite wing structure consists of classical upper skin ply share and blade stringers. For the strain allowable a conservative value of 3500µm/m has been selected as proposed in the Military Handbook [11]. Through a detailed consideration of stringer constraints and stiffness, the evaluation of a more flexible wing becomes possible, while relevant structural constraints are considered. The more flexible wing has been modeled with a stringer dominant structural concept of the upper cover. This includes a selected upper skin percentage ply share of (10/80/10) and the usage of I-stringers. Based on the modified structural concept a value of 5000µm/m has been selected for the strain allowable of the more flexible wing. In Table 3 the differences between the structural concepts of the conventional composite wing and the more flexible wing have been summarized.

For the wing optimizations a surrogate based optimization (SBO) method [12] has been selected. This global optimization strategy represents an adequate compromise between exploring the design space and locating the optimum.

		Structural concept of conventional composite wing	**Structural concept of more flexible wing**
Structural concept of the upper covers		Skin dominated design	Stringer dominated design
Stringer type		Blade stringer	I-stringer
Upper skin percentage ply share center wing box	0°/ ± 45°/90°	70/20/10	10/80/10
Upper skin percentage ply share inboard	0°/ ± 45°/90°	60/30/10	10/80/10
Upper skin percentage ply share mid wing	0°/ ± 45°/90°	60/30/10	10/80/10
Upper skin percentage ply share outboard	0°/ ± 45°/90°	40/50/10	10/80/10
Strain allowable	ε	3500 µm/m	5000 µm/m

Table 3: Structural concept overview.

The resulting wing geometry is presented in Fig. 6. for the twist, thickness and planform optimized configuration with the more flexible wing. In Fig. 6. the resulting wing deformations are presented for the cruise flight condition and the 2.5g symmetric pull up maneuver in comparison to the rigid jig-shape. The more flexible wings show higher deflections due to the modified structural concept and the increased strain allowable.

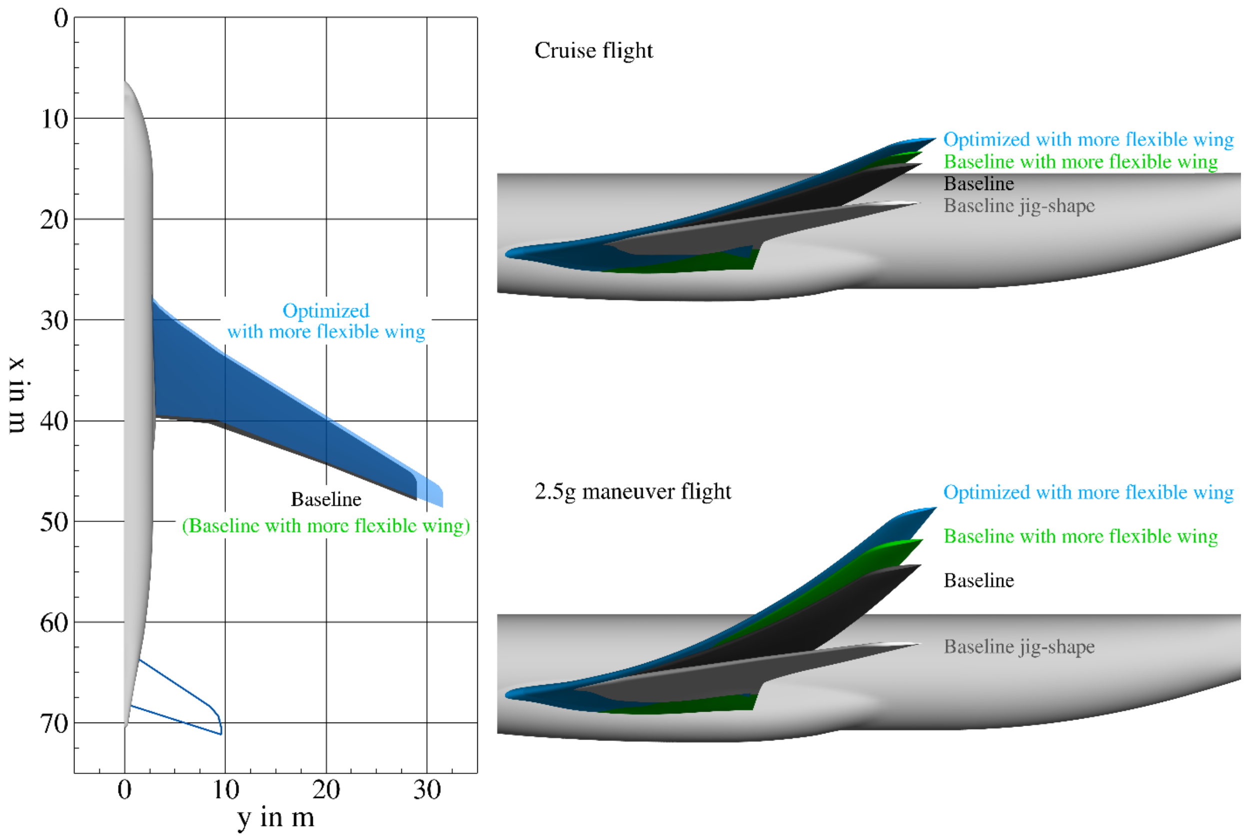

Fig. 6. Geometry and wing deformation overview.

With the introduced more flexible wing concept a reduction of the combined fuel consumption in the order of 3% has been achieved for a constant wing planform. The cruise flight performance of the more flexible wing has been slightly reduced and a significant mass reduction of the wing box in the order of 13% has been computed. This mass reduction of the more flexible wing can be explained with the increased utilization of the composite material and the passive load alleviation under maneuver flight conditions.

To find the optimum trade-off between aerodynamic performance and wing mass for the more flexible wing, the wing planform design parameters have been involved in the wing optimization. The results of this optimization show a reduction of the combined fuel consumption in the order of 5% due to an increased aerodynamic performance under cruise flight conditions. This increase in aerodynamic performance has been achieved with higher aspect ratio and reduced taper ratio of the wing.

In **Fehler! Verweisquelle konnte nicht gefunden werden.** an overview for the results of the aero-structural wing optimizations is shown. For all aero-structural wing analysis the combined fuel consumption, the wing mass ratio, and the corresponding cruise flight performance are summarized. The combined fuel consumption shows the potential of more flexible wings for reduction of the CO_2 emissions per passenger kilometer.

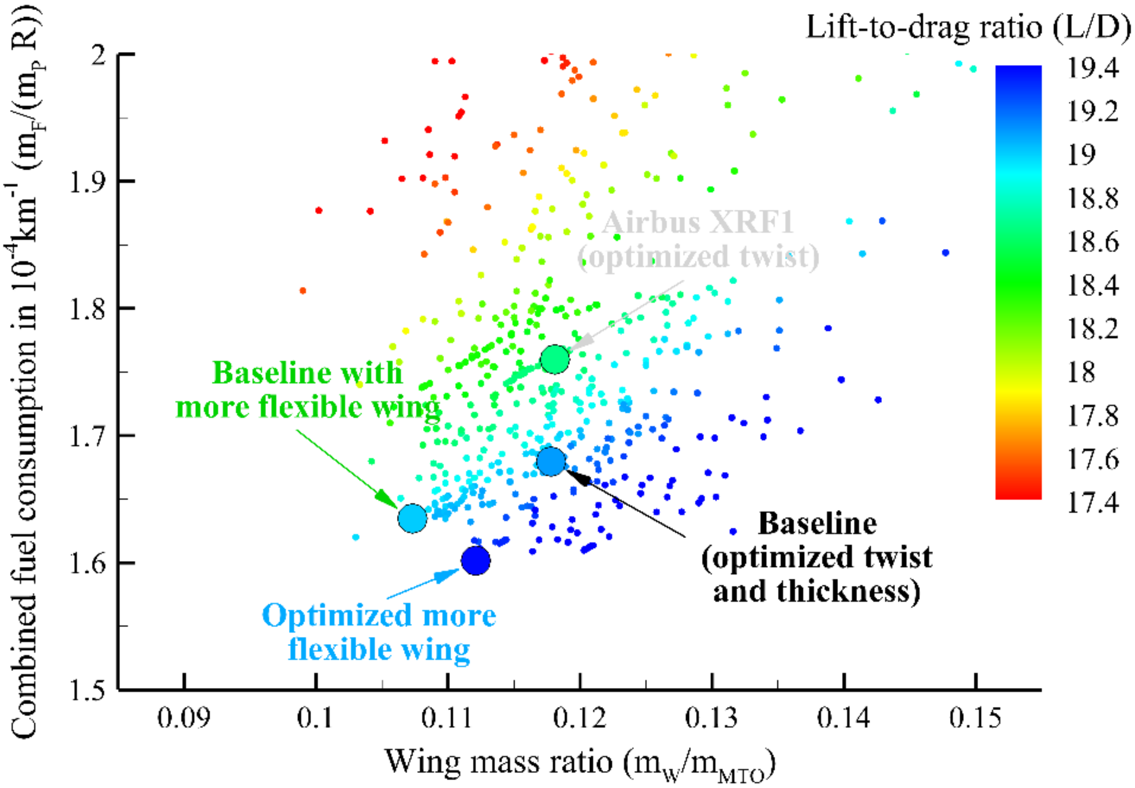

Fig. 7. Aero-structural wing optimization results overview.

4.2 Sensitivity-based multi-fidelity approach for efficient generation of Pareto fronts

The sensitivity-based multi-fidelity approach is described in detail in [16] and is used to optimize the trimmed, powered XRF-1 subject to global aircraft constraints, flutter constraints and a comprehensive set of loads. In terms of the outer shape, a set of 149 design parameters that control the XRF-1 wing planform, several sectional twists, the belly fairing, and seven sections along the wing's span are employed as listed in Table 4. The aeroelastic structural design process cpacs-MONA [17] was used to set-up the structural FE-model of the XRF-1 and to run the structural analysis for a set of 392 structural thicknesses under a subset of the computed 1,080 load cases. The constraints that are tackled in this optimization are listed in Table 5.

Parameter	***Type***	***Quantity***
Wing sweep	Planform	1
Aspect ratio	Planform	1
Twists	Sectional	11
Chord length	Sectional	2
Belly Fairing	control points	8
Profile shape	Sectional	126
Structure material	Thickness	392
Sum		**541**

Table 4: Design parameters for the gradient-based multi-fidelity, multidisciplinary optimization

Constraint	***Type***	***Discipline***	***Quantity***
$\sum F_{x,y,z} = 0$ $\sum M_{x,y,z} = 0$	Aircraft Trimming	RANS-based Aerodynamics	6
Take-off field length (@MTOW) Landing field length (@MLW)	Preliminary Sizing	Overall aircraft design	2
Longitudinal tip-over Lateral tip-over Nose landing gear effectiveness	Landing gear integration	Overall aircraft design	3
Static stability margin	Stability	Overall aircraft design	1
Approach speed (ICAO Category C) Wing span (ICAO Code E)	Airport requirements	Overall aircraft design	2
Flutter Structural strength Structural buckling Control surface efficiency	Structure related constraints	Structure Mechanics	20 15,680 15,680 1

Table 5: Design constraints for the gradient-based multi-fidelity, multidisciplinary optimization

The objective function to be improved in the optimization and which is employed to generate the Pareto front is:

$$Objective = W * (1/SR) + (1 - W) * (M_{Empty})$$

$$SR = \frac{C_L}{C_D} * \frac{M_{Empty\_reference}}{M_{Empty}}$$

Where W is the weighting factor, $M_{Empty}$is the empty mass of the aircraft, SR is the so-called specific range and C_L and C_D are the lift and drag aerodynamic coefficients.

For each new feasible design, the sensitivities of the cost functions, including objective and constraints, with respect to the design parameters are computed and forwarded to the optimizer to decide how to take the next step towards a new, better design.

The classical approach for generating a pareto front using gradient-based algorithms was employed for the single-point (Ma=0.83 and $C_L = 0.5$) MDO task with the multi-objective function mentioned earlier (fuel burn and empty weight). In this approach, several parallel MDO tasks that have different weighting factor (W) are executed. Here, W changes from 0 to 1. A value of 0 means that the optimization aims at reducing the empty mass, and a value of 1 means that the optimizer should improve the specific range, as shown in the formulation of the objective above.

For this study, 14 parallel optimizations were executed as depicted in Fig. 8. As expected and reported in the literature, this approach results in a non-homogeneous distribution of designs along the pareto front. In case the designers are interested in spotting designs in the empty regions along the front, they need to execute new optimizations by guessing the weighting factors, based on the results obtained.

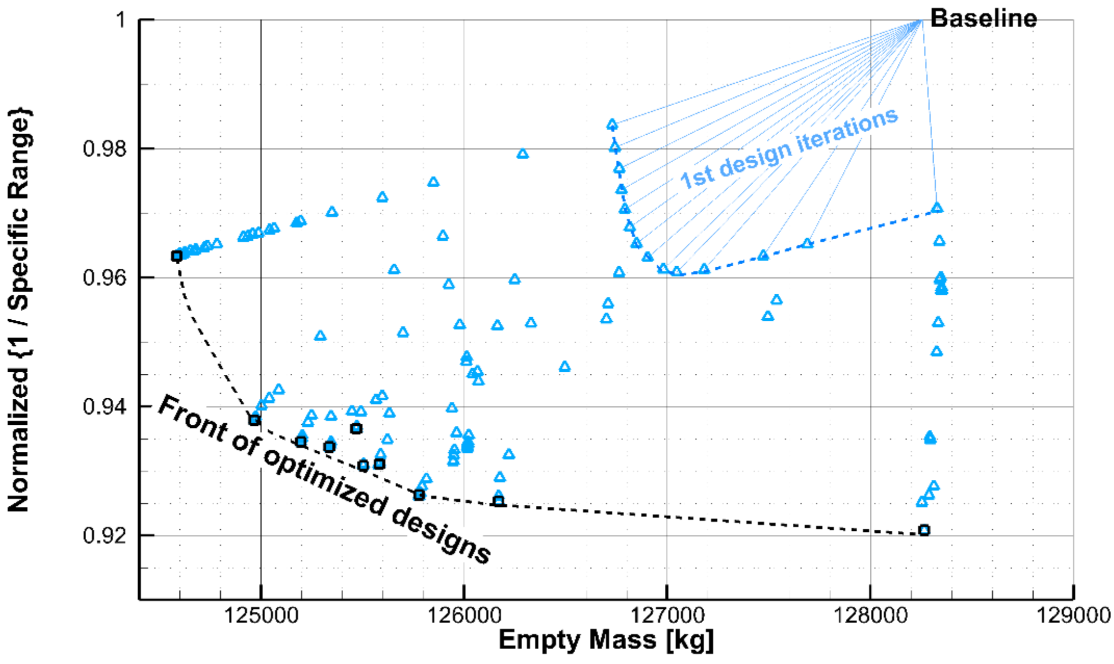

Fig. 8: convergence of the parallel MDO tasks and the resulting Pareto front

Fig. 9 shows the most extreme geometrical changes resulting within the Pareto front, namely for the empty mass reduction MDO and the specific range MDO. As shown in the figure, the mass reduction MDO, resulted mainly in reducing the aspect ratio of the wing which resulted in less mass and a higher bending at the wing tip, when compared to the baseline configuration. It can also be seen that the pressure distribution and the shock strength remained unchanged in the mass reduction optimization.

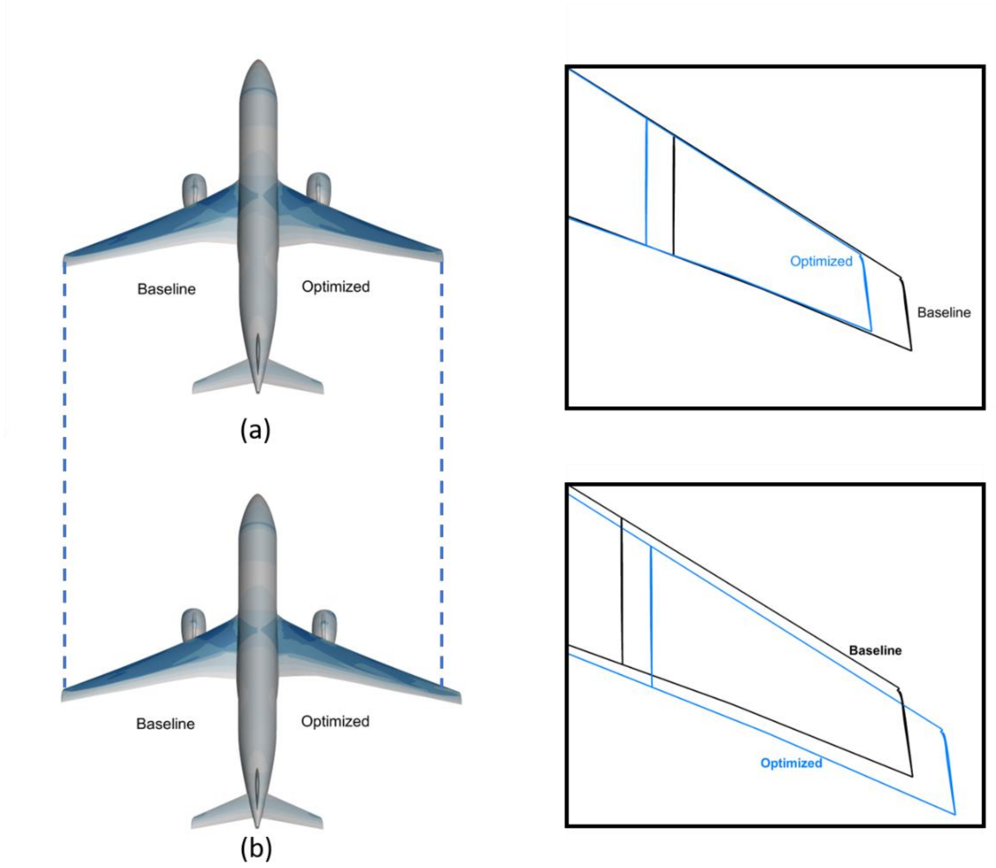

Fig. 9: Pressure distribution and main geometrical changes for the two extreme MDO tasks; the mass reduction (upper) and the specific range improvement (lower)

To understand the effect of shape changes on the loads, the two-dimensional load evaluation for the baseline and the mass reduction optimized configuration is depicted at different spanwise monitoring stations in Fig. *10*. In all four figures the convex hull for the bending (M_x) and torsional (M_y) moment of the main wing is displayed. The width of the convex hull remained unchanged for the two configurations at all stations, while the hull has been rotated counter clock-wise for the optimized design. That means that the optimized design has higher maximum and minimum torsional moments, while the maximum and minimum bending moments mainly scale down. The most vigorous rotation of the convex hull can be seen at the wing tip (η=0.92).

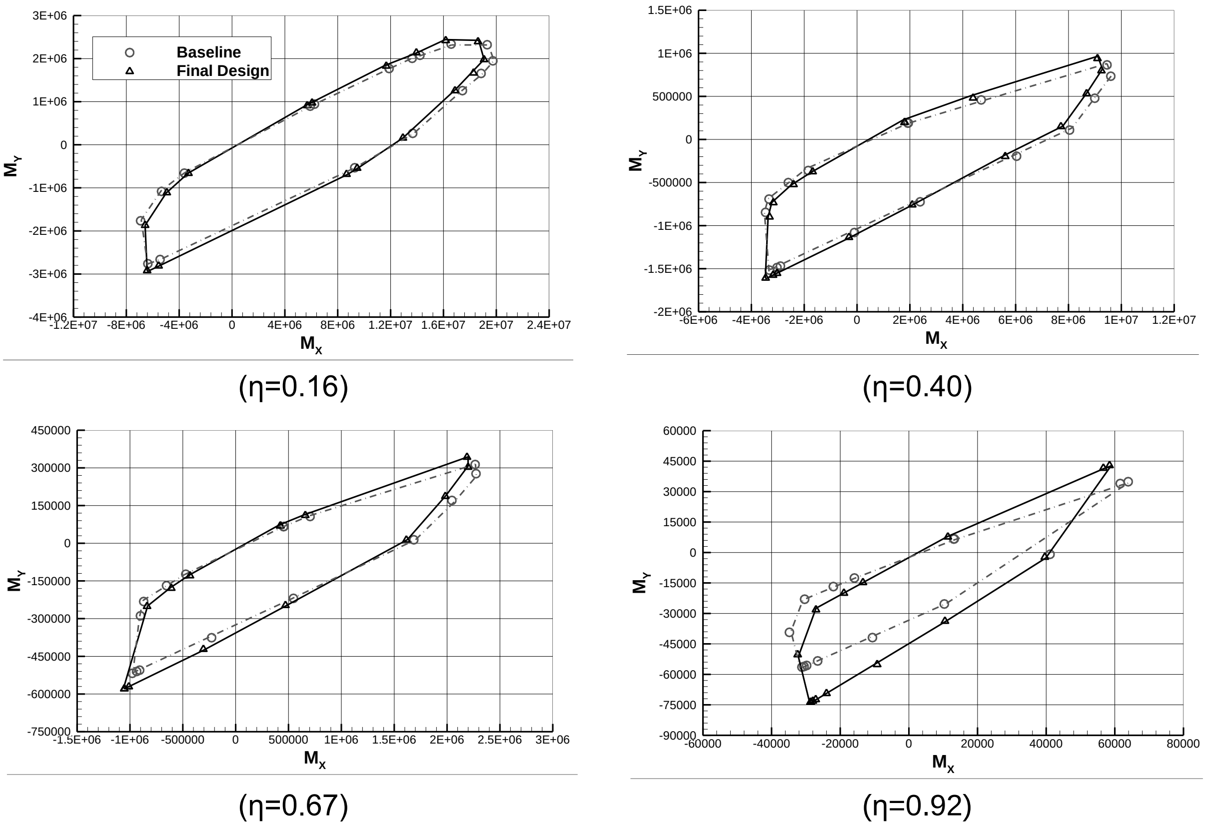

Fig. 10: Convex hull for the cutting loads Mx vs. My at different spanwise monitoring stations

Finally, a look at the change in thickness distribution is depicted in Fig. 11. The figure shows that the thickness increased close to the wing tip, while the thickness generally reduced otherwise. The reason for the increase seems to be related to the higher torsional moments close to the wing tip (Fig. 10, η=0.92).

The specific range improvement optimization, on the other hand, showed a different behavior and remarkably increased the aspect ratio and the wing sweep of the wing. These two factors affected negatively the structural mass of the wing, however they improved the specific range, mainly by reducing the aerodynamic drag over the wing.

Finally, it is worth reminding the reader here that obtaining the Pareto front for such complex and computationally intensive MDO tasks would have not been computationally feasible using genetic algorithms, and in any case not as efficient as shown here. The results here were obtained within 3-5 days for this single-point MDO task using 256x14 cores.

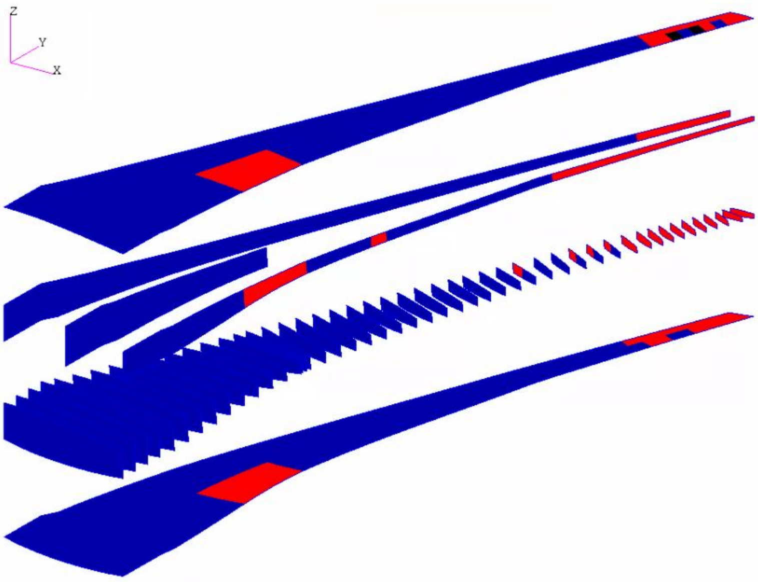

Fig. 11: Change in thickness distribution over the optimization; Blue regions: thickness reduction, red regions: thickness increase, black region: constant thickness

4.3 Many-discipline highly-parallel approach

The many-discipline highly-parallel approach, which is a novel approach for dealing with highly collaborative and computationally intensive multi-disciplinary aircraft optimization problems and is described in detail in [23], was so far employed to perform an overall aircraft optimization of XRF-1. The overall objective was to minimize mission block fuel. Four disciplines were employed, as follows:

- Overall aircraft design (**oad** in the figures below): a derivative-free optimizer using mission block fuel as local objective, and wing aspect ratio and leading-edge sweep as design parameters.
- Aircraft synthesis and mission evaluation (**acsyn**): a handbook method for mass accumulation (maximum take-off, cruise, maximum landing) and Breguet-based mission evaluation. This was a pure evaluation discipline; there was no local objective, constraints or design parameters.
- Aerodynamic wing airfoil design (**aero**): trimmed aeroelastic adjoint gradient-based optimization process, using a hybrid RANS mesh with 5,900,000 points. It had 126 airfoil shape parameters distributed among 7 spanwise sections, for controlling camber and thickness distribution, and 3 trimming parameters (angle of attack, horizontal tail incidence, engine throttle). The local objective was to minimize drag, while the constraints were three-degree of freedom force balance for steady flight.
- Design loads evaluation and sizing of wing and tail structure (**struct**): evaluation of 1,080 load cases with the aeroelastic structural design process cpacs-MONA [17] using a doublet-lattice method (DLM) for aerodynamics, a global dynamic FEM model with 42,000 elements and gradient-based structural sizing. There were 392 structural thicknesses of design regions as design parameters. The local objective was to minimize structural mass, and there was one strength and buckling constraint per design region and load case, yielding 846,720 constraints in total. A 1D-envelope reduction of the set of constraints is performed for each design, resulting in around 100 load cases (or 80,000 down-selected constraints) being applied within gradient-based sizing.

In fact, the complete set of design parameters was the same as in Table 4. The aerodynamic and structural disciplines were the same as employed in Sec. 4.2., but in a less coupled manner (e.g. no interdisciplinary gradients between them).

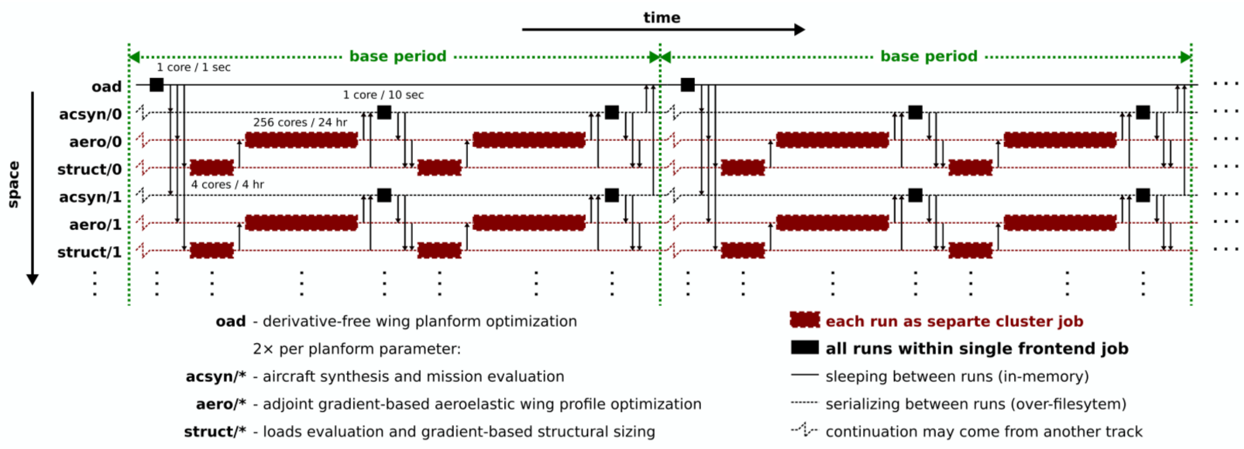

Fig. 12. Many discipline highly-parallel approach: process implementation of the Cybermatrix

The process implementation of the Cybermatrix from Fig. 3, containing these four disciplines, is presented in Fig. 12. It can be seen that the process has a repeating pattern in time, called the base period. Within one base period, first the optimizer issues several planform design evaluations (two per planform design parameter plus one, for total of 5). For each planform, first runs a struct block, then an aero block, and finally an acsyn block; this sub-pattern repeats twice within one base period. The struct internally performs two loads evaluation and structural sizing loops, aero performs one aero-structure coupled evaluation and gradient computation followed by one line search, and acsyn evaluates the Breguet mission and reassembles masses. The fuel mass is then sent from each planform back to the optimizer, to start the next base period. This is just one possible implementation pattern, which can be easily reconfigured within the process integration framework called MDO Driver [14]. The particular pattern on Fig. Y was driven mostly by a desire to reduce the use of Nastran licenses as much as possible, rather than, for example, by available computational resources.

The optimization run where all design parameters were employed achieved 10.4% drag reduction, traded off with a 16.8% increase in wing mass, resulting in overall block fuel reduction of 10.3%, compare Fig. 13 entry *optimized planform and airfoils*. The baseline and optimized wing planforms are shown in Fig. 14. It took 12 days of "clean" run time (wall run time was 16 days due to cluster maintenance, waiting for software license availability, and fixing some implementation defects that surfaced at process restarts) and used at peak 1,281 computational cores. Wing aspect ratio was considerably increased and wing leading edge sweep moderately so, wing sections were aerodynamically re-twisted to reduce shocks, while significant wing mass increase was caused by having a much more slender wing.

Another two optimization runs were performed, where some design parameters were frozen. In one case, first the airfoils alone were optimized for the baseline planform, then the planform was optimized with fixed airfoils (entry *optimized planform at fixed baseline-optimized airfoils* in the figures). The result was very little change in planform, due to airfoils being very tightly adapted to the baseline planform. In the other case, the baseline airfoils were preserved while the planform was optimized (*optimized planform at fixed baseline airfoils*). Here there was some change in planform, but far from the result with all parameters free. These runs demonstrated that it is crucial to optimize both airfoils and planform in a coupled fashion.

Furthermore, the "baseline" for comparisons is taken to be a result of an optimization run in which both the aircraft planform and airfoil design parameters were fixed to preserve the outer shape, while aerodynamic control parameters and structural thickness parameters were optimized to reach a feasible design. In Fig. 13, the baseline points are not connected to the rest of the convergence curve, because the optimization reaches a feasible design only in the final converged state. When only the airfoils and structural thicknesses were allowed to change (entry *baseline planform, optimized airfoils*) while baseline planform was kept fixed, the overall block fuel reduction was 5.6%, about half that of when planform was allowed to change as well. This quantifies the distribution of improvement between airfoils and planform.

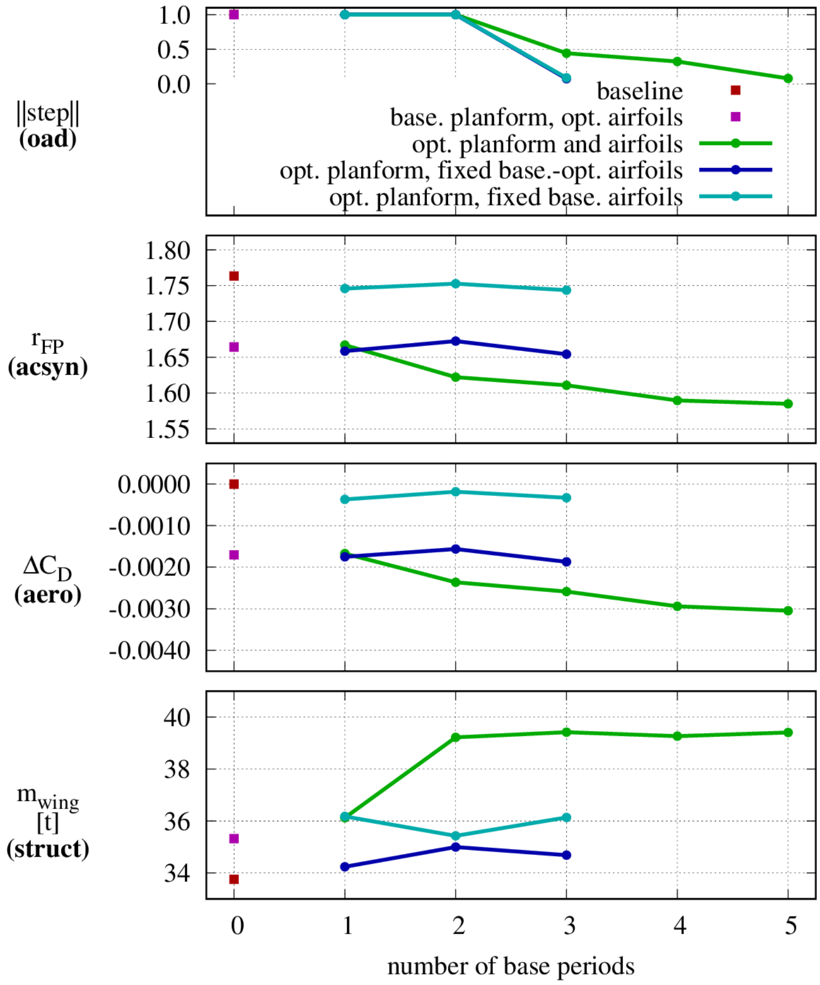

Fig. 13. Results of many-discipline highly-parallel MDO approach for XRF-1 in terms of norm of normalized planform parameter step (top), mission block fuel mass (second from top), drag coefficient (third from top), and structural wing mass (bottom), as a function of number of base periods, for different optimization setups.

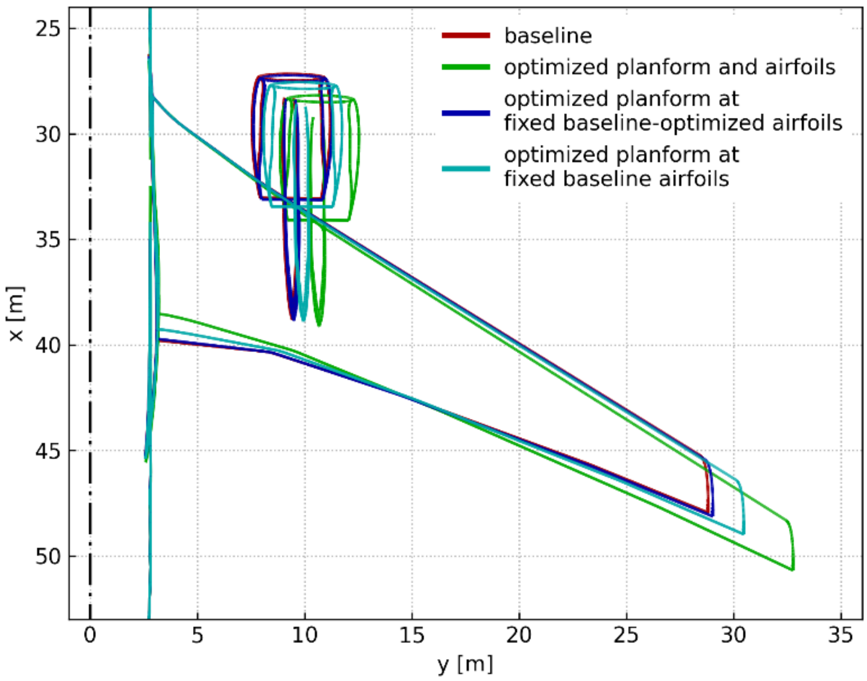

Fig. 14. Comparison of baseline and optimized planform (many-discipline highly-parallel MDO approach), for different optimization setups.

5. Further Development in terms of Disciplinary Sub-Processes, Geometry Sensitivities and Integration Environments

MDO approaches for overall aircraft design based on high-fidelity tools and methods usually go hand in hand with complex computational processes. This is especially the case as the number of the disciplines and the complexity of the disciplinary methods and models increases. Apart from aerodynamic performance analysis of the flexible aircraft using high fidelity CFD, further disciplinary sub-processes were part of the three previously addressed MDO processes. They were overall aircraft design (OAD) synthesis, loads analysis, structural optimization, and engine design. In the following, selected aspects of their complexity when dealing with a high-fidelity based MDO approach are explained. Also, further developments in terms integration frameworks helping to integrate and maintain a large number of disciplinary tools and processes are summarized. Finally, the complexity of having a fully differentiated analysis process in the context of gradient-based MDO is addressed in terms of efficiently computing consistent geometry sensitivities.

5.1 Overall Aircraft Design Synthesis

The overall aircraft design synthesis sub-process is necessary to ensure an aircraft design that fulfills the global requirements. As some results of the disciplinary methods affect also global aircraft parameters (e.g. wing position at the fuselage, structural weight, aerodynamic characteristics) an appropriate exchange of disciplinary results is considered. An important example of the necessity to incorporate OAD methods within the MDO process can be seen in the aircraft's consistent mass breakdown in Fig. 15.

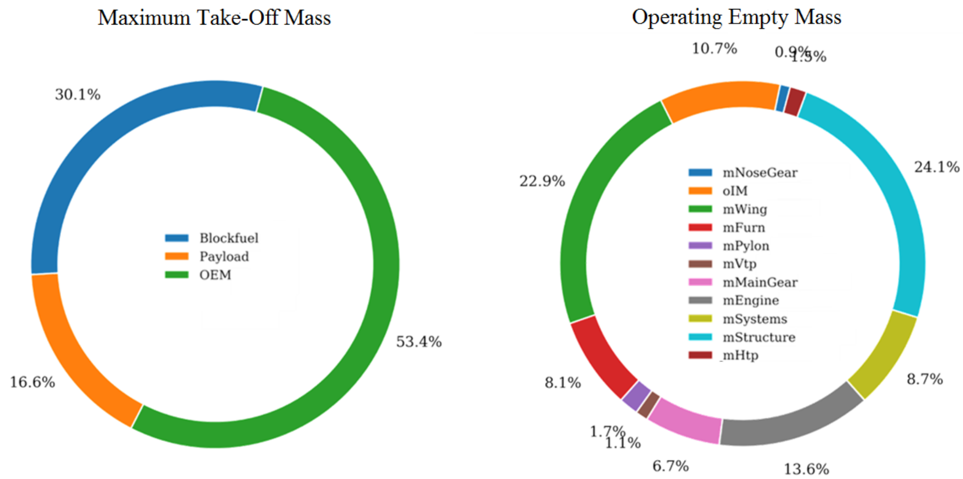

Fig. 15. DLR interpretation of the XRF1 mass breakdown as output of the conceptual aircraft design tool openAD

Along with the aerodynamic character and the engine performance, the gross mass and the related center of gravity is heavily impacting overall aircraft performance as shown in Fig. 16 for the flight trajectory and the payload range characteristics. Therefore it is vital to update the overall aircraft design in every MDO loop.

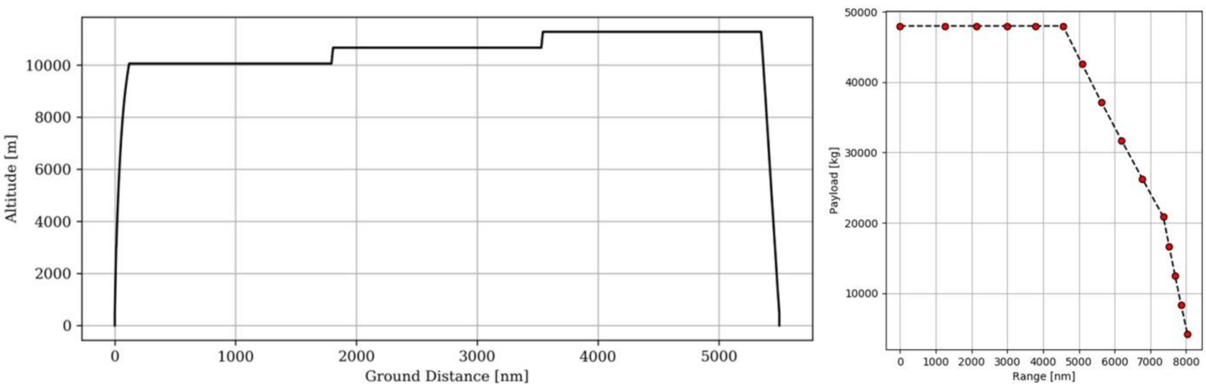

Fig. 16. Flight trajectory of the XRF1 design mission and payload range characteristics as output of a DLR mid-fi standard workflow for overall aircraft design

5.2 Loads Analysis

For the aero-structural wing optimization, apart from the aerodynamic optimization, an integrated and highly parameterized sub-process has been established, called cpacs-MONA. The aeroelastic structural design process cpacs-MONA starts with the parametric model set-up for the load-carrying structure, for the loads analysis of the complete aircraft and for the structural-optimization using finite element analysis. Afterwards a comprehensible loads analysis of the flexible structure is performed to estimate the loads the load-carrying structure of the aircraft has to withstand. These loads are furthermore used to perform a component-wise structural optimization, leading to a solid structural design. The structural modelling for the loads analysis and the gradient based structural optimization is founded on a common parameterization concept for the outer geometry and the housing basic load-carrying structure for the complete aircraft. The impact of the extensive loads analysis, covering maneuver and gust loads as well as conceptual ground loads, on the structural design, can be seen in the correlation of design fields to corresponding dimensioning load cases. Fig. 17a displays the impact of the landing loads on the area where the landing gear is attached to the wing box structure, while gust encounters evidently affect the wing tip region more extensive compared to the other load types. In Fig. 17b, the corresponding design responses are highlighted for each design field of the wing box. It can be seen, that buckling is a design driving criterion for the ribs up to the kink of the wing and mainly for the mid-spar, while the minimum allowable stress is dominating the upper and lower skin elements.

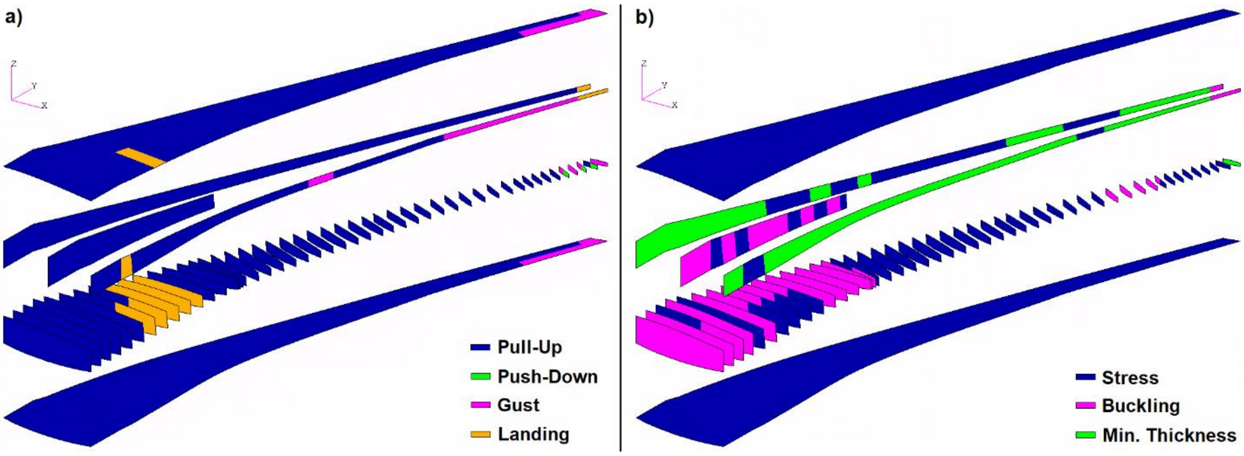

Fig. 17. Structural wing box of XRF1 showing areas where specific load types are dimensioning (a) or where specific design responses are dominating (b)

Furthermore, the comprehensive loads analysis allows for an even more sophisticated investigation regarding the design loads at arbitrary stations of the load reference axis of the aircraft configuration. In Fig. 18 it is shown that at a particular wing station the pull-up (*LLFPU*) and the push-down (*LLFPd*) maneuvers lead to the maximum respectively minimum loads, while the gust cases (*LLFGxxyy*) have to be also taken into account as design loads as far as they are part of the loads envelope. On the right-hand side of Fig. 18, the load cases selected for the structural optimization are listed using their internal load case keys. This key highlights the mass case, the design speed, the flight level and the load condition of the load case. Besides the load case parameters also the aircraft configuration is highlighted at the beginning of the load case key. It can be seen, that for the pull-up and push-down maneuvers the load alleviation configuration (*CML*) has been used to reduce the corresponding loads, while the gust case has been calculated using the clean (*CCD*) configuration. The visualization in Fig. 18 also gives the possibility to individually group the mass cases or the different maneuvers.

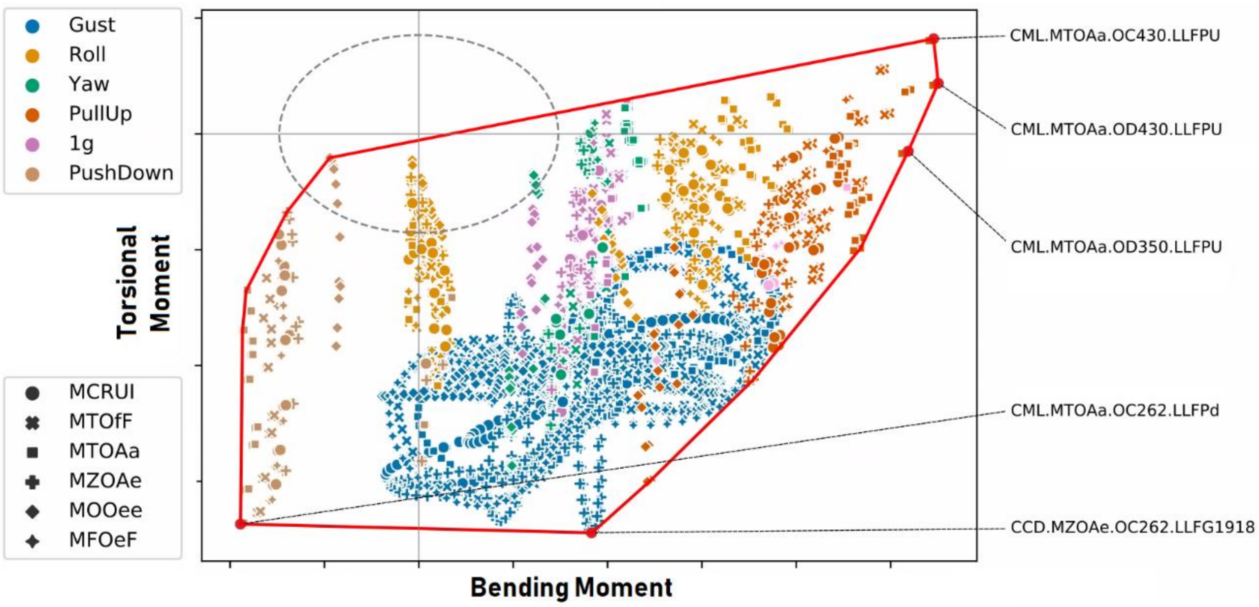

Fig. 18. Loads at a selected station of the XRF1 wing and the loads envelope

The loads analysis itself comprises the classical open loop maneuver and gust load cases, but allows also for the inclusion of an active flight control system. While the flight control system design is mainly driven by flying quality considerations, the influence of automatic flight control functions on structural loads can be substantial [24]. Furthermore, an active flight control system can enhance the characteristics of an aircraft by employing load alleviation functions and hence reduce the design loads in maneuver and gust conditions, as well as improve the drag performance by optimizing the lift distributions of flexible aircraft in cruise conditions [25].

In the so-called Control Configured Vehicle (CCV) method, the flight control law design is an integral part of the optimization and hence flight performance boundary conditions, active load alleviation etc. have a direct influence on the optimal aircraft configuration. The significance of the consideration of flight control methods for loads alleviation can be seen in Fig. 19. Therein the bending and torsion moment due to gust excitation at a specific station for a defined gust excitation at a specific flight point are displayed with (closed loop) and without (open loop) load alleviation.

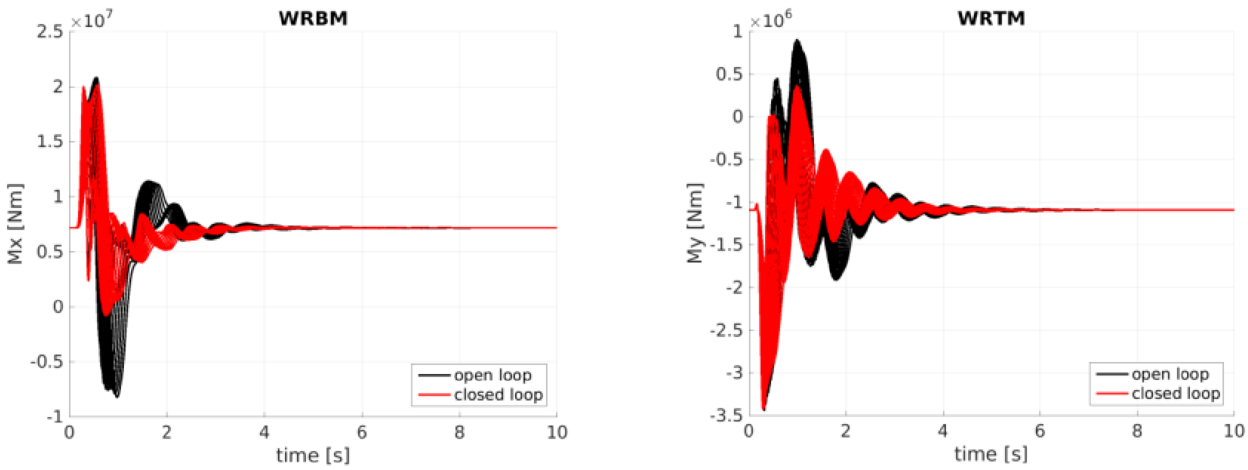

Fig. 19. Wing root bending and torsional responses of XRF1 due to longitudinal gust excitations

5.3 Structural Analysis and Optimization

In order to incorporate detailed structural aspects, within another MDO approach for the wing and the fuselage, detailed and component wise and independent structural simulation models were set-up parametrically and sized with loads from a separate loads analysis process. Within the loads analysis the individual structural models were integrated and condensed into a suitable structural simulation model for the complete aircraft. The sizing allows the mapping of design load cases to zones respectively local areas of the structure. Furthermore, enhanced failure criteria, like local buckling, can be considered for the sizing. The sizing results for the wing exhibit a thickness distribution on the different load carrying parts of the wing as seen in Fig. 20 (left). The high thickness of the wing mid spar in the center wing box is coincident with the high bending moment near to the wing root. For a detailed structural analysis within the sizing process, different methods for integrating further modeling details like maintenance manholes can be also used. Exemplary models with such detail element can be seen in Fig. 20 (right).

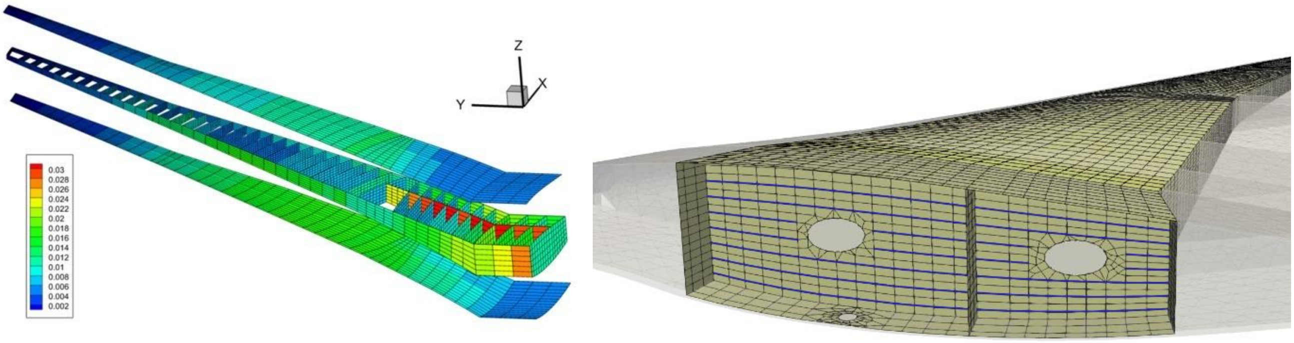

Fig. 20. Spanwise thickness distribution of the sized XRF1 wing (left) and finite element model of the XRF1 wing with detailed elements like manholes (right)

The parametric fuselage model includes a detailed representation of the local fuselage reinforcements to transfer the loads from the wings and empennage into the fuselage primary structure. Structural components in the center fuselage area such as load introduction frames, reinforced pressure bulkheads, the keel beam as well as the main landing gear bay are modelled individually using shell and partly beam elements for structural reinforcement. In similar detail the load introduction of the horizontal and vertical tailplane are modelled. Exemplary structural meshes are presented in Fig. 21.

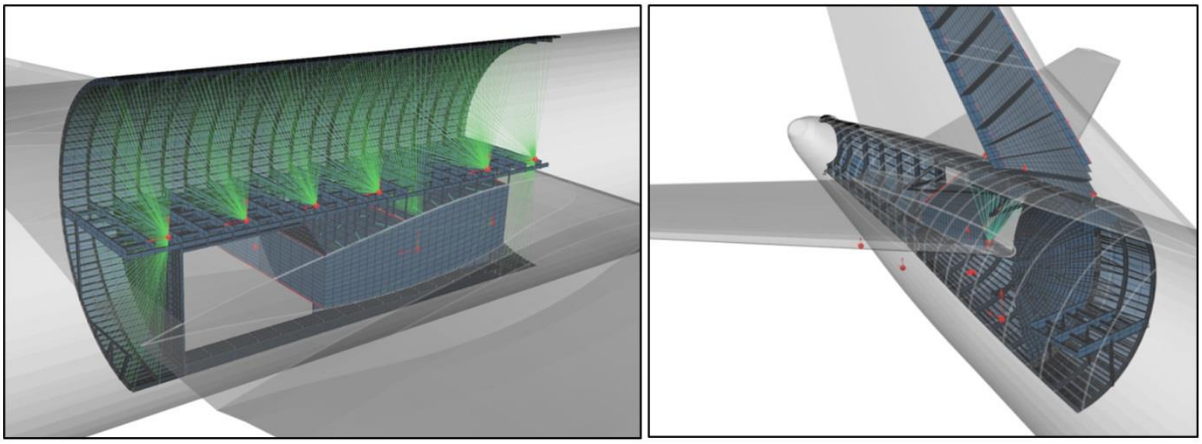

Fig. 21. Representation of load introduction areas of the XRF1 fuselage model

As a result of structural analyses and a subsequent sizing process under consideration of strength and stability criteria for the fuselage shell, the required shell thickness to withstand all relevant load cases from the loads analysis are calculated in an iterative way using a flexible in-house sizing algorithm that can be used together with various structural solvers such as ANSYS, NASTRAN or B2000++. For the solver B2000++ the DLR has access to the sources, so that it can be transferred to various hardware platforms and the analyses can be performed without proprietary licenses. In Fig. 22 an exemplary distribution of the required shell thickness of each skin bay between adjacent stringers and frames based on a few representative maneuver load cases is shown. As expected, the required shell thickness increases towards the center fuselage area and in the region of the window belt, where the distance or the stringers is larger and therefore the stability criterion forces the process to increase the shell thickness.

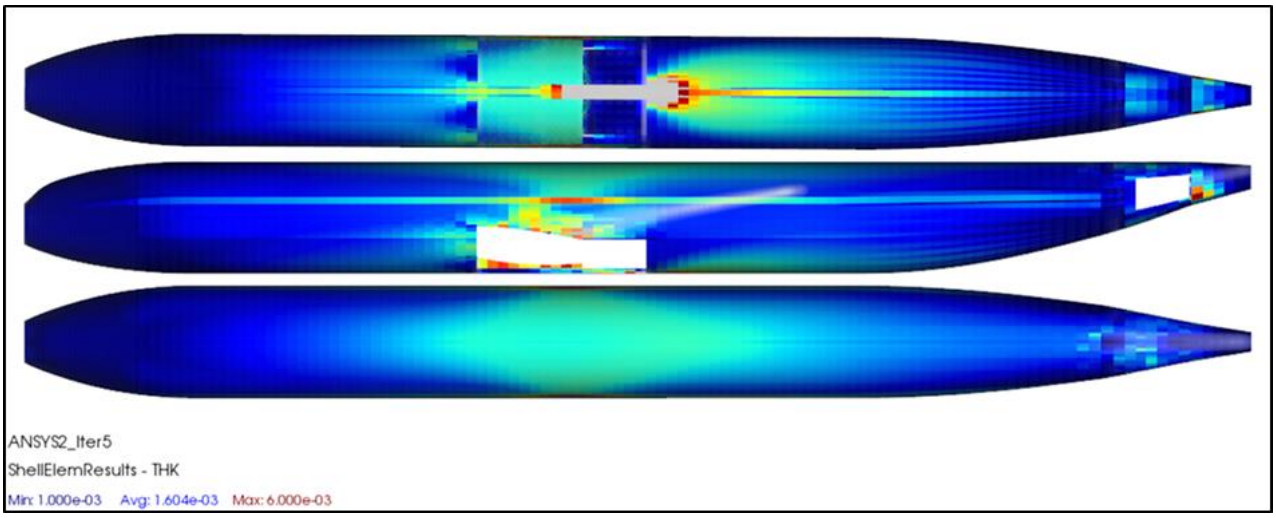

Fig. 22. Calculated shell thickness of XRF1 fuselage based on exemplary set of load cases

The consideration of carbon fiber reinforced plastic material for the wing is done in another gradient based structural optimization approach. Therein a parametrization concept with lamination parameters as design variables is used. Static strength criteria, like buckling and damage tolerance, are incorporated as well as manufacturing criteria. A semi-analytical approach is used to represent the stringer stiffener without modeling them in the connected FEM model. Thus an easy variation of stringer geometry and their properties is possible without rebuilding the FEM model. Feeding back the corresponding ABD stiffness allows a correct stress and deformation analysis. Fig. 23 shows the distribution of critical failure criteria for the reference XRF1. Local criteria are important as seen in Fig. 23, where the local buckling criterion is critical for the main part of the upper cover.

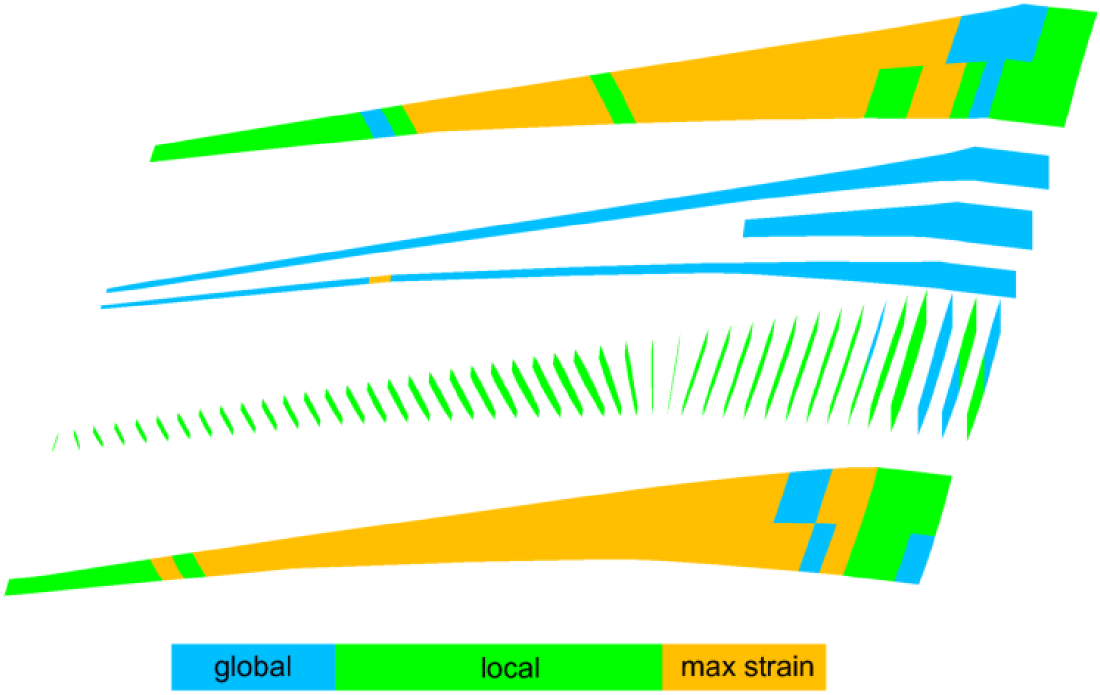

Fig. 23. Critical design criteria for the reference XRF1 wing

5.4 Engine Design

The virtual engine platform Gas Turbine Laboratory (GTlab) [26][27] is used for the engine design in VicToria. In order to cover the most important coupling influences between the aircraft and the engine during the MDO, not only performance parameters like the fuel consumption but also the engine dimensions, weight and center of gravity have to be provided. Therefore, an engine design methodology has been developed that combines thermodynamic cycle analysis with a knowledge-based procedure for geometry modeling and a semi-empirical part-based method for engine weight estimation [28]. The design of the thermodynamic cycle is performed within an iterative process considering technological constraints as well as requirements arising from the overall aircraft design, e.g. thrust demands, power off-takes and bleeds at different operating conditions. The engine geometry is modeled using the thermodynamic cycle data and a knowledge-base that is extracted from a well-known reference engine. For example, this knowledge-base includes nondimensional blade parameters and normalized B-splines describing the mean line and the annulus height of components. An exemplary geometry of a 3-spool turbofan engine that was created with the knowledge-based procedure is shown in Fig. 24. The engine weight is estimated based on the created geometry and thermodynamic cycle data considering the maximum load conditions. A material is selected for each component using the database within the GTlab framework and the yield strength is modeled as a function of the temperature. The thickness of casings is calculated considering blade-off scenarios. In a semi-empirical approach, the weight of parts is determined, e.g. blades, disks, casings, frames, shafts. The combination of the geometry and the weight of parts leads to the center of gravity of the engine. In order to integrate the engine design into the MDO process, the approach of a hybrid surrogate-based rubber engine model was pursued [28]. The rubber engine model covers a range of engine designs for different combinations of design variables and requirements. Thereby, the dimensions, weight and center of gravity as well as the detailed operational performance over the entire flight mission are provided for each engine design. This allows an engine sizing and the optimal selection of major engine design variables within the MDO process.

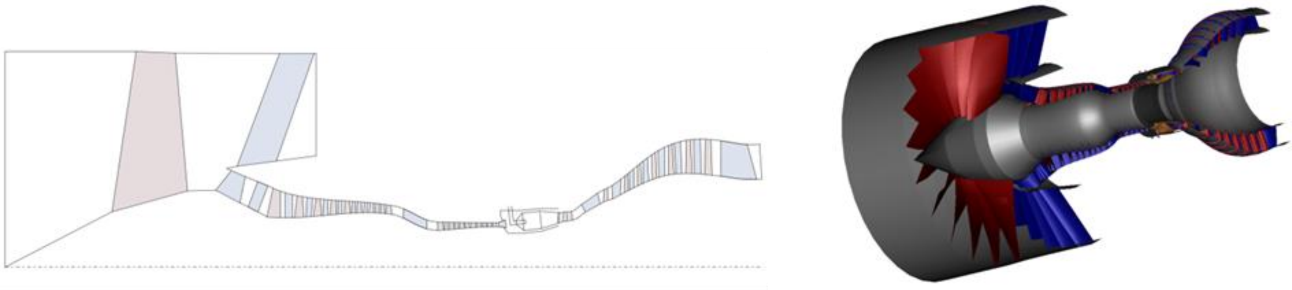

Fig. 24. Example of engine geometry created with the knowledge-based procedure

The results of an engine design study are shown in Fig. 25 to illustrate the described procedure. The thrust specific fuel consumption (TSFC) and the bare engine weight (W) vary with the bypass ratio (BPR) of the engine and the required thrust (FN) at cruise. The fan radius is depicted by dashed lines.

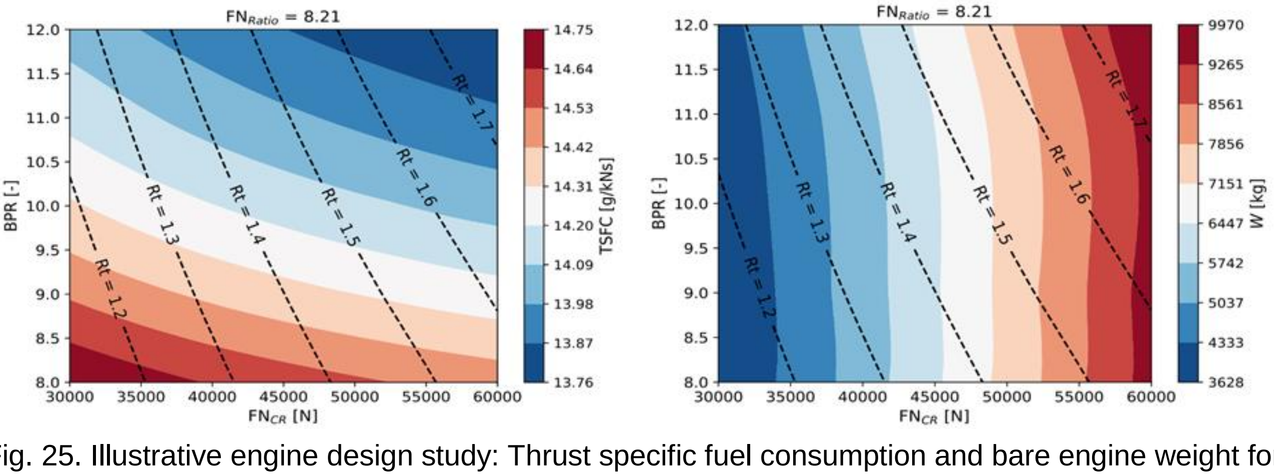

Fig. 25. Illustrative engine design study: Thrust specific fuel consumption and bare engine weight for a variation of bypass ratio and cruise thrust

5.5 Geometry and Sensitivities

When it comes to gradient-based MDO formulations as presented above, it is also required to be able to efficiently compute consistent geometry sensitivities, i.e., the sensitivity of the grid to the change in geometrical shape controlled by the design variables. The challenge is to map an existing mesh that corresponds to an initial geometry onto a second slightly altered geometry. The rationale for the latter is that the currently used geometry kernels are not differentiable in the AD-sense. As such, one has to fall back to either finite-difference approximations of gradients or to differentiated reduced-order models of the CAD kernel. The gradients one is interested in for shape optimization are, e.g., the derivatives of the mesh node coordinates with respect to geometrical design parameters. Hence, in order to calculate these gradients using a finite-difference approximation, one has to perturb the geometry a bit, and then relate this to the resulting deformation of the mesh. However, in order to compute the mesh deformation, it is not feasible to just remesh the perturbed geometry, since a mesher still might generate a new mesh that deviates substantially from the original mesh. In particular, the new mesh might contain different numbers of nodes and elements than the original mesh, thus making it impossible to track the movement of a single node.

A new geometry library called Maplib was developed to replace the second meshing step by firstly projecting the original mesh onto the original geometry, and then secondly mapping the resulting projected node coordinates onto a new geometry. Since the mapping step is realized by an elastic deformation, it is also ensured that small geometric perturbations result in small mesh perturbations, thus making the whole process continuously differentiable. This is illustrated in Fig. 26.

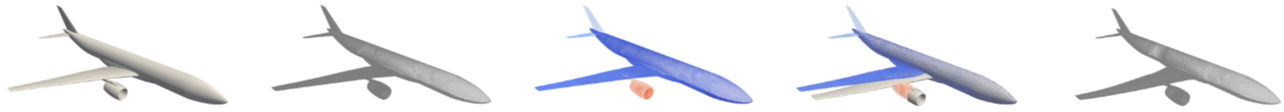

Fig. 26. Mapping an existing mesh onto a second slightly altered geometry to compute geometric sensitivities: initial geometry, initial mesh, projection of mesh into parameter space of geometry, new geometry, elastically deformed mesh to match the new geometry (from left to right)

5.6 Integration Environments

While an entirely new multi-disciplinary HPC integration framework was developed in VicToria to address the specific needs of the many-discipline highly-parallel approach [14], the integration environment RCE (Remote Component Environment) [29],[30] was extended in order to model the construction and execution of intertwined MDO processes and sub-processes. RCE allows users to implement multidisciplinary design optimization processes using arbitrary disciplinary tools such as structural solvers or optimizers. These tools can range from experimental self-developed software to industrial off-the-shelf solutions. While RCE allows for quick iteration on the composition of an MDO process, it did not previously provide facilities to extract and encapsulate sub-processes.

Fig. 27 (left) shows a simplified MDO process implemented in RCE. Here, the yellow boxes denote a top-level optimizer that drives the upper loop as well as disciplinary components. Conceptually, this workflow comprises two functions, namely the high- or low-fidelity simulation of some data in the upper part on the one hand, and the evaluation of that data in the lower part on the other hand. Moreover, the workflow contains two control structures. The optimizer component on the left-hand side drives the upper loop and thus controls the process on a high level. The left-hand yellow circle in the top half of the workflow denotes an exclusive choice between either high- or low-fidelity simulations. That choice is determined via some external input and controls only the upper part of the MDO process.

RCE was extended to allow encapsulation of such sub-processes, which enabled refactoring the workflow shown in Fig. 27 (left) into that shown in Fig. 27 (right). Here, only the top-level control element, i.e., the optimizer, remains visible, while the details of the simulation and evaluation of the data are hidden from view. This allows the designer of the MDO process to concentrate on one level of abstraction at a time, thus facilitating rapid development of such processes.

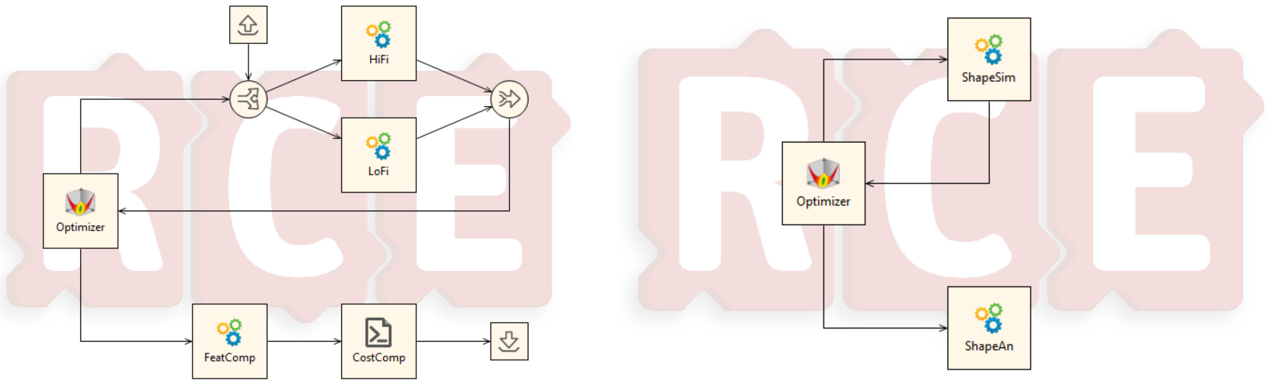

Fig. 27. An illustrative multidisciplinary workflow in RCE (left) and a workflow implementing the same multidisciplinary analysis using workflows as components (right).

6. Conclusions and Outlook

We have shown how we tackle complex collaborative MDO problems with three different strategies, making use of design tools of different fidelity, gradient-based and gradient-free optimization algorithms, and high-performance computing. The gradient-free MDO chain was used for optimizing a highly flexible composite wing. An efficient process chain based on high-fidelity simulation methods and a global optimization strategy was used for this purpose. The multi-fidelity gradient-based process aimed at combining aero-structural optimization with overall aircraft design, engine design, loads and aeroelastic stability analysis. It was shown to be very efficient when dealing with many design parameters and when computing Pareto fronts. Finally, the Cybermatrix MDO chain was developed to facilitate the coupling of many complex disciplinary design processes of different fidelity into an overall process running on an HPC cluster for the purpose of aircraft design. Typical wall-clock times of the many-discipline, highly-parallel Cybermatrix approach are on the order of 10 day, which is a drastic improvement over its precursor, which was a sequential collaborative multi-level MDO process.

All three chains were used to optimize the XRF1, which is an Airbus provided industrial standard multi-disciplinary research test case representing a typical configuration for a long-range wide body aircraft.

Apart from aerodynamic performance analysis of the flexible XRF1 using high fidelity CFD, further disciplinary sub-processes were part of the three MDO processes. They were overall aircraft design (OAD) synthesis, loads analysis, structural optimization, and engine design. Selected aspects of their complexity when dealing with a high-fidelity based MDO approach were summarized. Also, further developments in terms integration frameworks helping to integrate and maintain a large number of disciplinary tools and processes were summarized. Finally, the complexity of having a fully differentiated analysis process in the context of gradient-based MDO was addressed in terms of efficiently computing consistent geometry sensitivities.

The three different MDO process chains will be used and further developed in DLR's oLAF project (Optimally Load-adaptive Aircraft, 2020-2023), which is dedicated to the detailed investigation and quantification of the potential of aggressive load reduction in aircraft design. The focus is on the highly integrated design and optimization of a long-range aircraft, driven by load reduction aspects from the very beginning of the design phase, predominantly by applying high-fidelity coupled procedures for aerodynamics, structure, aeroelasticity, loads, flight control and systems, and on the evaluation of the resulting optimally load-adaptive solution with regard to flight physical performance, technical feasibility, operational capability, maintenance aspects and economic efficiency. In addition, existing simulation methods and processes for multidisciplinary analysis, design and optimization of load-adaptive aircraft will be sharpened and further developed. The goal is to come up an efficient MDO process with interfaces to overall aircraft design and engine design that is sustainable and modular, that can handle many design parameters and constraints and that has the ability to consider high-fidelity aerodynamic loads in the loads process by making use of reduced-order models for steady and unsteady loads on the basis of highly accurate CFD calculations.

7. Acknowledgments

The authors would like to thank Airbus for providing the XRF1 test case as a mechanism for demonstration of the approaches presented in this paper.

To limit the number of authors on the first page, the first author has chosen to list the "architects" of the three MDO chains and maximum two co-authors per department for every DLR institute involved in this project; however, this work is the collaborative effort of 41 colleagues from nine different DLR institutes at seven different sites, who all contributed over time with various levels of involvement. Aside from those listed as authors, the first author wishes to thank the following people, listed in alphabetical order, who also made significant contributions:

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9. Copyright Statement

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