On the Structural Design of a Hydrogen-Powered Commuter Configuration with Distributed Electric Propulsion in the Context of a Multidisciplinary Conceptual Workflow

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Abstract

The aeronautical industry is facing a fundamental transformation. Climate change and plain finiteness of fossil resources necessitate a strategic shift in the transportation sector while being confronted with an ever-growing demand. Airborne traffic, in particular, is vulnerable, due to its dependency on dense and efficient energy storage. Popular fossil alternatives, like fully electric or hydrogen powered, while promising in terms of reduction in emission of climate active gases suffer from increased complexity and - so far - worse energy density.

To face these challenges in an interdisciplinary manner, the German Aerospace Center (DLR) founded the Facility for Small Aircraft Technologies as a collaborative research platform on climate neutral aviation. As part of this part of this initiative, the project D-LIGHT+ aims to develop a hybrid electric commuter class aircraft featuring distributed propulsion and hydrogen powered fuel cells. This project combines the expertise in conceptual aircraft design, fuel cells, carbon fibre hydrogen tank design, electrical power trains, and loads analyses and optimization of load carrying structures. Furthermore, the project aims to compose a highly automated design workflow, interlinking the various disciplines, while accounting for their interdependency and various levels of fidelity.

This work focuses on the design of the primary lifting surfaces, with an emphasis on their structural design. Consequently, the challenges posed to the loads and optimization process emerging from the highly automated and intertwined workflow in combination with the deviation from classical aircraft design are discussed. The presented approach includes a semi-automated process for placement of topological components, the generation of distributed mass models using information provided by the partners, aeroelastic load analyses, as well as the generation of optimization models for the load carrying structures. In this context, software for generating structural optimization models is presented and the results of topology studies are discussed. Finally, the impact of the topological findings and structural optimization on the overall aircraft design is assessed.

Figure 1: Concept of the Hydrogen Powered D-LIGHT+ Commuter Aircraft with Distributed Electric Propulsion

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1 Aircraft Characteristics

The depicted configuration is a commuter class nine-seater with distributed electric propulsion. The desired maximum take-off-mass ($MTOM$) is set to 5700 kg in order to account for runway limitations of various European commuter airports. The target range is set to 600 km and a cruise speed of 300 km/h. Multiple aircraft parameters such as the position of the stabilisers and the wingspan are subject to optimisation and thus not fixed. Several approaches for the integration of the large fuel cells, the thermal management systems, and the hydrogen pressure tanks have been analysed throughout the project. Considerations for redundancy, crashworthiness, efficiency, and flexibility lead to the approach depicted in Fig. 2. This concept consists out of 10 individual, fully redundant *pods*, each combining a subsystem of fuel cells, thermal management, and electric propulsion. The hydrogen tanks are fastened on top of a wider centre wing box, encapsulated by a fairing.

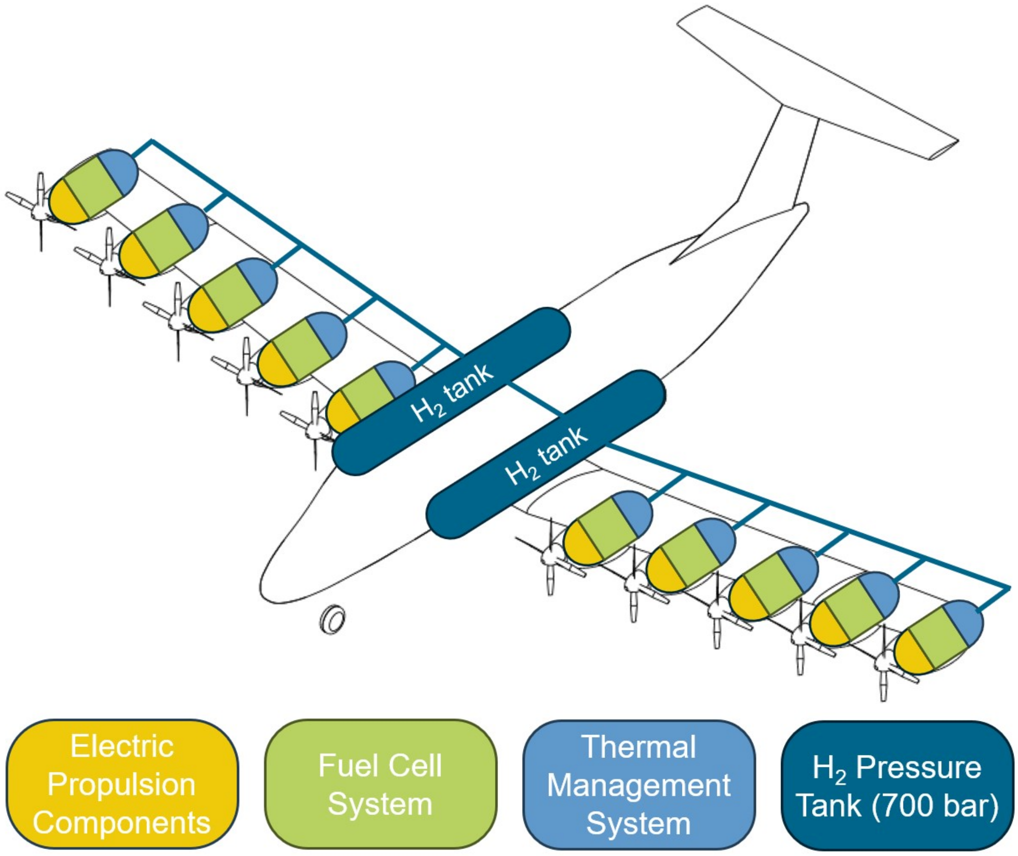


Figure 2: Project Workflow

2 Project Design Workflow

The D-LIGHT+ project combines the expertise of eight different DLR-Institutes, each specialising in various fields, such as aerodynamics, structural design, hydrogen fuel cells, hydrogen tanks, aeroelasticity, conceptual design, electric propulsion, or flight control. To account for the interdependency of all these disciplines, a tool chain (Fig. 3) is set up, linking each design software remotely by the use of the application *RCE*. By doing so, each software is encapsulated into its own virtual environment, decentralising the execution. In an effort to further increase the flexibility of the workflow, some tools are hosted in as containers in a kubernetis cluster in Würselen. Each set of top-level requirements is initially used for the compilation of conceptual design, before being handed to more focused disciplines. The results of the disciplines are then again compiled by a conceptual design. This sequence is repeated until convergence. Information is exchanged based on the descriptive language *CPACS*. Developed at the German Aerospace Centre (*DLR*), it is capable of describing whole configurations in a standardised manner.

The current state of the project is depicted in Fig. 4. The mass breakdown (Fig. 4a)) indicates, that

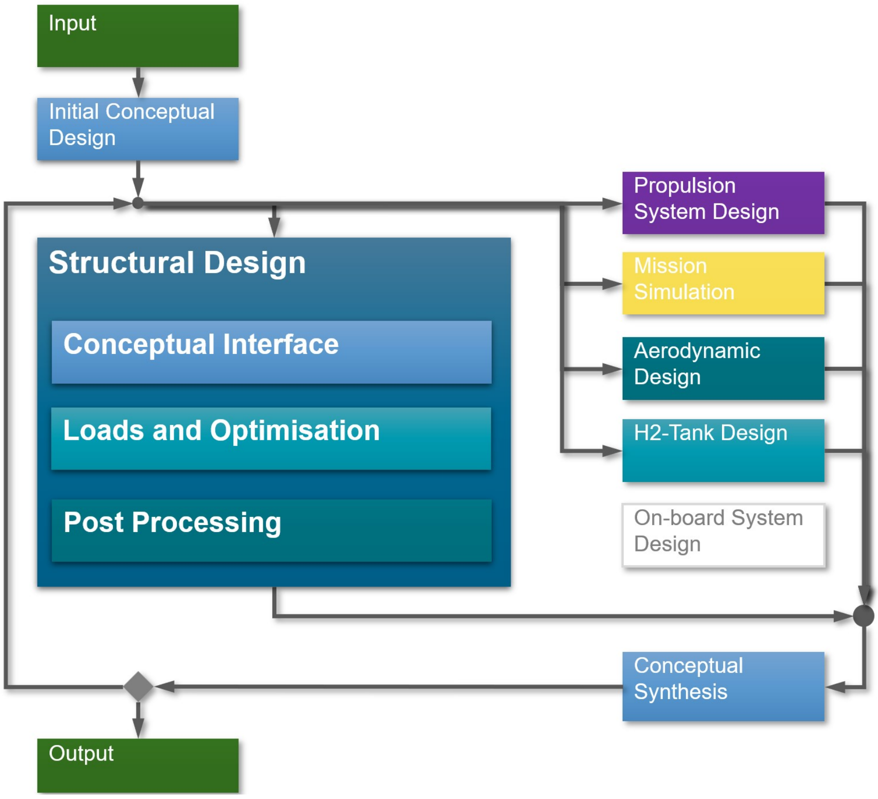
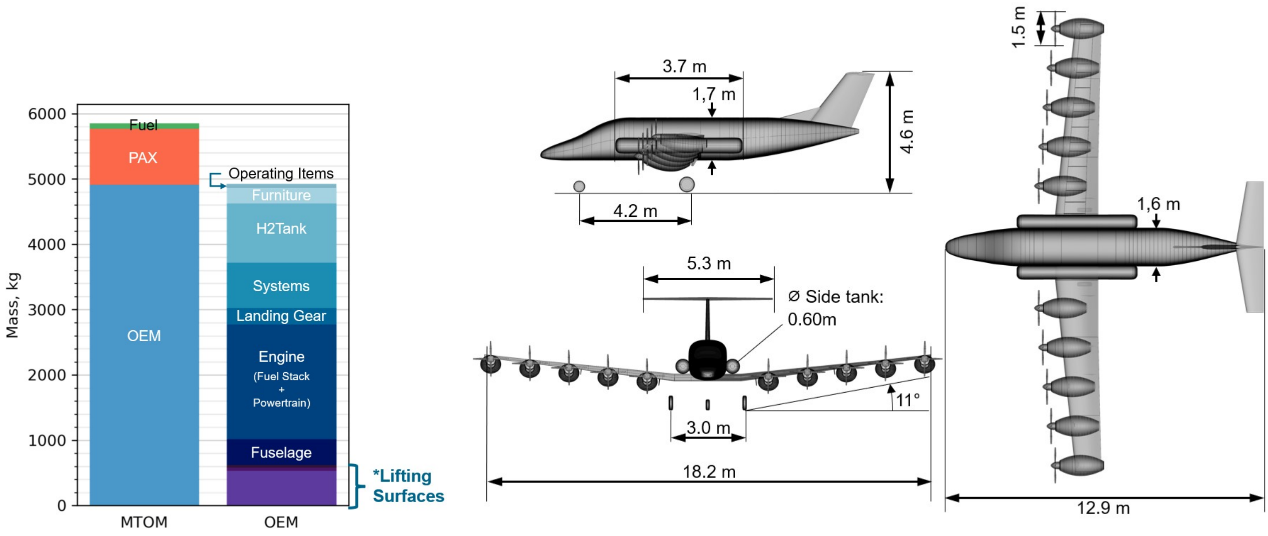


Figure 3: Project Workflow

the overall MTOM-target of 5700 kg is exceeded by 155 kg. Despite the overall mass being dominated by the heavy hydrogen systems, this circumstance motivated the assessment of topological aspects in the structural design of the lifting surfaces, as part of a broad effort to increase efficiency.



a): Mass Breakdown b): Aircraft Dimensions

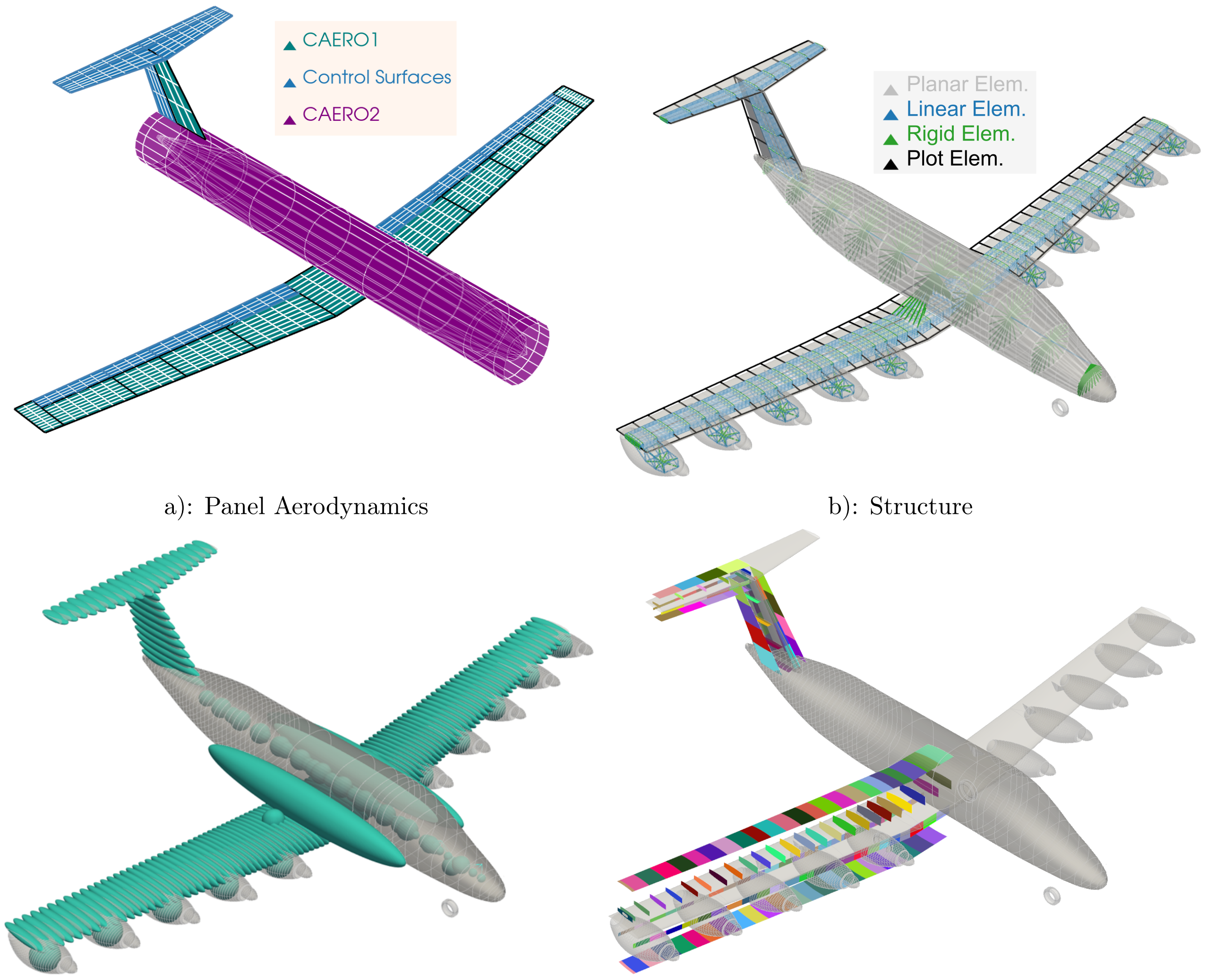
Figure 4: Workflow Results

3 Aeroelastic Structural Optimisation Procedure

The structural design of the lifting surfaces is separated into three modules. The first module composes an interface to the conceptual design. Since the aeroelastic simulations of the structural design are typically executed at the preliminary design stage of an aircraft, some data gaps have to be filled in order to enable more complex analyses. This included the synthesis of a mass envelope by blending stability and loading curves of the configuration. Another aspect is the definition of a topological layout.

Based on the geometry defined in the CPACS data file, topological features are placed parametrically inside the lifting surface shells. The position of the rear spar is limited by the position of the control surfaces. Upper and lower skin are determined by the shape of the aerofoils. The position of the front spar, the number of stringer, and the maximal distance of the ribs can be specified as parameters exposed by the software module. However, some ribs are mandatory. Two ribs are generally placed per engine pod. Additionally, ribs are placed at the beginning and the end of the wing box, as well as at the intersection of inner and outer wing box. Finally, the wing-wing and wing-fuselage attachments are defined.

The updated dataset is subsequently handed over to the loads and optimisation software cpacs-MONA. It uses the data to synthesise the flight envelope and to define load cases. Afterwards, a plethora of simulation models are composed, including panel aerodynamic (Fig.5a)), finite-element structure (Fig.5b)) and mass distributions (Fig.5c)).



a): Panel Aerodynamics b): Structure

c): Mass d): Design Fields

Figure 5: Aeroelastic Model Components

The aerodynamic model constitutes an assumption, since it represents a clean wing configuration. The current state of the software is not capable of simulating propeller engines and their interaction with the wing. Thus, no 1P-loads, no gyroscopic effects and no blown-wing characteristics are considered.

The structural model of the wing box is subsequently sized in a preliminary manner, using a cross-section approach (*PCS*) in combination with conceptual load estimations. In this stage, another parameter can be used to define how the required cross-section area is split between planar and stiffening bar elements. This factor, from here on called *PCS-factor*, is the ratio of the cross-section area of the stiffening elements over the cross-section area of the planar elements. Since the structural optimisation of the wing box focuses on the thickness of the planar elements, this factor is currently the only implemented way to alter the size of the stiffening elements. Consequently, reducing the size of the stiffeners increases the design space of the planar elements, potentially reducing structural mass in the optimisation. However, this comes at the cost of potential buckling of the stiffened panel, which is not constraint in during the structural optimisation.

After the PCS, coupled elastic load cases are simulated using the CSM-software *MSC.NASTRAN*. This work focuses on several manoeuvres, such as pull-up, push-down, rolling, yawing, Pratt-gust cases, and landing load cases. Cases identified as dimensioning are consequently used for structural optimisation. The optimisation has the target to minimise the structural mass, while satisfying stress and intracell buckling constraints. Aileron effectivity is ensured by a separate optimisation run. This procedure is carried out until the structural mass and maximum root loads converge. Finally, a flutter check is performed and results are parsed back to the CPACS dataset.

To enable the topological study, an additional linear buckling analysis is carried out in order to assess the minimal buckling load factor. This analysis can also be incorporated into the structural optimisation. However, due to limitations in the CSM-software, this approach affects the design of the wing box and is therefore not utilised.

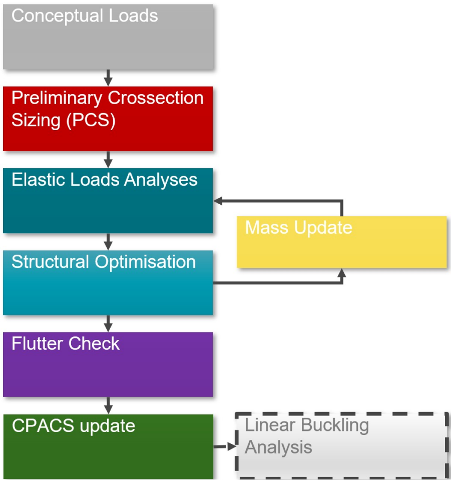


Figure 6: Schematic Diagram of the Loads and Optimisation Software cpacs-MONA

4 Topology Study

Of all the variated topological parameters, the aforementioned PCS-factor is the most sensitive with respect to the primary structural wing mass. In a range of 0.05 to 0.5, the mass varies between 180 and 255 kg. However, as Fig. 7 indicates, the tendency to cause buckling of a whole stiffened panel is also increased, as the moment of inertia of the stiffeners is not present to support it. In an effort to optimise the topology, five manual iterations are carried out, each with a set of parameter combinations. The best design features a relative front spar position of 0.2, six stringers, a PCS-factor of 0.195, and a maximum relative rib distance of 0.05. This way, the cross-section area of the stiffeners is reduced, while the increased number of ribs reduces panel buckling as a limiting factor. Overall, this approach reduces the primary structural mass of the main lifting surface by 19.7 % with respect to the reference design.

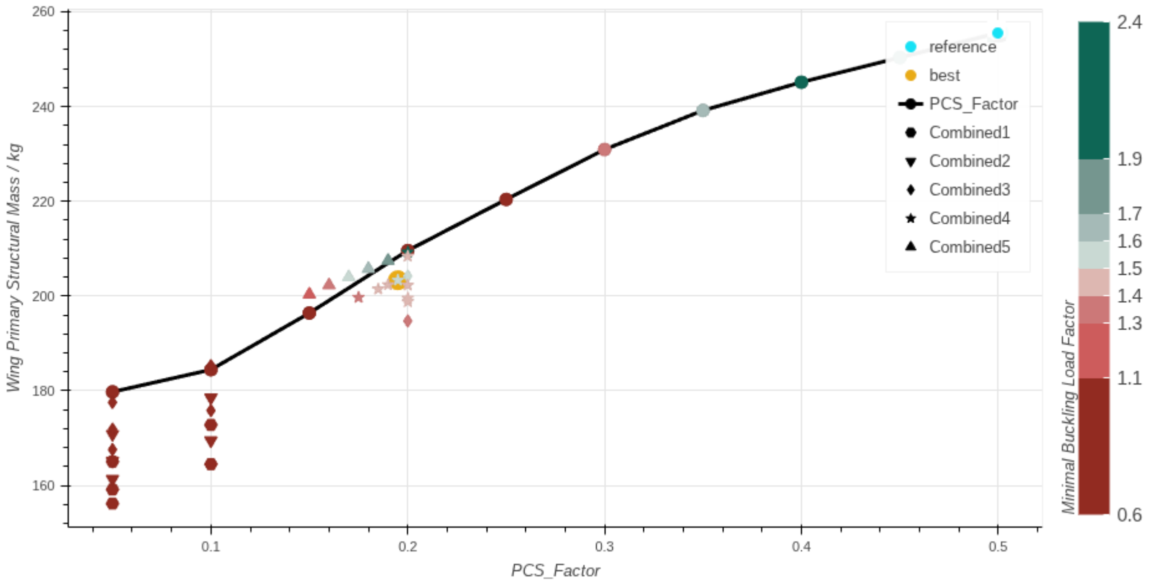
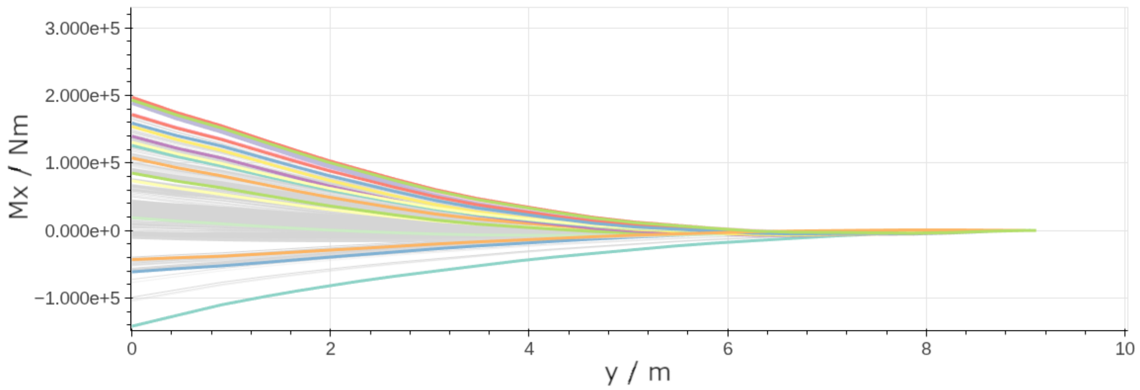


Figure 7: Primary Structural Mass of main Lifting Surface over PCS-Factor

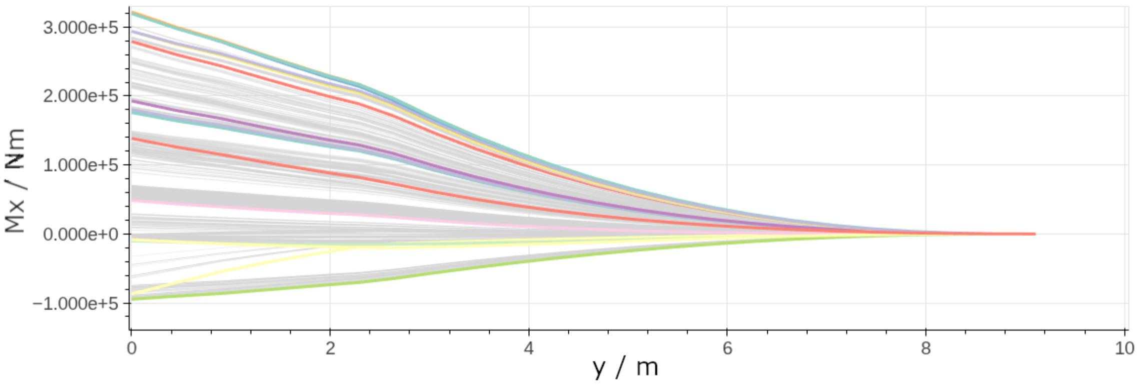
5 Impact of Distributed Powertrains

Since the aeroelastic model of the configuration is only capable of calculating inertia loads for the propeller engines, this study focuses on altering the mass distribution of the powertrain systems. Therefore, the best design emerging from the topology study is altered in such a way, that distributed masses are concentrated in the most inner pods. Furthermore, in order to generate a feasible design, the PCS-factor is increase from 0.195 to 0.25. By doing so, the size of the stiffeners is further increased to prevent panel buckling.

Fig. 8 compares the wing bending moment of the primary lifting surface of both configurations. This reveals an increase of 63 % for the root bending moment of the twin engine design, while the minimal bending moment is reduced by 33.0 %. Furthermore, the maximal torsion moment is increased by 80.3 %.



a): Distributed Configuration

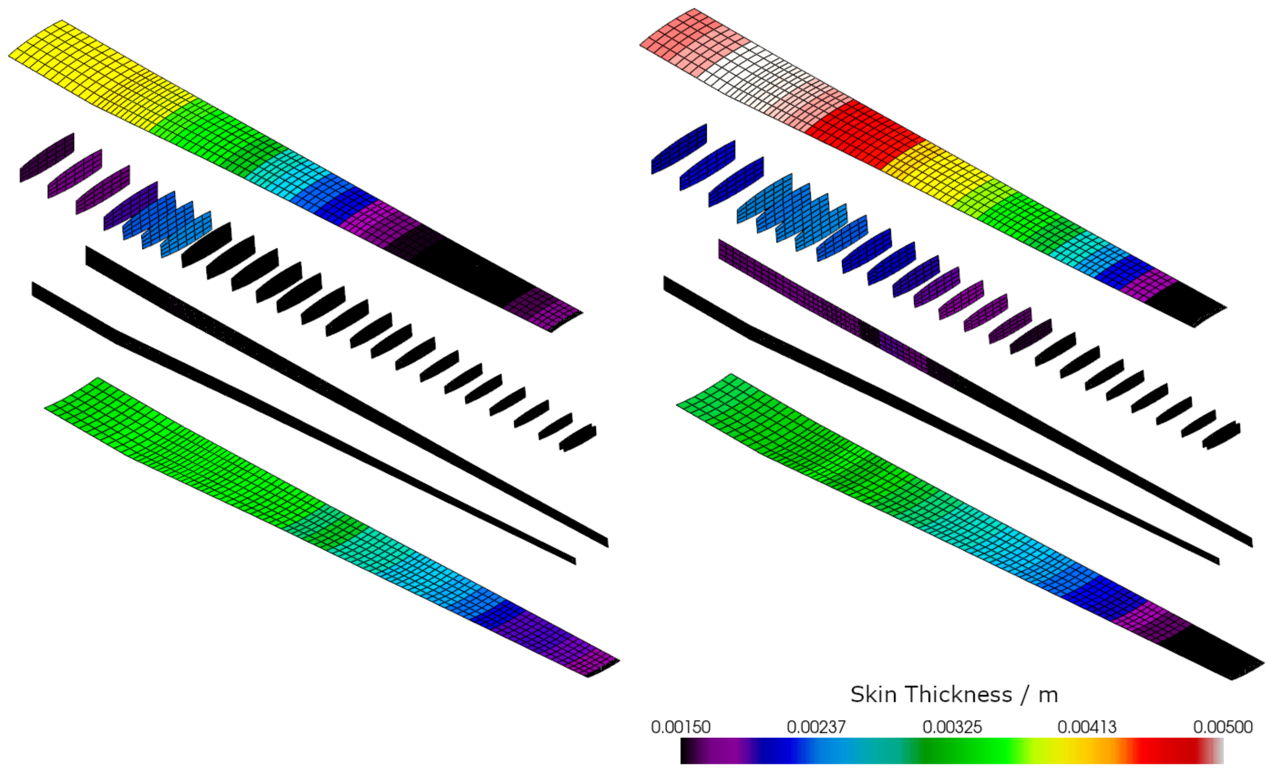


b): Twin Engine Configuration

Figure 8: Wing Bending Moment over Span

This difference in the cutting loads manifest in the skin thickness distributions depicted in Fig. 9. Comparing the distributed configuration to the twin engine design, the maximum upper skin thickness increases from approximately 4 mm to 5 mm, while the thickness of the lower skin is slightly reduced. However, the latter reduction is not enough to compensate the increase on the upper skin, causing a mass increase of 19.3 %.

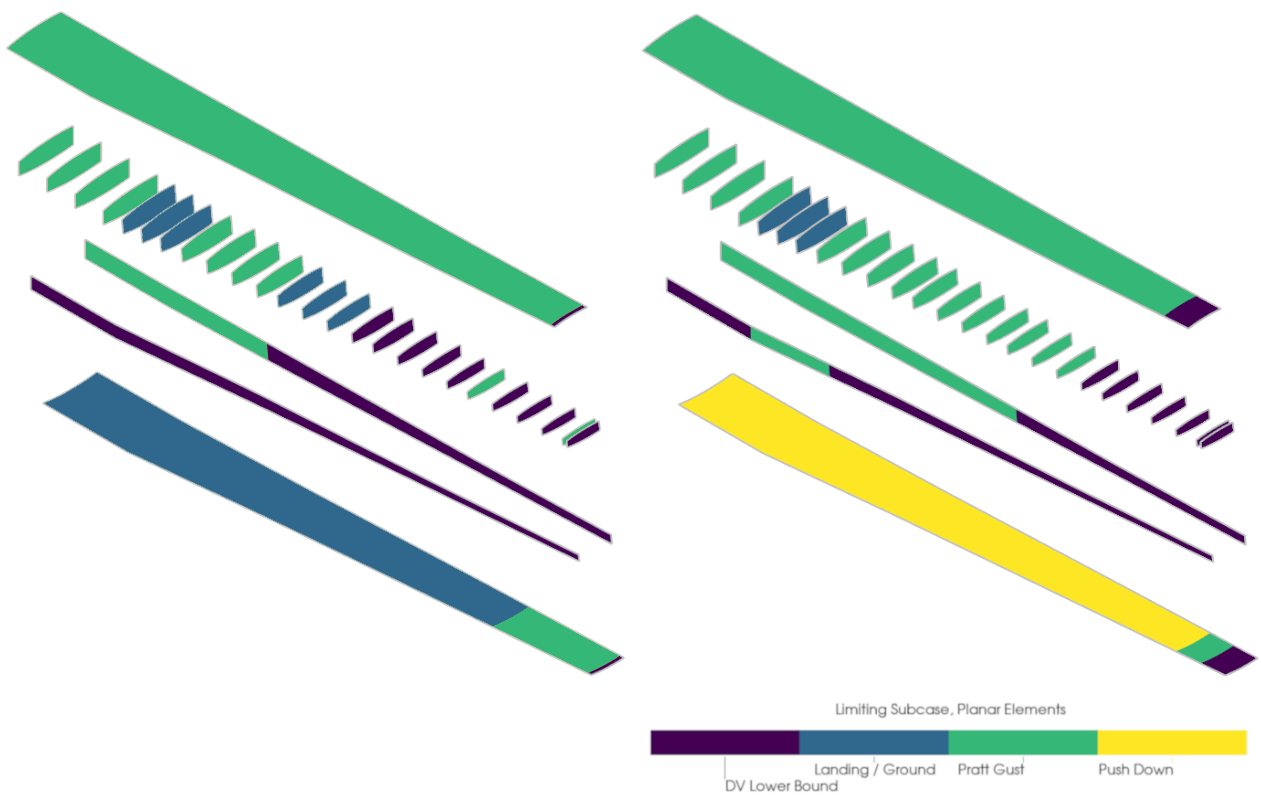
Fig 10 answers the question of why the minimal bending moment is reduced, yet not as significantly as the maximum bending moment increases. On the upper skin, both designs are dimensioned by Pratt-gusts, which constitute static calculations with a constant load factor. Thus, these increase in significance as the inertia loads grow. The lower skin of the distributed propulsion design is dimensioned by ground manoeuvres and landing loads. Thus, higher inertia loads outboard increase the bending. In that regard, the twin engine design is beneficial. However, only until the point at which the push-down manoeuvres take over, in which the outboard engines have an alleviating effect.



a): Distributed Configuration

b): Twin Engine Configuration

Figure 9: Skin Thickness Distribution, main Lifting Surface



a): Distributed Configuration

b): Twin Engine Configuration

Figure 10: Dimensioning Load Cases Types on main Lifting Surface